Lecture Notes in Energy 87

Tanay Sıdkı Uyar
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Renewable Energy Based Solutions

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Renewable Energy Based Solutions

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Foreword

This is a book, which is focusing on renewable energy-based solutions in multiple chapters. These chapters, of course, initially begin with the key introductory contributions, basically to outline the renewable energies, climate change issues, some water scarcity, etc. Also, there are following subjects dealing with cities and effects of climate change and also potential transition of energy systems to utilize renewable energy sources and then proceeding further to look at the technological and industrial dimensions of renewable energy systems, particularly with photovoltaic solar energy systems. In addition, the content is getting into more resilient grid-type approach to look at the smart power networks for local applications as well as making a prime focus on buildings. These are basically the buildings where there is an opportunity to implement renewable energy systems and make the building more sustainable.

To look at also other issues, these are considered essential to look at the electricity production of course in first hand to consider locally for Turkey and then looking at further to move to the regional applications, particularly in Europe as well as worldwide to consider various applications. In this regard, these renewable energy systems are considered in a way really to be part of the present grid system or making them more independent standalone-type applications. Of course, in this edited book, both Dr. Uyar and Dr. Javani are really targeting to make some specific focuses on various important aspects of renewable energy systems, especially with hybridized and integrated types of renewable energy systems. Hybridizing is first done with some conventional energy systems where there is still a use of fossil fuels such as coal and some biomass. To further look at the other types of the systems with cogeneration, trigeneration and even multigeneration, where there is an opportunity for communities to have multiple useful outputs, starting with power, going further to heating, cooling and fresh water.

There are various types of energy systems in particular with renewable energy systems, especially with wave, where there are of course tidal and wave together, and then geothermal, and also biomass, and wind, and solar, even to look at the energy storage aspects, especially with solar energy where there is intermittency and there is an opportunity definitely to look at various dimensions of energy storage applications. Further, there is a close look at the waste to energy option, especially bioenergy using digesters to look at the biomass and the food wastes, particularly for generating energy, primarily bioenergy. There is another key focus on wind energy which is becoming very important as well as in a hybridized manner with solar-wind type combination together for various applications, at the same time to look at the really freshwater needs to develop the systems further for various applications. In addition, there are various types of district energy systems to consider and further analyze and asses for performance evaluations. There are of course geothermal powerplants considered which are considered very important locally and globally. Another important topic, covered by this edited book, is carbon dioxide capturing, storage and utilization for synthetizing into various types of fuels. Here, the book is becoming a kind of important source in getting into hydrogen technologies and also providing a road map or major pathway for energy transition from fossil fuels really into hydrogen. Also, there are multiple chapters to look at the green hydrogen options. Green hydrogen options are really important with renewables and how to deploy 100% renewable energy to create green infrastructure and meet the needs of societies in a green manner.

There are of course various additional subjects where the edited book considers with hydrogen in various sectors, especially with the fact how values are generated by its utilization. In addition, there are of course technological works to consider energy systems in various options. So, this edited book on renewable energy-based solutions is really becoming a unique source as developed by the editors with 32 chapters, and I strongly recommend this for the readers coming from various sectors including academia, industry and governmental agencies, and even NGOs. I finally congratulate the editors and contributors for this publication.

Prof. Dr. Ibrahim Dincer

Preface

Planet-warming effects of fossil fuels terribly require a clear transition to renewable energies as an inescapable direction for humanity. The efforts of phasing out conventional fuels and replacing with renewable energies are on top of almost all governments to avoid catastrophic subsequences of greenhouse emissions. In retrospect, it is not hard to see that an uneven distribution of fossil fuels on the planet has initiated numerously hidden and visible confrontations among different countries. The manifestations of such conflicts can be seen easily all over the globe. On the other hand, wind and solar, as the main renewable energy resources, have somehow an unfluctuating distribution over a wide area of the planet and locally over the countries. Considering such a scenario, the first question naturally comes to an unbiased mentality is searching for different solutions to deploy various renewable energy resources. This is really the main motivation behind the current book, in which the editors have tried to bring different experts in the field together to put forward their thoughts and contributions for possible solutions. A broad spectrum is covered in the specified chapters ranging from climate change to photovoltaic and smart grids and dispatchable renewable energy sources. Numerous contributors also consider the solutions for alternative energy systems in different places, which help deliver a valuable viewpoint to the readers about the efforts taking place in different locations.

Geothermal, wave, and bioenergy conversion systems are discussed in this book. Moreover, taking into account the increasing role of hydrogen as a carbon-free energy carrier, hydrogen-related technologies, and applications to create a pathway to renewable energy transition have been discussed. The latest situation of green hydrogen in Europe is also discussed. The carbon-capture technologies, another hot topic of renewable energies, are covered in the book. Moreover, an unavoidable aspect of renewable energy systems is energy storage due to their intermittent nature. Different energy storage options for renewable energy systems, including thermal and cold energy storage, solar ponds, and mobility, are intensified in this book.

In closing, the editors warmly thank all the authors and contributors for their diligent contribution and gratefully acknowledge the support provided by Prof. Ibrahim

Dincer. The editors also hope that this edited book will be a useful source in the area of renewable energy.

Istanbul, Turkey

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Renewable Energy, Climate Change and Water Resources

Zekai Şen

1 Introduction

Human existence on the earth since time immemorial started to be friendly with the natural environmental resources for the daily needs of feeding, clothing and sheltering in a balance manner even without the full consciousness of the completely worldly opportunities. Wondering and hunting movements were the primitive activities for survival and sustainability.

Human as a creature is under the continuous influences of internal and external motivations through worldly social life and these motivations mold his/her life with alternative happiness and sorrow (depression) periods depending on time and circumstances. In general, as a part of this universe, human is integrated into spatial and temporal operations and changes in the forms of improvements or deteriorations that appear in the process of flowing material and spiritual media. To examine his/her integration with these motivations, it is illuminating to separate the external part as the external environment which consists of material, extraterrestrial and terrestrial types in addition to the internal environment of spiritual existence and reflection. It is possible to divide further the terrestrial environment into various sub-environments as the socio-environment concerning relationships among individuals, institutions, foundations, government and state in general; bio-environment that concentrates on the human interaction with other creatures and plant life; geo-environment concerning the lithosphere and land-scape and all types of natural sources that are at the service of creatures at their habitat on the earth; hydro-environment with water resources, their occurrence, distribution and continuous movements in the universe and especially in the lower layers of the atmosphere.

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Since the creation, in the early periods of human existence on earth, all these environments had impacts on daily human life and survival but as the time passed away with the wisdom and intellectual ability granted to human beings by God, they started to obtain their fundamental needs as food, shelter and clothing by exploiting natural sources in the nearby environments at reasonable rates. These, initial requirements were all very innocent because they were essentials for survival. Although at micro scales the destruction of the environment was started but it took many centuries even millions of years for the human beings to realize destruction of their nearby environment by killing many animals; polluting the air and water sources especially after the invent of fire and its extensive use; through wars inflicting losses on human wealth; forest devastations and many others. At the beginning, human as a warrior against nature consciously and unconsciously continued the destruction at times seemingly for useful activities, but later especially, the scales and extents of environmental destruction were at an unprecedented level alarming each country to ponder about the possible increasing trends towards future and their irreversible damages. Recently, human beings realized that exploitation of nature at the present rate threatens their very existence on the earth. Therefore, many national and international scientific, social, political, and NGOs started to function at full ranges and scales for environmental and ecological protection all over the world.

Unfortunately, materialistic deteriorations in the nearby atmo-, hydro-, bio- and litho-environments coupled with extravagance and luxurious standards of life gave ways to additional comfortability provided by the unprecedented technological developments abasing respects and regards in the traditional, social, religious and cultural lives. Consequently, demoralization in the society in addition to hollow ambitions and feelings without beneficial purposes started to flourish everywhere beyond limits. Parallel to this materialistic destruction in the environment, moral and ethical values also deteriorated with positivistic scientific evaluations void of faith. In the meantime, social ethical illnesses spread out in the society at the expense of innocence, sincere faiths and beliefs which are undeniable elements towards better standards of life. At times human beings found themselves at amidst of chaos and irreversible social, economic and especially environmental unrest and deteriorations. Of course, later it is understood that even the most advanced scientific techniques and technologies are insufficient to restore the genuine original aspects of the environment as they used to be naturally in the past. Furthermore, a new concept as "natural conservation without technological restoration and aid" started to spread within the social, scientific and administrational circles.

From the beginning of the scientific thought, human beings are integrated with nature both as subject and object ends to harmonize their mutual consciousness. Like one of the Turkish sayings as "healthy mind exists in a fit body" we can infer that "emotionally and socially comfortable human beings exist in a healthy environment". This is tantamount to saying that as the environment is rendered into an unhealthy surrounding with pollution in its genuine properties so will the human beings be affected from these pollutions and they will tend to lose their ambition, eagerness and finally thrust in the scientific and technological achievements for preservation of the ecological life and environment. Besides, recent scientific findings regard the human being not as a distinct part of nature but a part of nature active in its change especially related to environmental issues. Hence, social, cultural, moral and faith affairs should be considered as prerequisites in an effective environment and ecological sustenance and control.

Educators, engineers, planners, designers, administrators and managers must consider in their nature interactive designs not only materialistic but equally human internal, spiritual, moral, ethical and social ingredients. This is the only way to minimize the side or after effects that might lead to social and physiological instabilities as well as degradations in the ecology and environment.

2 Environmental Issues

The living creatures sustain and continue their life in different environmental spheres such as atmosphere, hydrosphere, biosphere, lithosphere, which are in harmonious balance and interference among each other.

Human beings, animals and plants are dependent on some gases, water, nutrients and solids that are available in nature rather abundantly but in fine balance and measures and almost freely for their survival. Among these essential commodities, the most precious ones are the air in the atmosphere that living organisms breathe and the water that is available in the form of hydrosphere. The atmosphere has evolved over geological time, and the continuation of life on earth is closely related to the composition of the atmosphere, hydrosphere and lithosphere (Harvey 1982). From the geological records it seems that about 1.5 billion years ago free oxygen first appeared in the atmosphere in appreciable quantities (Harvey 1982). The appearance of life was very dependent on the availability of oxygen, but once sufficient amount was accumulated for green plants to develop, then photosynthesis was able to liberate more into the atmosphere. Unfortunately, during the last century these basic precious commodities for the survival of all creatures are polluted unilaterally leading to global warming and climate change by human beings initially unconsciously at the expense of other creatures and nature but recently for themselves also.

Although emissions may originate from natural or man-made activities, the term emission is often restricted to considerations of air and water quality as modified by human actions, particularly when they are emitted from industrial, urban, commercial and nucleated areas at rates more than the natural dilution and self-purification processes prevailing in the lower atmosphere (troposphere). Emission seems as a local problem with three distinctive geographical factors. First, the wealth of human beings defines the distribution of housing, industry, commercial centers and motor vehicle transportation between these centers. Such a system forms the major source of man-made emission. The second agent that plays a significant role is a natural phenomenon in the atmosphere and hydrosphere which controls the local and temporal climatic weather and quality variations because of which the emissions introduced into these spheres are either scattered in various directions or carried away by as currents. The interaction between the emissions and the spheres may well be modified by

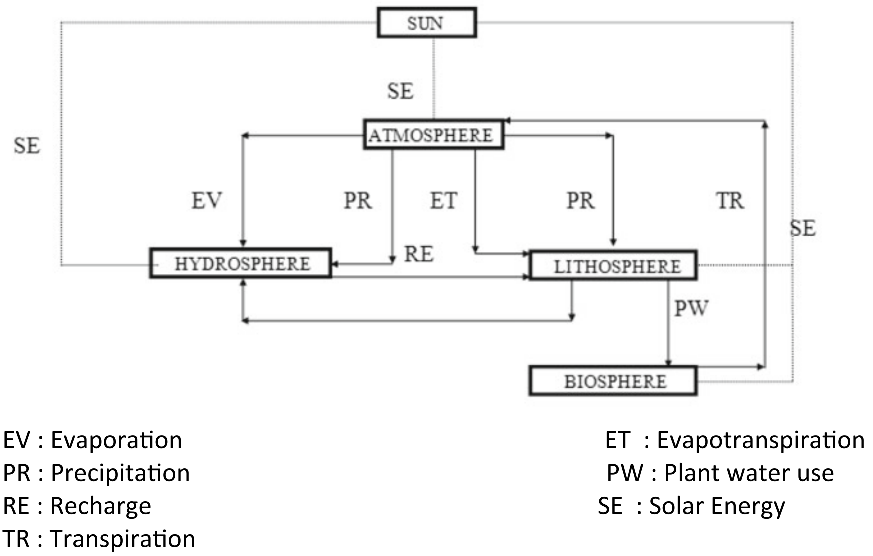

Fig. 1 Various spheres and their environments

local relief factors. Finally, atmosphere, hydrosphere and lithosphere were created in harmonious balance and measures for the sustenance of biosphere where the living creatures' survival. Hence, the equilibrium between these spheres and their harmony with the human beings in the center constitutes the environment and ecology.

In Fig. 1 the four environmental spheres are shown with inter activation elements and especially atmospheric and hydrosphere domains are the most affected elements from the climate change impact and their preservations necessitates the use of renewable energy sources for mitigation and adaptation.

Based on this figure the following inferences can be explained for the integrative action of their combined implications.

(1) The sun is the main source of energy with its clean, friendly, renewable and inexhaustible potential. All the spheres are fed by the solar energy automatically, but the practical benefits from the solar energy will increase by the time and hence, the greenhouse gases (GHGs) emissions to the atmosphere will reduce for better socio-economical sustainable lives.

(2) Atmosphere has the filtering function of the solar irradiation comings from the sun, but it also covers as protective layer the whole world. Any disturbance or damage on the atmosphere shows initial and immediate effects on socio-economic life pattern.

(3) The water vapor in the atmosphere originating from the water resources (fresh or saline) is one of the most essential elements, which gives rise to precipitation in general and rainfall, snow, hail, fog, in particular. The lower layer of the atmosphere is the troposphere, where there are air movements for the existence

of water related activities depending on the surface topography and distance from the equator and sea coastal areas as well as the mountain elevations all of which are the surface features of the lithosphere. Apart from the fossil fuels, minerals and ores groundwater resources are preserved in the depths of the lithosphere.

(4) Hydrosphere includes all of the water related activities qualitatively and quantitatively including rivers, lakes, seas and oceans at the surface depressions of the lithosphere. These are the origin of evaporation from the water surfaces and evapotranspiration from the plants that constitute and continuously feed the atmospheric humidity in the form of vapor. Hence, there is mutual interaction between the atmosphere and hydrosphere environments and the harm on anyone jointly affects the other.

(5) Another very important element is the biosphere including plants, grass, trees and especially forests, which are altogether GHG sink locations. The more is the greenery in the biosphere the less is the GHG emissions, and hence, protection of the troposphere from the global warming and climate change impacts.

Unfortunately, unlimited and uncontrolled technological developments affect the environment leading to various human health problems and spherical emission. Accordingly, measures should be taken for reducing risks concerning environmental emissions and possible ecological imbalances. The various spheres and their interactions for human survival on the earth are shown in Fig. 1. All these spheres and interactions are created by Allah (God) in balance and proportional measurements in harmonious manners which are exposed to human for reflection.

Even though the natural circulation within and among the spheres provides scavenging effects, continuous and long-term loading of atmosphere, hydrosphere and lithosphere have already given signals for undesirable and dangerous expectations in the future which might increase if the necessary precautions are not taken. For this purpose, more research activities are necessary to appreciate the natural events in the atmosphere; pollution in the lower troposphere and transboundary between the troposphere and hydro-lithosphere; energy, transport and industrial emissions generation and their movement; effects of acid rain; waste water leakage into the sub-surface, and especially ground water resources. It seems that success in these areas necessitates, at first glance, sound scientific basic researches and their proper applications. To this end, more extensive climatically, meteorological, hydrological and hydrogeological observation networks should be established for spatial and temporal monitoring of the uncontrollable variables. There should be ever greater cooperation in detecting and predicting atmospheric changes, and assessing consequential environmental and socio-economic impacts, identifying dangerous emission levels and GHGs. It should be emphasized at these stages that from scientific and technological points of view, almost every effort has been done for keeping ecological balance and stopping environment degradation. A major question is whether the scientific approaches in their inhuman consequences towards environment with the lack of moral and faith are enough to restore the balance for sustainable ecology and clean environment?

The emphasis in this section is given on the nonscientific aspects of human behaviors which are among the most necessary ingredients for cleaner and friendly environment and sustainable ecological balance in the long run. Human faith, moral and behaviors furnish, perhaps, the basic requirements for sustainable environment and ecology. Continuous and accumulated environmental degradations in many forms such as, air and water pollution, stratospheric layer pollution, deforestation, desertification, water shortages and pollution, soil erosion etc., are widely spread and often associated with population growth and migration. The environmental degradation impacts are enormous and mediated through social, economic and political structures. Emission movements take place due to either environmental factors such as the climate change, desertification and extreme natural disasters on the one hand, and due to social, political and economic causes on the other. For instance, the climate change might cause human migration because of the:

(i) Diminishing agricultural productivity;
(ii) Sea level rise subjected coastal areas;
(iii) Droughts, wind storms and floods;
(iv) Exacerbation of environmental problems including resource depletion, thereby increasing future conflict factors.

Figure 2 presents the interactive connections among the global warming, climate change, energy and water resources aspects briefly with consequent results.

A detailed study of this figure indicates the following interactive demographic, social, economic and end products.

(1) The major initial effects are population growth, which are rather non-limitable human survival activities in many countries. However, there are works and operations to limit the growth rate especially in developed countries, but this causes to cheap human power immigration that is not wanted for the integration of the country concerned.

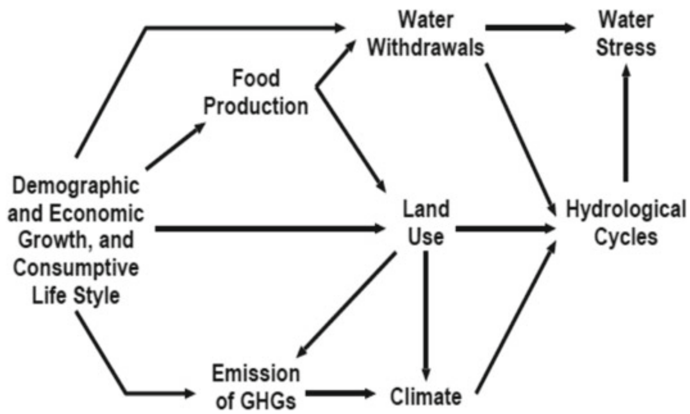

Fig. 2 Climate change, urban areas and water cycle (Oki 2005)

(2) Another growth rate is related to economy, which has as its driving factor the energy for almost all socio-economical, agricultural, transportation, industry and household activities. In many countries currently fossil (coal and oil) energy resources are used in big rates, and they GHGs into the troposphere, which are the main triggering factors for global warming and its consequent impacts in the forms of climate change effects. Although, natural gas has replaced these fossil fuels, but natural gas as fossil fuel origin does not emit GHGs at high rates, therefore its common use is preferable. In the future, fossil fuel replacements are found to increase steadily at increasing rates by renewable energy sources (hydro power, wind, solar, geothermal, current, wave and biomass).

(3) The social incentives in the forms of extravagant life style depending on the consumption ambitions are among the most important anthropogenic activities that should be braked down by each individual. Unfortunately, all over the world advertisements encourage more wastage through consumption. Although there are materialistic movements of "zero waste", however, this is necessary, but not sufficient activity. Instead, cultural, traditional and religious virtues must also be implemented to reduce the wastage.

(4) All the previous items drive towards more food production, land use and change activities paralleled with GHG emissions that are bound to alter the chemical composition of atmosphere. It must be kept in mind that all there involvements are interrelated and reduction in one does not guarantee additional reduction in the others. The primarily important human actions against the climate change impact are the mitigation and adaptation works, which cannot be achieved by scientific solutions only, but at the light of the scientific solution. Implementation suggestion by local and central authorities in addition to public awareness knowledge must be taken into consideration.

(5) The climate change impact appears first of anything on the water resources that are essential sustainability and survival principles of humanity. Due to the climate change, in many regions the rainfall and snow amounts are retracting and these cause not enough replenishment of surface and groundwater resources. Consequently, surface reservoir storages depletes, groundwater levels fall, water stresses, pressures and dry period appearances start to take place leading to meteorological, hydrological and agricultural droughts and insistent continuation may end up with famine.

(6) Water problems start not only between two neighbors, but also among societies, regions and even countries as international conflicts. It is, therefore, necessary to care more carefully on the water resources conjunctive management programs, studies and cooperation between shareholders.

(7) All the aforementioned items jointly lead to hydrological cycle intensification in terms of its weak circulation and meager water potentials compared with the past. This is the worse situation, which may lead to extreme droughts, floods, flash floods and soil, plant and water pollutions in not returnable manners.

The following points are among the most desirable activities to be able to control the impact of climate change in future.

(1) Population growth,
(2) Increase in income, welfare and comfort level of the society,
(3) Increase in the service sector,
(4) Increase in waste, pollution and contamination,
(5) Development of the industrial sector,
(6) Increase the education quality and level,
(7) Increase the artificial intelligence facility usage.

3 Climate Change Effects

Climate is concerned with regional and long term temporal meteorological events that leave trace on the environment among which are atmosphere, hydrosphere, biosphere and lithosphere. Human activities for socio-economic life sustainability necessitate exploitation of these spheres in a balanced manner for environmental protection, and global warming, and climate change impacts reduction.

Climate change is one of the greatest economic, social and environmental challenges of our time (Parkinson et al. 2016). One of the most important implications of climate change is the alterations in regional hydrologic cycles and subsequent effects on the quantity and quality of water resources (Gleick 1996). These together affect water resources in terms of supply, quantity and quality depending on the local conditions. Apart from climate change on the average also climate variability has additional effect on water resources to a wide range of scales. It is well-known that temperature increase causes to evaporation increase and unwanted decrease in the surface water reservoir volumes. The impact on the rainfall regime is another risky situation as for the hydrological cycle normal circulation is concerned.

Anyone concerned with the assessment of climate change should be ready for rational statistical treatment of available temperature and precipitation data with physical interpretations. The selected topics should illustrate the basic assumptions of most statistical methods and/or demonstrate in research as necessary components of one's general understanding of the "quantitative nature" of reality (Nisbett et al. 1987). Further information on each of those concepts can be found in statistical textbooks. Recommended introductory textbooks are: Kachigan (1986), and Runyon and Haber (1976); for a more advanced discussion of elementary.

3.1 Climate Change Adaptation Plan

Adaptation to climate change; It is the process of strengthening, developing and implementing strategies to combat the effects (risks) of climate events, capitalize on opportunities and manage impacts (IPCC 2007, 2013). Studies aimed at reducing and coping with the negative effects of global climate change are generally called "adaptation" studies (UNEP 2011).

In order to adapt to climate change, it is necessary to be prepared for the sustainability of socio-economic activities at the least risky levels by being perceived by the society against the increases in primary energy use and extreme events (temperature increases, flood, drought, etc.) that may occur in changing environmental conditions. In order to ensure the sustainability of Turkey, whose economy is growing rapidly, it should also follow a policy of adaptation in accordance with international climate change conventions (IPCC 2007, 2014). In particular, in order to reduce its dependence on foreign sources in terms of primary (fossil) energy with different adaptation policies, in addition to increasing the energy efficiency of these fuels, reducing the amount of energy used for unit production, making more contribution of renewable energy sources in the energy sector, and climate change by focusing on nuclear energy production. Change needs to make adjustments by adjusting its carbon emissions with policies in a way that does not harm the economy. In terms of energy policies, the basic approach should be to ensure supply security. In order to integrate with international climate change adaptations, it is an appropriate behavior to bring sustainability and dynamism to international integration by paying attention to the socio-economic aspects of preserving the national characteristics in terms of location, development policies, industry and other sectors. For this, it is necessary to adapt climate change policies according to development policies at a level that can make low carbon intensity. Scenarios that will reduce greenhouse gas emissions by including all sectors in order of importance, not according to a specific sector, should be put forward under different policies, and it should try to implement the adaptations with the most suitable one for the socio-economic structure of the country. Instead of making climate change adaptations only by the central authorities, local governments should be involved and attention should be paid to the use of international adaptation principles that may be appropriate for the regional adaptation studies. Although the principles of international harmonization are clear, it must be tried to update the existing harmonization policies on a large scale in the light of new information, taking into account the fundamental conditions of the country's economic development.

The success of adaptation studies is primarily important for determining the effects of climate change impacts on different sectors, especially for energy, agriculture, transportation, industry, housing, waste, land use-land change situations and the vulnerability of forest areas for adaptation processes and sanctions. For any country the following points should be taken into consideration in order to adapt to climate change.

(1) Within a national planning, scenarios that may cause the least damage to the economy are prepared by taking into account the energy use, socio-economic and environmental conditions of the country, the amount of GHG emissions that may cause climate change in the next 20-year, 30-year or longer periods, according to a few of them, the harmonization studies should be started as soon as possible.

(2) Revealing the vulnerabilities of different sectors separately and making a strategy planning in which greenhouse gas emission reductions can be achieved with priority and low cost.
(3) Temperature increases, floods, droughts, etc. that may be caused by climate change. Developing infrastructure and superstructure elements that can minimize the damage of incidents.
(4) In addition to the works to be carried out by local governments on local GHG reduction and climate change, it is very useful to get the support of the central governments, raising the awareness of the administrators and taking the necessary measures on time by making harmonization studies about the characteristics of their own regions.
(5) Providing necessary information trainings to provide basic information that the public can adapt to climate change, albeit on a small scale. In this regards, for example, they reduce the use of consumer goods that can be called waste without the essential need of the people.
(6) Attention should be paid to less use of energy resources of primary fuels (coal, oil, natural gas, etc.) throughout the country; focusing on their more efficient use; giving importance to technological innovative devices for more efficient use of unit energy; obtaining energy technologies in an understandable and applicable way when necessary.
(7) Strive for solutions that can give less GHG emissions to the atmosphere by increasing the quality of coal, which may be the national primary energy source, or by taking measures to reduce the amount of emissions to the atmosphere.
(8) Determining the best management strategies of water and energy resources in adaptation studies and trying to increase sustainability in these matters,
(9) It should be tried to keep the relationship between the environment, ecosystem and energy policies at the best possible and balanced level.
(10) Determining the roles of the society and individuals in cohesion policies within the framework of an effective energy economy model.
(11) Try to increase the forest areas by taking into account the land use of additional sinks.

During any project work in addition to the above-mentioned points, reasonable adaptation opportunities may be put forward by the stakeholders. In order to reduce the effects of the emerging climate change event (with global warming) on different sectors, the adaptation capacity should be reduced. For this, sensitivity analysis, determination and implementation of appropriate adaptation measures, reducing the normal state level and increasing the existing ecosystem resilience should be carried out. Adaptation to climate change is the process of strengthening, developing and implementing strategies to combat the effects (risks) of climate events, and to capitalize on opportunities and manage impacts (IPCC 2012, 2014). Studies aimed at reducing and coping with the negative effects of global climate change are generally called "adaptation" studies (UNEP, 2011). The success of country-specific adaptation studies is important for the determination of the effects of climate change impacts on different sectors, especially for energy, agriculture, transportation, industry, housing, waste, land use-land change situations and the vulnerability of forest areas for adaptation processes and sanctions. In fact, a strategy planning should be made to reveal the vulnerability of different sectors separately and in which GHG reductions can be made with priority at low cost.

At the beginning of the adaptation studies for our country, first of all, determining the types and quantities of the energy tally (inventories). Adaptations need to be made primarily in the energy sector. Fossil-based energy types (especially coal and oil) should be avoided as much as possible and renewable energy sources should be introduced for contribution to the country's economy and reduction of GHG emissions. It should also be decided where to grow plants, vegetables and trees that will reduce GHG in the agricultural sector and provide adaptation to climate change. The industrial sectors, which are also dependent on energy and contribute a lot to the country's economy, should be adjusted to generate the best cost gain for adaptation. Adaptation studies in the transportation sector are possible with the technological development of vehicles, engines and devices that work with electricity, even if it is public transportation and hybrid (hybrid). Apart from these, studies on housing, waste, land use-land change and increasing green areas (foresting, afforestation, etc.) can be planned and put into operation in a way that does not require much direct investment.

There are three interrelated basic stages to combat against the global warming and climate change impacts on societal life and economy.

(1) Political affairs: Effective implementation of existing policies within the framework of adaptation to climate change and strengthening and developing the necessary capacity to develop new policies and strategies.
(2) Scientific affairs: Provision of tools to support compliance efforts using the best available technologies and data, and strengthening and developing the necessary capacity to deliver information to all levels of society.
(3) Implementation affairs: Implementation of practices for harmonization at varying scales and levels from local to central, and strengthening and developing the necessary capacity to monitor and evaluate processes from an economic, social and environmental perspective.

4 Renewable Energy Desires

Clean energy sources are of interest not only to environmentalists, but also to other broad-based occupational groups. Fossil and nuclear energy resources are so important for today's industry studies and developments and for the units that produce for the benefit of society that the research and development of clean energy resources that can replace them is of such importance. Thinking that the amount and production of fossil and nuclear energy resources, which are conventional sources, may decrease over time with effects on energy diversity, efficiency, savings, design, technological developments, energy policy, social structure, economy and even planning. Such thoughts may affect the balance of nature and modern societies in the future. Currently, exact solutions for the use of clean and renewable energy sources that can replace fossil fuels cannot be fully realized even today. However, there is a fact that it is necessary to research and develop energy resources with qualities such as clean, friendly, renewable and sustainable, which will constitute an alternative to fossil energy resources, and their use should be made widespread. Although there are many opinions about clean energy sources, there are some uncertainties and differences of opinion in terms of practical, political and economic aspects of replacing fossil fuels completely. There are differences in the opinions of different experts on these issues. In this respect, the dissemination of research, development and use of clean energy sources are rather slow and constantly faced with questionable obstacles. Making definite proposals and solutions in this regard depend on future technological developments and political decisions. The most reliable aspect of renewable energy sources is that they are potentially available in quantities that can be used in the future. For this purpose, continuous research and development activities are carried out in various countries of the world. Researching clean energy sources requires interdisciplinary cooperation and among the occupational groups that may be related to this the following topics are of interest.

(1) Environmental Sciences: On the one hand, the polluting properties of fossil and nuclear energy sources on the atmosphere (atmosphere) and hydrosphere (hydrosphere), the comparative analysis and explanation of the effects of clean energy sources on their long-term use are among the subjects of environmental sciences. It is one of the important decision variables to investigate the effects of emissions in the air and atmosphere with the use of fossil energy on living things (human, animal and plant). Important issues include the GHG effect, acid rain, and water pollution. Among the relevant issues, climate dynamics and its effects on the biosphere should also be considered.

(2) Most of the environmental problems are related to the quantity and quality of water. Human beings consuming fresh water resources also cause a decrease in the flow rate in rivers. As a result, it is possible that decreases will occur in the amount of water energy (hydro-electric energy) that can be produced over time. Many developing countries cause environmental pollution by using fossil (petroleum and coal-based) energy sources for development. If these countries do not focus on making their development processes sustainable as their economies develop, these problems will increase. Countries need energy consumption for their development, and since a large part of this need is provided by fossil (oil, coal) resources, they are released into the atmosphere with carbon dioxide, methane gas, etc. Atmospheric pollution occurs as a result of the emission of gases. The most reliable future measure of this is the use of clean renewable energy sources by putting them into the stream.

(3) Earth Sciences; Determining the physical assets and dimensions of renewable energy resources, their chemical composition, examining the quality of their

waste, and investigating how the resources are formed are among the subjects of earth sciences. Earth sciences include disciplines such as hydrology, geology and meteorology. In particular, the discovery, distribution, quality and amount of coal, oil, natural gas, geothermal energy are included in the scope of earth sciences.

(4) Technology: Planning the design, production and maintenance units of renewable energy sources and carrying out technological studies are especially important in terms of increasing energy efficiency. Technological developments are needed to make it possible to jointly use and distribute renewable energy resources with currently used fossil resources. Related topics include buildings, machinery, equipment, etc., in addition to researching and increasing the efficiency of current energy uses. Further improvement studies should be carried out in consumer units.

(5) Social Sciences: Technological, social and philosophical issues should be utilized in evaluating the status of small-scale systems compared to larger-scale systems. It is necessary to determine the roles of clean energy resources, which appear in different places at different times and in different amounts, in contrast to the fossil resources collected in certain regions in many countries, in the industrialization and development of that country.

Here, the political decisions of that country are also important. For example, the increase in oil prices has a great impact on the world economy and energy resources.

(1) Planning: Energy production units are dams, thermal power plants, transmission network, wind turbines, biomass cultivation areas, etc. Evaluations of the structures from different aspects should be made and appropriate decisions should be taken. It is necessary to comply with the existing legal and social sanctions in the establishment of these units. Even in the planning of the transportation system, there are benefits to consider not only oil but also renewable energy sources. Energy orientation and designs should be included in a country's 5-year development plans at certain intervals in the coming years.

(2) Policy: Almost every country has a ministry dealing with energy, which examines the country's energy policies through bureaucrats and consultants who are experts in the subject, and tries to make the necessary laws up-to-date. For example, due to the falling prices of wind turbines, which have now come to feasible economic levels, it tries to enact legal adaptations in order to generate electricity from wind energy in appropriate places in order to contribute to the energy grid. In particular, since fossil and renewable energy resources are insufficient for the development of the industry in some countries, options for future energy policies should be produced by providing the necessary cooperation with neighboring countries and countries rich in natural energy resources in political environments.

(3) Operation: It is necessary to plan and produce in advance how the energy resources exist in a country or imported from abroad will be used for the benefit of the country, where and how much energy will be allocated, and how the operation scenarios will be in order to distribute the resources in the

best way. It is important that many dams that contribute to the generation of hydroelectric energy from renewable energy sources, should be operated in a way that will provide the most efficiency. In particular, it is necessary to operate the dam water amounts due to uncertain precipitation and subsequent flows with the least damage, taking into account the possible drought uncertainties for the future.

(4) Education: In order to reveal the best situations, and closely follow the developing energy technologies, from time to time, in-service training courses or scientific meetings such as symposiums and congresses should be held, where researchers, politicians and operators meet jointly. It should be ensured that people related to the subject such as engineers, managers and technicians gather together. It is beneficial to determine the energy research policies of the country by adhering to the common views that will emerge from the discussions held here.

4.1 Problems of Fossil Energy Resources

With the use of fossil fuels, some undesirable problems arise in nature and the environment. Today, the leading ones are always those related to environmental problems. About 20 years ago, sustainability in energy, that is, continuous energy supply, was a problem. Problems such as running out of oil were discussed often. Although these problems are still on the agenda, environmental problems are now leading the list of problems related to energy.

At the beginning of these are problems such as global warming, climate change, atmospheric pollution and GHG effect, which always present the same problem under different names. Such problems have now become the common property of the world public opinion. The main reason for all this is the increase in the concentration of harmful gases released into the atmosphere by fossil fuels used in large quantities. Global warming is the gradual increase in the temperature of the earth due to these gases. It is argued by many researchers and authors that the global warming caused by the gases that cause the GHG effect increases the atmospheric temperature by 0.3 °C every 10 years. As stated by Houghton et al. (1990, 1995), the most important of these is the carbon dioxide (CO_2) gas released by fossil fuels into the atmosphere. Almost 4.5 billion years ago, when the big bang took place, the earth's atmosphere contained plenty of CO_2. This is similar to the presence of 90% CO_2 gas in the atmospheres of the planets Mars and Venus. Although this gas transmits short-wavelength radiation from the sun, it prevents the long-wavelength radiations reflected from the earth causing the earth to overheat. With the natural filtering of the atmosphere of for millions of years, the CO_2 gas, which had a very high percentage in the past, has decreased to 3.5 (0.035%) in ten thousand, where living things can live and its benefits, and its equivalent in ppm is 350. The burning of fossil fuels today increases the amount of CO_2 in the atmosphere. Fortunately, it is possible to predict how dangerous this is and how it will affect future generations, and we can work as the world's public vote to take appropriate measures. In other words, in order for the secretions resulting from the consumption of fossil energy sources not to be released into the atmosphere, we must either reduce their use or provide technological developments that will not release them into the atmosphere by collecting the secretions somehow.

The energy sources are renewable as a gift in nature in different parts of the world not like non-renewable (fossil) energy sources. Tropospheric CO_2 cycle is shown in Fig. 3.

Energy demand is partly determined by weather conditions, and it is natural that climate change and air temperature will have direct effects on energy systems. Changing regional climate patterns will also affect future energy consumption behavior in various parts of the world. The net effect will depend on the region still having a very 'cold' and 'hot' climate, which will vary from season to season. The following points are among the most important energy improvement concerns.

(1) Increasing energy efficiency.
(2) Encouraging energy saving, especially in housing and other sectors.
(3) Optimizing energy management.
(4) Using technologies to prevent energy losses in buildings.

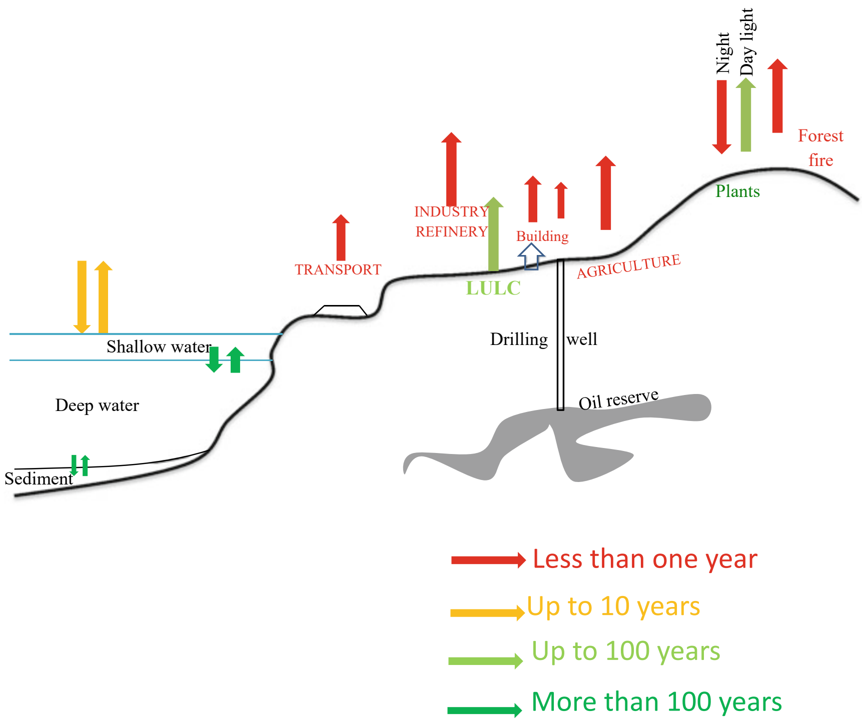

Fig. 3 Tropospheric carbon dioxide cycle

(5) Using advanced energy conversion systems (such as fuel cells).
(6) Increasing land use and areas of forests without destruction.
(7) Moving to high efficiency boiler technologies.
(8) Renewable energy sources are encouraged and necessary R&D studies must be done.
(9) Minimizing the losses in the electricity distribution and transmission network.
(10) Use of energy efficient production technologies.
(11) Ensuring heat recovery with advanced technologies.
(12) Use of advanced boiler technologies.
(13) Increasing energy releases pharynx.

This figure is full of anthropogenic (human) activities for different purposes among which are social, economic, industrial, food and energy securities purposes. Compared to 120 years before there were not such activities, and the nature was in balance from every aspect as for the atmospheric composition, agricultural and many aspects. As explained in Section two extravagant life support and desires gave rise to unbalanced exploitation of natural sources among which the main factor for GHG emissions and consequent climate change impacts is the use of fossil fuels. In the last 20 years global awareness focused on the replacement of the fossil fuels by environment friendly renewable energy sources. These resources are water and wind power, solar irradiation conversions, biomass, geothermal, current and wave energy sources. It has been stated by Şen (2018) that the hydropower can be defined as a source of renewable energy obtained from flowing water in rivers. Hydroelectric energy is the conversion of hydropower to electricity generation from the running water through turbine, generator, and convertor. Hydropower stations are at the downstream location of dams, where the potential energy (PE) accumulation behind the dam is converted to kinetic energy through the pressurized pipes leading to electrical energy. The conversion station may have large-scale generation structures as dams or in small scales as "run-of-river" installations. In both falling water in dams and running water in river channels turn one or more turbines. In nature, it is impossible to create or destroy energy but its form can change. For instance, in electricity generation no new energy is created. In order to generate electricity from water it is necessary that there should be movement, which turns turbine blades and in this manner water kinetic energy is converted to mechanical (machine) energy. The turbine turns the generator rotor, with the help of a magnetic field the mec hanical energy converted into another energy form, which is electricity. In any energy generation, if the initial source of energy is water then it is referred to as the hydroelectric power (HEP) or hydropower. Some HEP plants are located on rivers, streams, and canals, but for a regular, steady, reliable, and sustainable energy generation, water storages behind dams are necessary. Dams are engineering structures that store water for later release to serve irrigation, domestic, and industrial purposes in addition to the power generation. The reservoir acts much like a battery, storing water to be released as needed to generate power.

Hydroelectric energy is the most important naturally supported renewable and clean energy alternative especially in subtropical climate belt of the world. It is one of the most reliable, technically exploitable and environmentally friendly renewable energy alternatives. Hydropower is a capital-intensive energy source with low operations and maintenance cost and essentially no fuel costs (Wilson 2015). Continuously increasing use of renewable energy sources, including hydropower, is a key strategy to limit the extent of future climate change (Harrison and Whittington 2002). Steady rise in the energy demand, coupled with reduced hydroelectricity generation, could lead to a substantial impact on the hydropower operations (Madani et al. 2014). Finger et al. indicated that hydropower accounts for about 20% of the worldwide electrical power production (Finger et al. 2012). Demands for power vary greatly during the day, night, and considerably from season to season. For example, the highest peaks are usually found during summer daylight hours when air conditioners are running. Nuclear and fossil fuel plants are not efficient for producing power for the short periods of increased demand during peak periods. Their operational requirements and long startup times make them more efficient for meeting baseload needs. Since hydroelectric generators can be started or stopped almost instantly, hydropower is more responsive than most of other energy sources for meeting peak demands. Water can be stored overnight in a reservoir and kept until needed during the day, and then released through turbines to generate power to help supply the peak-load demand. This mixing of power sources offers a utility company the flexibility to operate other renewable energy sources most efficiently as base plants, while meeting peak needs with the help of hydropower. This technique can help to ensure reliable supplies and may help to eliminate brownouts and blackouts caused by partial or total power failures.

As for the scientific facets of hydro energy almost all of the aspects are covered in the literature concerning the hydrological, hydraulic, and water resources topics. In many countries industries obtain low-cost energy from the hydroelectric plants from major dams. The environmental issues that are related to hydropower energy generation units, such as dams, run-of-river, and pumped storage plants, have ignorable effects on the atmospheric pollution and also adjacent areas. It is also well known that hydropower plants can enter energy generation interconnected systems instantaneously, whereas other energy sources, such as thermal units, require longer time durations to serve the energy distribution system. All these aspects of the hydro energy re-explained in the following sections of this chapter.

basis of different sets of available literature. The existing calculation formulations are discussed in a detailed manner with their pros and cons, and finally, a new methodology, the energy tree (ET) concept, is presented with applications to two river drainage basins from Turkey and United States. Compared to classical gross hydropower calculation methodologies, ET method provides at least 0.4 to 6.5% improvement, which is a significant addition at the hydroelectric energy plant planning stage.

The knowledge and information in this chapter are useful basic backbone of anyone who would like to work further on the scientific, technological, industrial, environmental, and economical aspects of hydro energy.

Energy efficiency is an important issue for GHG emission reduction studies. The following points are among the factors that will bring benefit.

(1) Reduction in energy costs.
(2) Support energy supply with less energy demand.
(3) Reduction in foreign dependency in energy.
(4) Reduction in GHGs emissions.
(5) Protection of the atmosphere environment.
(6) Insurance of sustainability in energy and environmental issues.

5 Energy-Economy-Environment

In the project studies to be carried out, energy (fossil fuels and renewables) and economy (minimizing GHG emissions with the most economical scenario) and reducing the effects on the environment (GHG emissions released into the atmosphere-GHG-effects) will be involved in three stages. The points to be considered in the study are given below.

(1) Energy studies: Many countries are foreign dependent in terms of primary energy types (oil and natural gas) and import a large amount of fossil fuels every year and releases GHGs into the atmosphere by using them, as in every country. As a result of these emissions, the temperature of the atmosphere increases over the years and as a result of the emergence of climate changes that show themselves differently in different regions, changes in the natural chemistry of the atmosphere occur. Thus, new terminologies such as "greenhouse gas effect", "global warming" and "climate change" have emerged in the international arena. As a result of providing energy resources required for different sectors by burning these fuels, it has come to the fore to combat the emissions of basic atmospheric polluting gases such as carbon dioxide (CO_2), methane (CH_4) and nitric acid (N_2O).
(2) Energy modeling studies: One of the main problems of combating climate change is trying to control the emissions of the energy source to the atmosphere. The economy is very important for the development of every country, and the GHG emissions, which are released into the atmosphere by the use of energy in different sectors that are the supporters of the economy, come to the fore.

Figure 4 shows the simplest energy modeling components in the form of a black-box.

Economic model elements for greenhouse gas reduction is shown in Fig. 5 with all inclusive elements.

Key variables include GHGs released into the troposphere. For instance, undertakes to consider HFCs, PFCs, SF6 and NF3 gases, including CO_2, CH_4 and N_2O, in its goodwill document.

Fig. 4 Energy black-box model

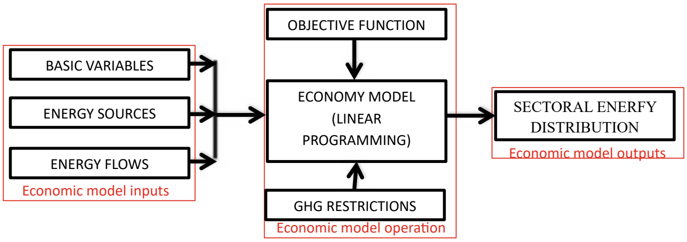

Fig. 5 Detailed economy models

The limitations to be imposed for each of these gases will also provide information on how the economic model will distribute economically the energy for each of the sectors, among the outputs. Furthermore, Fig. 6 presents the tropospheric GHG emissions roadmap about the fossil fuel activations.

By taking the scenario that may arise until 2030 as a basis for the ordinary situation and by putting the additional elements specified in the figure into action, different projections are obtained, among them the cheapest in terms of GHG reduction, It will be tried to reach the best (optimum) analysis in terms of the country's economy.

As a more detailed energy supplement with fossil and renewable energy sources are presented in Fig. 7.

In the non-ordinary energy model, the factors mentioned in the energy studies section must be put into effect. Among these, it is very important to reduce the use of fossil fuels and make them more efficient by improvements, and to use domestic renewable energy sources as much as possible instead of the reduced fossil energy sources. Thus, the development of basic methods, economic and climate models provide for additional contributions to the country's economy and sustainability. It is possible to reach at tangible and soft information by means of the aforementioned models as well as numerical and verbal domestic information in the light of the available data, on what kind of energy policy or policies to be pursued in the future long years. In the following is the list of points related to the model structure.

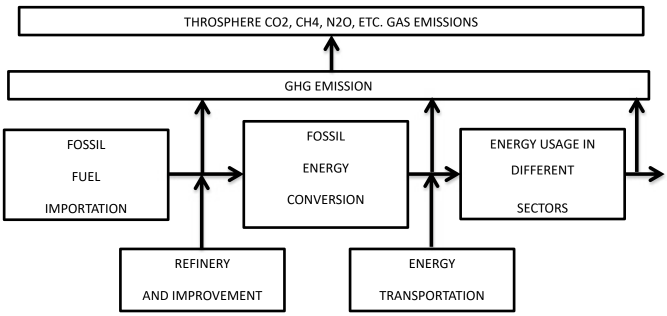

Fig. 6 Fossil fuel emissions into the troposphere

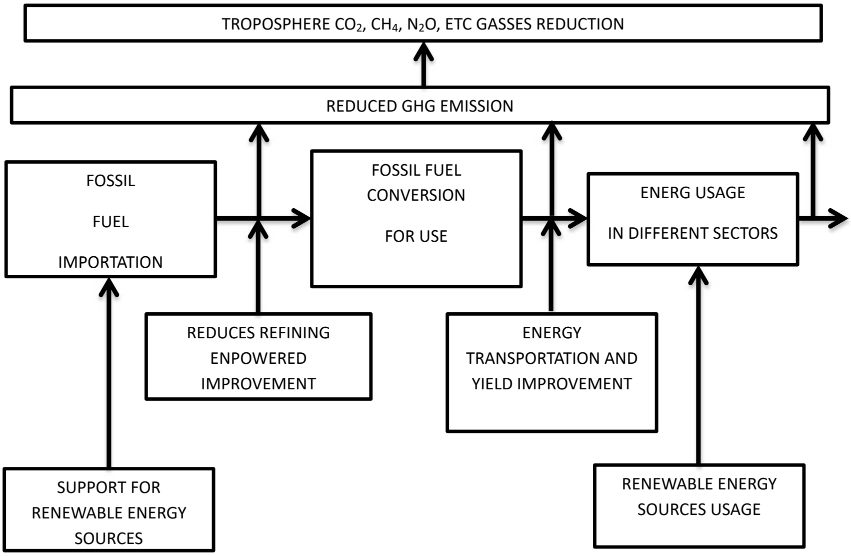

Fig. 7 Fossil and renewable energy sources model

(1) Logic, formula, method, algorithm, mathematical structure, etc. of the internal structure of the model to be used. It is to understand the operating style thoroughly and to calculate the GHGs contribution values in different countries accordingly. In addition to the general structure of the model, it is necessary to understand its economic importance. It is recommended to indicate the similarities and differences by comparing different models with each other.

(2) In addition to the determination of the input data by thoroughly researching and understanding the model components in accordance with the conditions of a country, the full description of the model and the explanation of its parts.

(3) Verbal and numerical definition must be grasped concerning the initial and boundary conditions for the model structure, parameters and sizes. During the optimization study the model constraints should be determined in addition to the investigating the causes of errors and inconsistencies that may arise during model processing and adapting it according to local and national conditions.

(4) The step-by-step usage flow diagram of the selected model should be specified and the model operation management features should be determined. Verifying the model first with a well-known input–output set.

(5) Running the model software in a way that includes all the available data, extracting the results and presenting them in the form of tables, figures and algorithms with verbal comments.

6 Water Resources Assessments

Water is such a commodity that cannot be substitutable by any existing materials and its internal structure is the combination of flammable two hydrogen and extinguishable one oxygen atoms.

Engineering structures help to manage the water resources utilization according to demand and supply side requirements in the best possible (optimum) manner. Different alternatives are developed and applied in water sector over many years, but they do not take into account the climate change affects explicitly. However, some countries water resources managers become to care about the climate change effects, which is rather significant in the coming decades especially in the mid-latitudes and some subtropical climate belts of the world. If reservoirs are full after a wet period then a short-lived summer flood may not end a water resources drought caused by prolonged lack of reservoir inflows. Hence, droughts are not dependent on possible climate changes only but critically on the water resources system characteristics and especially on their management. In-stream and off-stream consumptive and non-consumptive exploitations of water resources are expected to be affected in the long-run.

There are several indicators of water resource stress, including the amount of water available per person and the ratio of volume of water withdrawal to volume of water potentially available. When withdrawals are greater than 20% of total renewable resources, water stress is often a limiting factor on development (Şen 2009); withdrawals of 40% or more represent high stress. Similar water stress may be a problem if a country or region has less than 1700 m^3/year of water per capita. Simple numerical indices, however, give only partial indications of water resources pressures in a country or region because the consequences of "water stress" depend on how the water is managed (IPCC 2007). The potential impact of climate change on the hydrologic regime is a crucial question for water resources management. Potential change in hydrologic regime resulting from changed climate is an important topic in contemporary hydrology and water resources management.

There are four major ways of storing water, namely, in the soil profile, in underground aquifers (including underground dams), in small reservoirs and in large reservoirs behind large dams. Storage in the soil profile is extremely important for crop production, but it is relatively short-term storage, often only sufficient for a period of days. Other three kinds store water for periods of months, in small reservoirs, or years, in aquifers and large reservoirs. Aquifers, small and large reservoirs all serve an indispensable role in water storage and each alternative has strong comparative advantages under specific conditions of time and place. If it is possible to do so substantial gains can be achieved by combining all three storage technologies in an integrated engineering system. Any configuration consisting of a set of engineering storage structures for water resources management is referred to as an engineering system. Man can generate and enhance water storage by such activities as water conservation tillage, constructing dams and dikes to impound water and artificially recharging groundwater. Regardless of the method or type of storage, the purpose is to capture water when and where its marginal value is low or, as in the case of floods, even negative, and reallocate it to times and places where its marginal value is high.

Engineering structures include dams, reservoirs, weirs, levees, aqueducts, dikes, wells, qanats, culverts, canals, distribution pipe network, treatment and desalination plants etc., which help human to cope, adopt, operate and manage inherent temporal and/or spatial variability in water resources planning, design, operation, management and maintenance. To the average citizen engineering structures are largely invisible and taken for granted. Yet they help insulate people from wet and dry years and moderate other aspects of our naturally variable climate. Indeed the engineering structures help us to almost forget about our complex dependences on climate.

Water resources engineering systems are major social engineering units that are essential for individuals, societies, countries and humanity, in general. The development of any country is measured with the water resources system availability and adaptation to natural (droughts and floods) and man-induced variations (including climate change).

Engineering systems help to manage the water resources utilization according to demand and supply side requirements in the best possible (optimum) manner. Climate change can be regarded as one of the accumulating variability. Different management alternatives are developed and applied in water sector over many years, but they do not take into account the climate change effects explicitly. However, some water resources managers become to care about the climate change effects, which will become rather significant in the coming decades especially in the mid-latitudes and some subtropical climate belts of the world. If reservoirs are full after a wet period then a short-lived summer flood may not end a water resources drought caused by prolonged lack of dam inflows. Hence, droughts are not dependent on possible climate changes only but critically on the water resources system characteristics and especially on their management. Climate change will affect the complex infrastructure of engineering systems in place to manage the society's water and existing climate variability. It is not that the construction of additional dams which indicates the development level of a country, but rather an efficient management program of the existing dams.

It is important to estimate the magnitude of potential changes in dame at the land surface (e.g., lakes, seasonal snow-packs, soil moisture, groundwater, glaciers, and ice sheets), changes in fluxes of water (e.g., precipitation, evaporation, runoff, and groundwater recharge), and changes in atmospheric water storage and transport, all of which have profound influences on the earth's energy cycle, hydrological cycle and global climate change processes. Toward this end, a better understanding is needed of what causes both short-term and long-term variability in these fluxes that couple the surface dams of water with each other as well as with the oceans and atmosphere.

An understanding of mechanisms linking large-scale climate variability with regional conditions also forms the basis for reducing the uncertainty associated with assessing regional impacts of climate change over decadal-to-centennial periods. A region-specific ability to project the consequences of global change is now required, for example, by decision-makers concerned with long-term fixed capital investments in infrastructures such as dams, water diversion systems, and flood damage mitigation systems that are vulnerable to shifts in hydro-climatic regime. The IPCC (2007, 2012, 2014) review reports of climate impact studies suggest large differences in the vulnerability of water resource systems to climate variables. Isolated single-reservoir systems in arid and semiarid areas are extremely sensitive. They lack the flexibility to adapt to climate impacts that could vary from decreases in reservoir yields in excess of even more than 50% at one extreme to increased seasonal flooding at the other. In contrast, highly integrated regionally interconnected systems are inherently more robust.

Changes in the quantity, quality, and timing of runoff stemming from greenhouse warming would affect in-stream water uses such as hydroelectric power generation, navigation, recreation, and maintenance of ecosystems. These changes might also affect in-stream water demands, directly or indirectly. For example, changes in streamflow would alter actual and potential hydroelectric power generation through dams, which in turn would affect the demand for substitute sources of electricity. Maintaining minimum in-stream flows to protect an endangered species or recreation benefits when supplies become scarcer requires major adjustments in the use of water. On the other hand, protecting off-stream uses could threaten the sustainability of some aquatic ecosystems. Tradeoffs between in-stream and withdrawal water uses would increase if water supplies became scarcer or more variable as a result of climate change. The optimum and sustainable maintenance of streamflow volumes is possible through a rational, integrated and inter-regional management programs. Climate change has the potential to either aggravate or alleviate an area's water situation. On balance, however, the impacts are likely to be adverse because the existing water infrastructure and use are based on an area's past climate and hydrology records. During most of this century, dams, reservoirs, pumps, canals, and levees provided the primary means of adapting to climate and hydrological variability and meeting the growing demands for water. While the focus was on supply-side solutions, institutions that establish opportunities as well as incentives to use, abuse, conserve, or protect water resources were slow to adapt to the challenges of growing scarcity, rising in-stream values, and the vulnerability and variability of supplies. In recent decades, however, the high financial and environmental costs of water projects, along with limited opportunities for building additional dams and reservoirs to develop new water supplies, have shifted the focus away from new construction to improved management of existing supplies and facilities, and also toward demand management. New infrastructure may, in some instances, eventually prove to be an appropriate response to climate-induced shifts in hydrological regimes and water demands. But it is difficult to plan for and justify expensive new projects when the magnitude, timing, and even the direction of the changes at the basin and regional levels are unknown. Narrowing the range of uncertainty for improved water planning, operation and management depends on a better understanding of:

(1) The processes governing global and regional climates;
(2) The links between climate and hydrology;
(3) The impacts of the climate on unmanaged ecosystems;

(4) The impacts of ecosystem change on the quantity and quality of water;
(5) The impacts of increased atmospheric CO_2 on vegetation and runoff.

In the meantime, the possibility that a warming could result in greater hydrological variability and storm extremes should be considered in evaluating margins of safety of long-lived structures such as dams and levees that are under consideration anyway. In particular, low-cost structural and managerial modifications that ensure against the possibility of a range of climate-induced impacts should be sought. Unlike the structural supply-side approach, demand management that introduces additional incentives to conserve and opportunities to reallocate supplies as conditions change does not require long lead times, large financial commitments, or accurate information about the future climate. Integrated management of existing supplies and infrastructure at the river basin and watershed levels offers a potentially cost-effective means of increasing reliable supplies and resolving water conflicts in many regions. While the prospect of climate change adds another element of uncertainty to the challenge of matching future supplies with demands through different storages (dams, weirs, dikes, etc.), it does not alter what needs to be done to ensure that water is managed and distributed wisely.

In general, climate change is expected to lead to more precipitation coupled with more evaporation, but the important question is how much of this precipitation will end up at water deficit areas? If not then regional management of water engineering infrastructures comes into view with sustainable water distribution programs. On the other hand, probable precipitation increase in some areas and decline in others is another indication for regional water resources distribution to needed areas through an efficient management programs. The main solution for reducing the local and regional vulnerability to climate change requires improved water resources engineering systems management prior to any capacity increase with new engineering structure design and construction (dams). In this manner the existing supplies will be used efficiently. Long-term management studies will also indicate for the necessity of engineering structures, if any for the region. Efficient management strategies should include regulations and technologies for directly controlling land and water use, incentives and taxes for indirectly affecting behavior, the construction of new dams and pipelines to boost supplies, and improvements in water-management operations and institutions. Other adaptation measures can include removing levees to maintain flood plains, protecting waterside vegetation, restoring river channels to their natural form, and reducing water pollution.

Vast and complex infrastructure of dams and pipes can be planned and built to provide justified fresh water resources distribution based on an effective management program which takes into account a multi-purpose optimization helping to industry, disposal of wastes, transportation facilities, hydroelectricity generation, crops irrigation, and floods and droughts risk reduction.

The vulnerability and sensitivity of water engineering systems and management rules, the strengths and weaknesses of technologies and policies might help to cope with adverse impacts and take advantage of possible beneficial effects. Certain aspects of water resources and engineering infrastructure are very sensitive to both climate and to how to manage complex water systems. It is, therefore, necessary to have mediators in the form of engineering structures (such as dams) in order to offset or diminish the sensitivity to various expected and unexpected changes in the future. Changes in management of the engineering systems requires understanding what changes would be most effective and then applying the will and direction of those responsible. Water managers and policymakers must start considering climate change as a factor in all decisions about water investments and the operation of existing facilities and systems.

A continued reliance solely on current engineering practice may lead to make incorrect and potentially dangerous or expensive decisions. Conventionally, water resources system operation and distribution practices should be designed and for the most part are operated assuming that future climatic and hydrologic conditions will look like past conditions, which is no longer true. Accordingly, two of the most important coping strategies must be to try and understand what the consequences of climate change will be for water resources and to begin planning for and adapting to those changes through real-time operation and management programs. Dynamic management strategies of dams can be effective in mitigating the adverse impacts of climate change, but such policies need to be implemented before such changes occur to maximize their effectiveness.

Water engineering systems including more than one dam are highly developed and water managers have a long history of adapting to changes in supply and demand. Past efforts have been focused on minimizing the risks of natural variability and maximizing system reliability. Many of the approaches for effectively dealing with climate change are little different than the approaches already available to manage risks associated with existing variability. Tools for reducing these risks have traditionally included supply-side options such as new dams, reservoirs, and pipelines, and more recently, demand-management options, such as improving efficiency, modifying demand, altering water-use processes, and changing land-use patterns in floodplains. This work is going on largely independently of the issue of climate change, but it will have important implications for the ultimate severity of climate impacts.

Sole reliance on traditional dam management responses is a mistake. First, climate changes are likely to produce, in some places and at some times, hydrologic conditions and extremes of a different nature than current systems were designed to manage. Second, climate changes may produce similar kinds of variability but outside of the range for which current infrastructure was designed and built. Third, relying solely on traditional methods assumes that sufficient time and information will be available before the onset of large or irreversible climate impacts to permit managers to respond appropriately. Fourth, this approach assumes that no special efforts or plans are required to protect against surprises or uncertainties.

The role of subsurface dams must not be forgotten in the management of groundwater resources especially in arid and semi-arid regions where evaporation losses are high. Records of past climate and hydrological conditions are no longer considered to be reliable guides for the future water resources system design, operation and management. The design and management of both structural (dam, weir, dike, etc.) and non-structural water-resource systems should allow for the possible effects of climate change, but little professional guidance is available in this area. Further research by hydrologists, civil engineers, water planners, and water managers is needed to fill this gap, as is broader training of scientists in the universities. There should be a systematic re-examination of engineering design criteria and operating rules of existing dams and reservoirs under conditions of climate change. Information on economic sectors most susceptible to climate change is extremely weak, as is information on the socioeconomic costs of both impacts and responses in the water sector. More work is needed to evaluate the relative costs and benefits of non-structural management options, such as demand management and water-use efficiency, or prohibition on new floodplain development, in the context of a changing climate.

The flexibility of large storage structures is further reduced when they are multi-purpose and potentially conflicting demands (for example, hydropower generation and irrigation) exist. Other factors limiting the flexibility of large dam operations are the many parties and levels involved in their management and countless institutional prerequisites. Small dams have the advantage of being operationally efficient. They are flexible, close to the point of use and require relatively few parties for management. Because of these attributes, they can be responsive to demands, the supply to demand mismatch can be small and managerial and institutional issues are easier to handle. Large surface dams have the advantage of greater yield relative to the available inflow than small reservoirs, and their yield is generally more reliable. This is because of lower evaporation loss fractions in large reservoirs are due to their greater depth. Large dam reservoirs are more complex to operate than small reservoirs and groundwater systems from the standpoint of meeting the needs of the individual user. If climate changes, as a result of global warming manifests, the need for freshwater storage will become even more acute. Increasing storage through a combination of groundwater and large and small surface water facilities (dams) is critical to meeting the water demands of the twenty-first century.

Reservoirs emit greenhouse gases due to the rotting of organic matter, including submerged vegetation and soils and the detritus that flows into the reservoir from upstream. The diffusion of carbon dioxide into the atmosphere from reservoir surfaces accounts for most of the global warming impact of dams in boreal and temperate regions, as well as deep tropical reservoirs. For shallow tropical reservoirs, however, methane bubbling up from the reservoir bottom appears to contribute most to their climate impact. Some researchers believe that releases of dissolved methane from water discharged at turbines and spillways may prove to be the largest component of the warming impact of tropical hydropower.

7 Combined Discussion

The elements of renewable energy, climate change and water resources as essential environmental survival elements are also in an interactive manner affect each other.

(1) Compilation: Physical and physical information about past and future climate changes.
(2) Data base.
(3) Adaptation: Climate on the biosphere and socio-economic systems assessment of the effects of change.
(4) Mitigation: GHG emission reduction.
(5) Prioritization of Technology Research and Development (R&D) issues.
(6) Determination of plans and targets with reliable efficiency and potential.
(7) Opening the way for the renewable energy sector by enacting the necessary laws.
(8) Sufficient state, industry and university for R&D studies providing support.
(9) Buying and using the produced energy immediately and protecting the producers enactment of laws.
(10) Establishing and guaranteeing environments where producers can sell their production.
(11) Infrastructure required to take the energy to be produced to the main distribution network.
(12) Preparation of necessary promotion and training programs.

It is the most important thing to establish a sustainable energy future that will generate for a country where resources are used more rationally, negative effects on the environment and human health are minimized, energy services are diversified with new technologies in addition to new resources, alternative energy resources are put into service in the most beneficial way, and people's economic and social expectations are met.

Protection of the ecology and total environment between various spheres has been foreseen so far through the scientific and technological means but unfortunately as can be witnessed today by everybody these materialistic approaches failed although billions of dollars are spent on much diversified projects. Nobody should deny that the scientific measures and controls are necessary for combating the ecological and environmental pollutions and destruction, but they are not sufficient because in the vary basis of these activities are the human ambition, desire and intentions for domination on nature and extra benefits. The very purposes of the science and technology lie within the human intention, intellect and heart. It is, therefore, necessary prior to anything to control and improve these spiritual ambitions for the sustainable achievements in the environmental issues. It must not be forgotten that although science brought materialistic achievements for human comfort in this world, but in the meantime it did not care about other virtues for the sustenance of human race in this globe among which are the ethical, moral and cultural well beings depending on faith. Due to the religion-science fights in some cultures, for the last 5 to 6 centuries the religious virtues including belief, moral conduct, behavioral manners and especially faith were not cared for the sake of scientific and technological achievements. The positivistic scientific activities excluded metaphysical, religious and ethical virtues should suffice for the prosperity of human comfort and happiness. Consequently, the societies and societal lives become miserable with many spiritual illnesses and their curing are not possible by materialistic medicines suggested by medical doctors only but also by unmaterialistic medicines provided by faith and religion. The basic philosophy in scientific and technological advancements is the intellect in a rational and limitless manner and experimental knowledge only. These limitations are imposed through the faith and belief virtues that should be heeded by any Muslim. During the scientific achievements heartily, affairs are ignored completely giving sole weight to mind, intellect, rationality and their various combinations. The love for science comes through the intellect but it is not welcome to say that "One loves other by his/her mind". The love for almost everything is by heart and in Islam love for knowledge and scientific achievements are through the restricted rationalistic activities of the mind but supplemented by faith they become knowledge or science after the approval in the heart. Without such an approval the science is destructive and there are not long-term benefits from it. In our modern times, this becomes very evident that for a long-time activity in the materialistic scientific affairs starting almost from the sixteenth century onwards, furnished in front of the eyes that the side effects of gigantic scientific achievements are damaging not only the ecology and environment but additionally the morality and faith. Knowledge and science are supported in Islam but with restrictions based on the moral, faith and spiritual virtues.

The final goal of many activities should be under the light of sayings of Prophet Mohammad (p.b.u.h.) as:

> the best of a human being is who serves other human beings

It is that human beings care for benefit whatever affair they execute, but there are differences in the types of the benefits. In general, it is possible to divide the types into two categories as materialistic benefits and the rest. Herein, the rest includes the benefit of the community, humanity and society. In Islam, the benefit for oneself is also accounted in the materialistic category after the basic rational and materialistic survival benefits are excluded. If this principle is worked out with the advancement of science and technology then the scientific achievements should have restrictions coming from the preservations of balances in and among different spheres such as atmosphere, hydrosphere, lithosphere, biosphere and human relationships. After all what have been explained in the sections, it is possible to derive out the following perspective and further research needs for better protection and conservation of the environment according to Islamic virtues.

(1) In the preservation of environmental surrounding not only the materialistically oriented targets but at the very basis faith, belief and religious orientations must be considered.
(2) The scientific and technological achievements are very mechanistic if they are not coupled with metaphysical basis especially faith and ethics.

(3) In the long run it has been observed all over the world that religious thoughts are becoming asymptotically convergent to each other and from now more effort is necessary for the achievement of such togetherness.

(4) Modern time without faith has almost every material for the comfort and extravagant life but it is not without surprise to observe that within the same societies moral and ethical values are devoid of faith and consequently depressions, stresses and suicide rates increase. On the other hand, in the traditional societies, although materialistic well beings are not abundant but environmental and internal peace prevails. It is therefore necessary to combine the qualities of both societies for the sake of better greenery and sustainability.

(5) Since ethics and moral provide common basis for the faith there should be approach between great religions of the world within dialogues and mutual understanding for nature preservation and ecological balance restoration.

(6) Rather than scientific and technological developments to control the nature they should be controlled for the common interest of human safeguard in the world through ethical and faith virtues. So, ways towards to this end should be sought through gatherings and critical discussions among different cultures.

(7) Education circles in different universities and even secondary schools should include in their curriculum ethical, moral and faith principles with the purpose of fulfilling their duties to the humanity in general and to keep environmental balance, in particular.

(8) Medieval and other era scholars' and philosophers' views should be reevaluated with the present day ecological and environmental issues.

(9) The life of human beings on the earth should be coupled with the balance and order in the universe and nature as created by God.

8 Recommendations

After all what have been explained in the previous sections, the following recommendations provide individual, institutional and national care for renewable energy generation, climate change and water resources maintenance and conservation away from extravagant style of life.

Although there are many studies with comprehensive explanations of the climate change and variability scientific works on meteorological, climatologic and hydrologic assessments for vulnerability, mitigation, adaptability and capacity increment topics, still many gaps and uncertainties are among the unanswered questions. As for the engineering water structural aspects and causes for their future behaviors or new planning, design, operation, maintenance and management the literature has not systematic information source. The following points may be counted among the necessary further considerations.

(1) Existing energy and water structures must be reviewed under the light of climate change and the necessary implementations and improvements must be considered according to local and regional climate projections.

(2) Extreme events, especially floods, flash versions and droughts in addition to desertification possibilities must be searched not only scientifically, but additionally strategically, socially, economically, ethically and morally.
(3) Although there is climate adaptation guidance, in general, for many regions, but one should concentrate on local adaptation possibilities by taking the views also from shareholders.
(4) General Circulation Model (GCM) results and their future projection by means of effective downscaling procedures must be reviewed and revised at least after each 5-year or 10-year periods. In the meantime the resolution of downscaling methodologies must be refined by innovative approaches and methodological techniques.
(5) Climate change and variability impacts must be evaluated specifically for Metropolitan Cities for social sustainability within physiologically endurable limits.
(6) At coastal regions, the necessary precautions against the possible climate change and variability impacts in addition to the sea level rise problems must be taken by suitable engineering structures and scientifically appropriate solutions.
(7) Early warning is much in discussions, but in many places these are taken as advises without actual applications, and even the ones might not be based on the possible climate change and variability impacts.
(8) Especially in arid and semi-arid regions intensive rainfall events and their aftermaths as floods bring erosive material into engineering water structures such as dams and cause sedimentation, which reduces the storage capacity (Bussi et al. 2013). It is, therefore, advised to cause settlement before surface water entrance into the impoundment structures by settling basins in the upstream of the structure.
(9) Water management systems must be revised such that they adjust not only according to climate change projections, but also about the capacity of engineering water structure.
(10) Engineering water structures are given dimensions according to the classical methodologies, but they must be managed according to their capacities with consideration of the climate change and variability impacts and the future structures must be coupled with climate projections.
(11) In many locations, due to climate change trend searches are intensively used especially for precipitation within the same drainage basin there may be differences in some branches, and therefore rather than a single point assessment regional trend maps must be prepared.
(12) Floods are one of the most dangerous natural events that cause human life and property, but unfortunately their flood hazard maps are not ready in many regions.
(13) In humid regions, due to climate change impact groundwater resources are abstracted more than recharge, and hence groundwater levels fall and the storage volume reduces in addition to water quality deterioration.

(14) In arid and semi-arid regions, the sole water resource is groundwater storages; their levels also fall, but due to floods and flash floods the storages can be artificially recharged through runoff harvesting methodology.
(15) Even though the significance of groundwater resources is emphasized in various publications as a remedy for water supply, but the infiltration capacity of soil has not been sufficiently investigated under the climate change impact.
(16) In order to set up functionality of regional water resources management through water transfer possibility among drainage basins necessary engineering water structures must be considered for improved planning, design operation and maintenance purposes.
(17) Especially, karstic groundwater resources are susceptible to climate change, but in the literature there are rarely researches about them and the fractured medium water availability under climate change with suitable engineering water well fields. Due to the climate change, the solution cavities in karstic medium are bound to expand leading to additional groundwater recharge.
(18) In IPCC (2007, 2014) reports most often humid region drainage basins are considered, but arid and semi-arid region water resources calculation methodologies and formulations need some modification under the climate change impact so as to dimension the water structures accordingly in an adaptive manner with climate change coping.
(19) In the design of engineering water structures rather than future trends more importantly variability (jumps, abrupt trends, shifts, extremes) play significant role and their further researches are necessary.
(20) Real time climate change adaptive water structure impoundments must be managed including their multi-purpose and multi-storage operations.
(21) Innovative techniques and suggestions are among the software information that should come especially from the local experts for better climate change adaptation (Nassopoulos et al. 2012).
(22) Engineering water resources units must be equipped with new technologies that are friendly with the environment leading to less GHG emissions.
(23) Apart from the flood hazard map and early warning system, flood inundation maps are also necessary for climate change mitigation.
(24) In order to identify dry and wet periods and make water structure design accordingly rather than monotonic trend determination partial trend sequence must be searched in a given record.
(25) As mentioned in the text water structure dimensions and performances are dependent on intensity and frequency of extreme events, but there are rare investigations on these features.
(26) Climate change variability is a major factor that causes to fluctuations in hydroelectric power generation, and therefore, time changes in this energy generation affect production.
(27) Substantial snow-pack drainage basins are expected to change as a result of global warming in runoff occurrence timing and intensity with earlier peak runoff discharge. It is, therefore, necessary to manage these changes with existing system modifications for future operations adequately.

Water harvesting in the forms of rainfall and runoff provides opportunity for water resource augmentation through proper structural hardware. These structures reduce downstream runoff discharge, but provide additional surface and groundwater storages. The rainwater harvest on the surface is a traditional method by digging vast ditches, but more developed techniques include bends, small dams, weirs, underground tanks and ponds. Şen (2015) has explained the principles of runoff harvesting for the purpose of groundwater recharge. For harvesting, in general, the following water structural units may be used.

(1) Pits: These are constructed for shallow groundwater storage recharges, and in general, they have 2 m length, 1 m width, and about 3 m depth. These pits are filled back by boulders, gravels and coarse sand.
(2) Trenches: These are useful harvesting construction when the stream is permeable at shallow depths. Depending on the water availability their dimensions may have 0.5–1 m width, 1–1.5 m depth and 10–20 m length. They are filled back by filter materials.
(3) Hand-pumps: Shallow/deep aquifers may be recharged by simple hand pumps. It is necessary that water should pass through a filter prior to its entrance into hand pumps.
(4) Recharge wells: In general, their diameters vary between 100 and 300 mm, and they are employed for deep aquifer recharges. In order to avoid chocking of the well periphery water must pass through an effective filter.
(5) Recharge shafts: This is useful for shallow aquifer recharge below clayey surface. They may have diameters from 0.5 to 3 m with 10 to 15 m depths. Similar to pits they are backfilled by boulders, gravels and coarse sand.
(6) Lateral shafts: These are coupled with one or two bore wells for groundwater recharge to shallow or deep aquifers. Their dimensions are 1.5–2 m width and 10–30 m length. They are also backfilled by boulders, gravels and coarse sand.
(7) Spreading technique: The use of this technique is suitable with the start of permeable layer right from the surface. Water from the streams can be spread by small dams, gabion structures, percolation ponds or cement plugs.

Another water harvesting type is to accumulate rainfall and runoff water behind small surface or subsurface dams and in large scale ditches so that on one hand, local people can benefit from the surface water and also it replenish subsurface groundwater reservoir by natural or artificial recharges. Effective harvesting applications necessitate the following components.

(1) The horizontal projection of drainage area with its main channel and branch tributaries.
(2) The locations suitable for groundwater recharge especially along the main and branch channels.
(3) Storage facilities may be composed of surface and subsurface dams, weirs, cisterns, ditches.
(4) Additional water structures such as the injection wells with inlets at a set of elevations.

9 Conclusions

The future human activities are bound to concentrate on the impacts of climate change and global warming related socio-economic activities among which the most pressing ones are the fossil energy usage reduction and its replacement by renewable energy sources and also the precious water resources for sustainable life aspects. The triple combination of climate change, renewable energy and water resources must be carefully studies in a better and refiner forms for each location, region and country and even through corporation among neighboring countries and especially those riparian countries that share transboundary water surface or groundwater resources. The initial problem solution must be directed towards the replacement of fossil fuels by renewable energy (hydro, wind, solar, wave, current, hydrogen) sources. This chapter presents some basic principles concerning the triple individual and interactive operative activities.

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Cities, Climate Change and the Transition of Energy Systems

Baha Kuban

The world's urban population has multiplied more than ten times during the last 100 years and within the next decade, there will be more than 500 cities with population exceeding a million people, in addition to many 'megacities' with populations exceeding 20 million (Fig. 1).

The urban population of planet earth has passed the rural population in 2008, a trend that was apparent in developed countries by mid-century. The twentieth century development has of course been the rapid pace of planetary urbanization which requires re-visiting the term urban.

What is urban? Traditionally, the definition of "urban" is contrasted with rural, where there is a juxtaposition of relatively autonomous groups. There is interaction among villages, but they can survive (almost) independently. In the urban world, on the contrary, every part of the territory makes a contribution to the functioning of the whole. Every urban neighborhood depends on the contributions of others for its survival. In this way, the big city, with its different neighborhoods and districts, traditionally embodies the urban. Today, however, the urban has exploded spatially. The so-called "global" city is deeply embedded in international flows of goods, people, materials, and capital: for example, the head office of a company may be in Paris, but its factories and customer-service centers will likely not be in the Parisian suburbs, but rather in Wuhan or Rabat. This exemplifies the concept of "planetary urbanization, which is intrinsically linked to the globalization of capitalism. Basically, the spread of planetary urbanization involves four inextricably connected processes: (1) the disappearance of "wild" zones, (2) the global interconnectedness of territories, (3) the blurred division between town and country, and (4) the globalization of urban inequalities (Fig. 2).

Meanwhile, cities have strengthened their role as drivers of innovation and entrepreneurship that account for a disproportionately strong share of a country's

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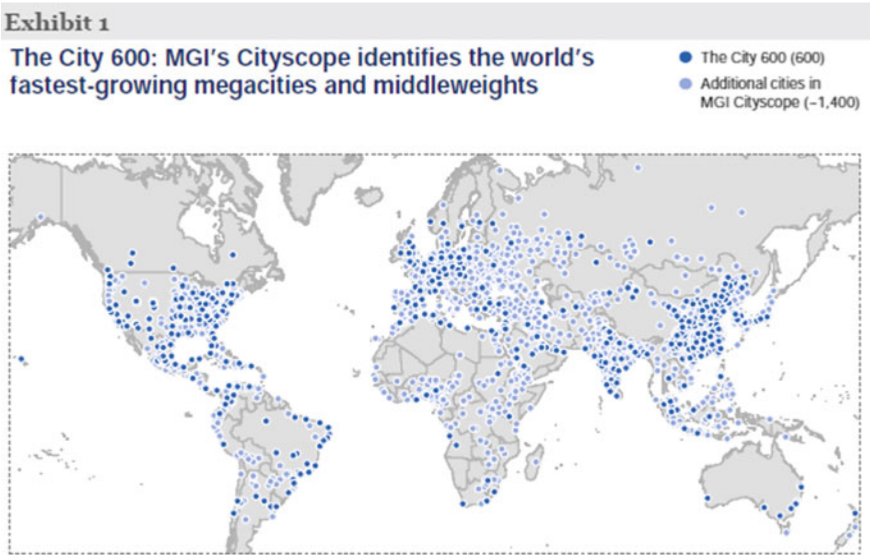

Fig. 1 McKinsey's city 600, the geographical distribution of globe's fastest growing cities (McKinsey global institute, cityscope 1.0)

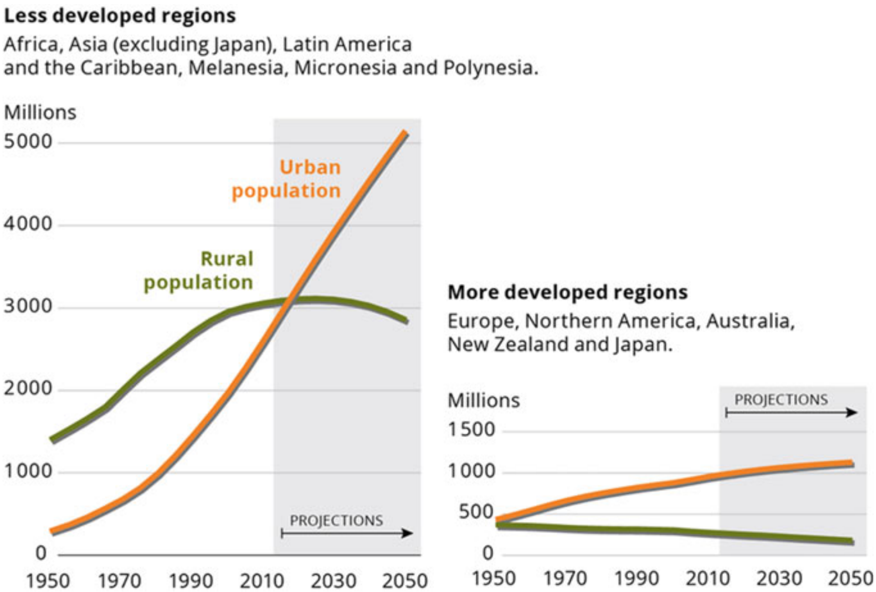

Fig. 2 Urban versus rural population change in the world. (European environmental agency https://www.eea.europa.eu/data-and-maps/figures/urban-and-rural-population-in)

GDP per capita. It can be argued with some force that, the innovative activities are the products of cities or regions and that cities and urban regions are not just mere containers for innovative activities but are actively involved in the generation of new ideas, new organizational forms and new enterprise. Most of the challenges societies face today are exacerbated within urban areas; this is both one of the underlying reasons for greater innovation in cities, and one which can eventually be overcome by harnessing this same, vital innovation. The high level of provision of education, services and leisure activities, combined with a high population density and the very high frequency of interactions notably found in cities, favour technological and social innovation, entrepreneurship and creativity. However, some cities are able to harness most of their potential and do more with their tangible and intangible resources than others. Cities that succeed in innovating are those where people are less mechanical units of production and more the creators of wealth. Cities shift from having a density of resources to a density of networks and circuits where proximity to resources was substituted by proximity to knowledge' (Fig. 3).

As shown in the McKinsey City Scope 1 Report, just 1000 large cities account for around 70% of the global GDP with estimates of 75% for the top 2000 cities. Planetary urbanization has made cities both the source and solution of climate change problems.

- Cities are the major contributors to CO_2. Roughly half of the world's population lives in urban areas, and this share is projected to reach 60% by 2030. Cities

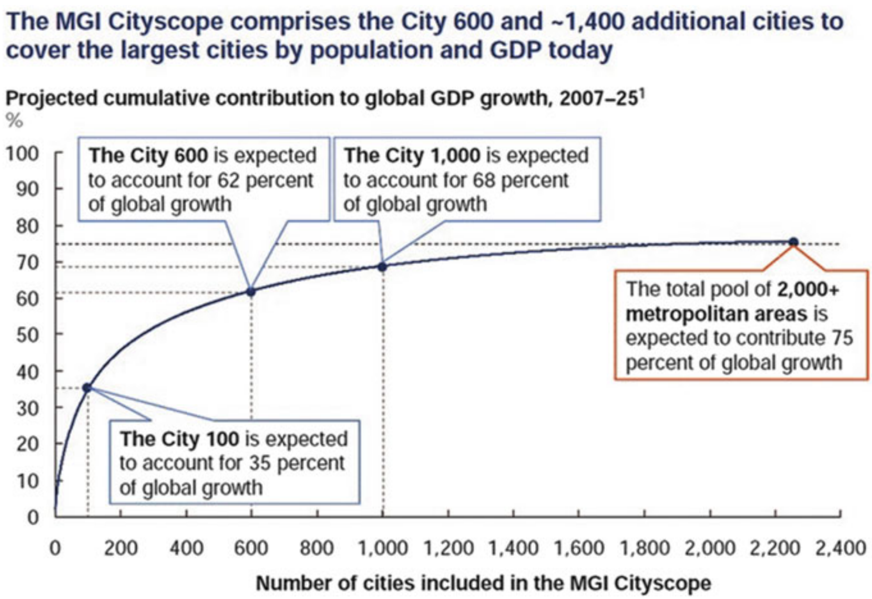

Fig. 3 Projected cumulative contribution to global GDP growth by cities (McKinsey global institute, cityscope 1.0)

consume between 60 to 80% of energy production worldwide and account for a roughly equivalent share of global CO_2 emissions.

- Cities are also highly vulnerable to climate change. Many of the world's largest cities are located in coastal areas. This increases their vulnerability to rising sea levels and storm surges, risking livelihoods, property, and urban infrastructure. Heat waves will be more intense in urban areas due to urban heat island effects. Urban heat waves have killed tens of thousands of people in the world in the recent years.
- City policies and urban action are part of the climate solution. How cities grow and operate influences energy demand and thus greenhouse gas emissions. Lifestyles, spatial form and public transport availability are also crucial. Urban policies (e.g. densification or congestion charges) can complement global climate policies and reduce the overall cost of emissions abatement.
- Robust frameworks for multi-level governance and enabling national policies will advance climate actions. Local authorities can help achieve national climate goals through urban policies to reduce energy demand and improve resilience to climate change. National governments can help create a sound institutional foundation and knowledge base to support local decision makers engage with stakeholders to identify and carry out cost-effective actions.
- Cities and regions must play a key role in fostering the green growth agendas. Cities are policy laboratories for action on climate change. Urban governments are taking serious action on climate change—even in the absence of national policies—through local regulations, urban services, program administration, and city purchasing and property management. Cities can stimulate green jobs by raising consumer awareness, raising the eco-efficiency of local business, facilitating cleantech start-ups and supporting training programs.

Climate change mitigation and the options for abatement are best summarized by Marginal abatement Cost Curves (MACC) where the relationship to urban energy options are made clear via the various abatement options. A marginal abatement cost curve (MACC) is an estimate of the amount and cost of opportunities that will reduce emissions in a given year (Fig. 4).

Each box on the curve represents a separate opportunity to reduce emissions. The width of each box represents the emission reduction potential which a specific opportunity will deliver in the chosen year, compared to business-as-usual. The height of each box represents the average net cost of abating one ton of CO_2e (carbon dioxide equivalent) through that activity in that year. Capital costs are annualized to make all opportunities comparable.

The graph is ordered left to right from the lowest cost to the highest cost opportunities. Those opportunities that appear below the horizontal axis offer the potential for financial savings even after the upfront costs of capturing them have been factored in. Opportunities that appear above the horizontal axis are expected to come at a net cost.

A real MACC curve looks like the one below, generated by McKinsey for the year 2030 (Fig. 5).

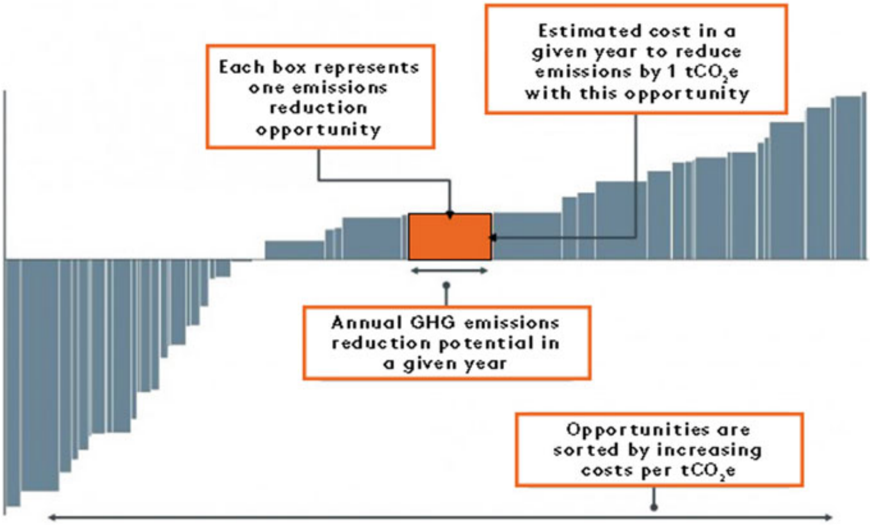

Fig. 4 The marginal abatement cost curve—MACC (http://www.climateworkscentre.org/resource/how-to-read-a-marginal-abatement-cost-curve/)

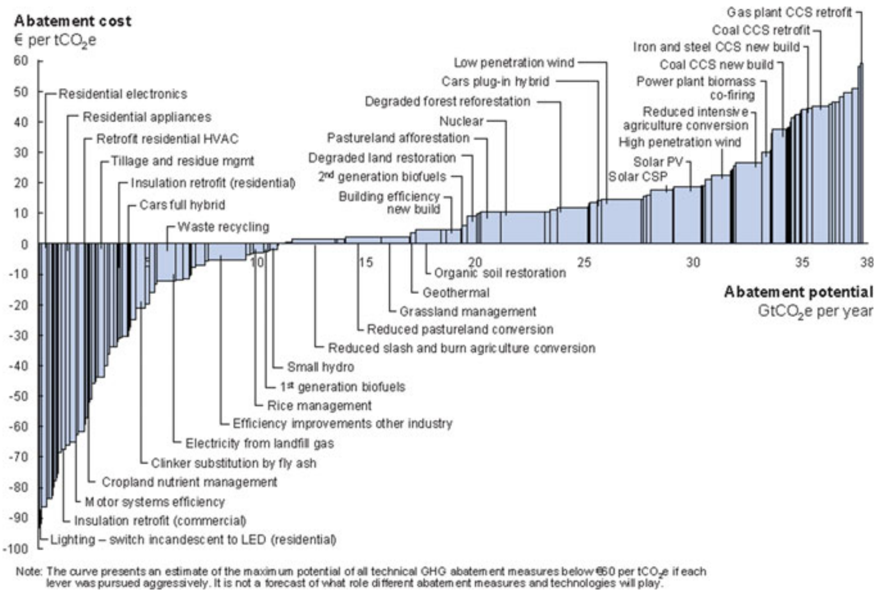

Fig. 5 McKinsey's global climate change mitigation MACC curve (Climate Policy 12(2), 2012)

A careful look at the MACC curve quickly reveals the *urban potential* for climate change mitigation. The highly feasible options for abatement come from building related interventions such as building insulation, energy saving techniques in the built environment and alternative fuels in urban transport.

Legal commitments to reduce CO_2 emissions require policy makers to find cost-efficient means to meet these obligations. Marginal abatement cost (MAC) curves, which illustrate the economics associated with climate change mitigation, attract a great deal of attention. A number of limitations with MAC curves are explained by the implication they should be just one tool in a broader set of decision-making aids used in assessing climate policy. MAC curves, for example, omit ancillary benefits of greenhouse gas emission abatement, treat uncertainty in a limited manner, exclude intertemporal dynamics and lack the necessary transparency concerning their assumptions. MAC curves based on the individual assessment of abatement measures suffer from additional shortcomings such as the non-consideration of interactions and non-financial costs, a possibly inconsistent baseline, double counting and limited treatment of behavioral aspects. Reducing emissions from deforestation and forest degradation exhibit many of the above-mentioned problems, making it particularly difficult to capture in a cost curve. Policy makers should therefore be cautious when interpreting MAC curves, pay attention to the underlying assumptions, consider non-financial costs and be aware of the important uncertainties and underlying path dependencies.

1 Urban Energy Systems; Policy and Socio-Technical Transitions

The production, distribution and consumption of energy and emission of greenhouse gases are entrenched in and conditioned by large infrastructure systems—of energy, of transport or of the built environment. They are a constitutive part of our societies' metabolism with nature—the flow and exchange of resources—and are tightly interlinked with the social organization of production and consumption in growth oriented, modern economies. A substantial reduction of carbon emissions as urgently demanded by International Treaties such as the Paris Accord of 2015 inevitably require radical re-structuration of these socio-technical systems of energy, transport and built environment. Increasingly, cities are recognized as important arenas for innovative policy and action to reduce greenhouse gases and energy consumption. Many initiatives and programs for sustainable transport, sustainable buildings, energy efficiency or the use of renewable energies are crafted and implemented at the urban level. Thousands of European and other cities have signed the European Covenant of Mayors CoM and many more are producing climate neutrality goals and targets. However, what ambitious greenhouse reduction targets and related infrastructure policies require is nothing less than an 'energy transition'—i.e. a radical reconfiguration of the way generation and use energy in cities and beyond, is undertaken. Given the global reach and interdependency of infrastructure systems—technologically, politically and economically—the capacity to achieve energy transitions primarily at an urban level may seem questionable. However, the distributed nature and specific socio-technical dynamics of such processes nevertheless make cities an important arena of infrastructure transformation and a crucial nexus between different levels of governance and strands of socio-political discourse. A growing body of research has been dealing with transitions of unsustainable current configurations of systems of energy, mobility or agriculture. As researchers of urban change have noted, dimensions of space and scale have so far been insufficiently integrated in these concepts and consequently underestimate the role of cities as crucial loci of change within broader transitions towards a less carbon-intensive world. Some of the crucial questions are; To what extent can local infrastructures and socio-technical constellations be shaped independently from general patterns of provision and consumption, global or national market dynamics and higher-level policies? Can such deviations even influence the transformation of dominant, large, highly integrated infrastructures which (materially and institutionally) reach far beyond city boundaries (impact on the broader transition regime)? In other words, to what extent can alternative urban energy visions be implemented and stabilized at a local level and how is this process shaped by, and is shaping socio-political and sociotechnical contexts at different spatial scales?

Science and technology studies (STS) have gained a sophisticated understanding of the interdependent processes of social and technical change. Energy systems are socio-technical configurations where technologies, institutional arrangements (for example, regulation, norms), social practices and actor constellations (such as user–producer relations and interactions, intermediary organizations, public authorities, etc.) mutually depend on and co-evolve with each other. Innovation processes are becoming increasingly distributed and complex and are an outcome of the interaction between a multitude of actors, related to many different institutions and locations. Many of these approaches analyze the interrelation of stability and dynamics of socio-technical change and refer to the multilevel perspective of technological change (MLP). This perspective distinguishes three levels of structuration: a level of confined technological niches as a source of variety, as a testbed for new technologies and as an 'engine for change'; a level of socio-technical regimes (for example, the energy system) providing stable structures and a selection environment for innovations and, thirdly, a broader context of the socio-technical landscape, which encompasses cultural norms, values or only slowly changing broader social structures (Fig. 6).

The central element in this concept is the meso-level of the socio-technical regime at which socio-technical configurations are temporarily stabilized and supported by a rule set that structures the socio-technical co-evolution process. The regime level incorporates the mutually reinforcing technological and institutional structures of specific domains such as the energy system and is characterized by a resistance to

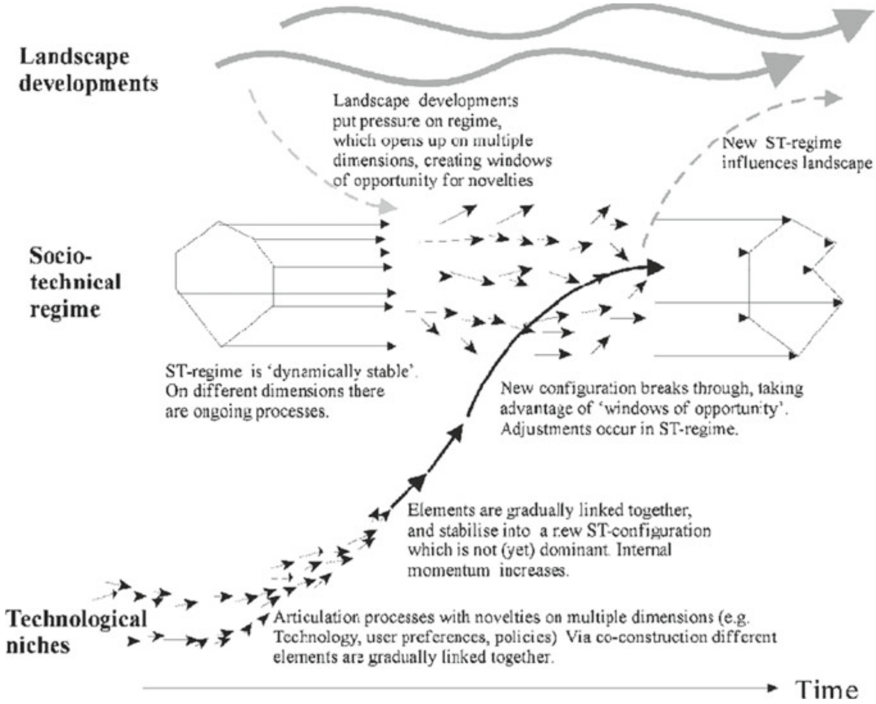

Fig. 6 "Low carbon transitions", GoodFellow publishers, 2016

change (which, for example, may cause promising new technologies to fail). Nevertheless, under specific circumstances regimes may undergo fundamental transformations, especially if radical innovations (technological and/or institutional) coincide with strong outside pressures on the regime.

The considerable importance given to the analysis of differences between different types of innovations, i.e. incremental, radical and disruptive, is another key feature of the socio-technical transition approaches. *At the heart of innovation lies the fundamental understanding that it challenges the 'status quo' making things–better, different… using resources, capabilities, competences in new ways.* Some attributes for innovations could be stated as; stay relevant in existing markets—incremental innovation, stay engaged with developing and possibly changing markets-radical innovation, and, stay ahead of markets with things that were not possible before-disruptive innovation (Fig. 7).

The creation of novel technologies and radical change thus is brought about by the interactions of multiple levels: niche innovations creating novelty and building up momentum, destabilized regimes creating windows of opportunity for transformative change and changes at the macro level of sociotechnical landscapes creating pressures on the regime. This underscores the multidimensionality of processes of socio-technical change, the multiplicity of actors involved in the process and the

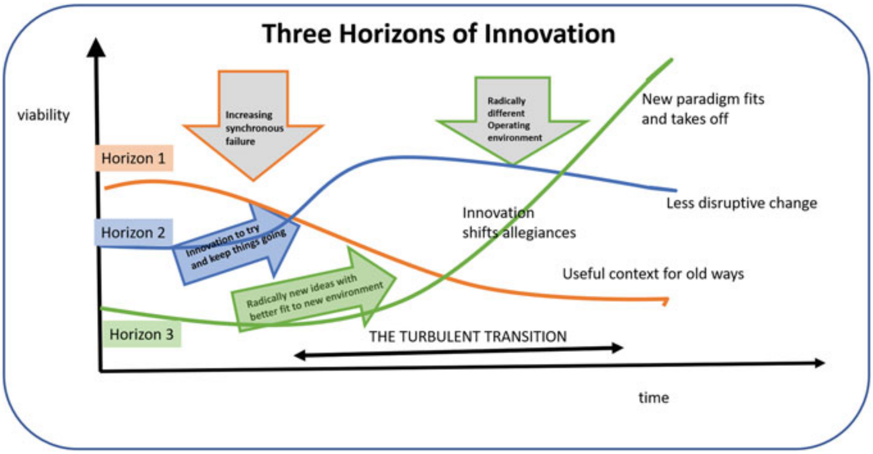

Fig. 7 Taxanomy of innovations

embeddedness of local practices and niches in various social contexts with their own specific history and dynamics (Geels 2002). Socio-technical niches often play a key role for the emergence of radical innovations as they provide 'incubation rooms for radical 'experiments' and spaces for the formation of networks, the shaping of expectations and learning processes, for example, about technical specifications, user preferences, public policies or symbolic meanings (Kemp et al. 1998). Different patterns of how niches may impact on regimes, such as niche accumulation or the hybridization of niches with established technologies have been identified although these linking mechanisms between niches and regime still lack analytical depth.

Further work has focused on niche-internal processes such as the formation of social networks, the shaping of expectations and learning processes (Geels and Schot 2007; Geels et al. 2016).

With the primary focus being on the transition of national infrastructure systems, cities and regions have rarely played a particular role in transition studies so far—and if so, then mostly as a context for niche experiments. As Hodson and Marvin demonstrate, the role of place and differential capacities of city and regional level actions to shape and manage technological transitions has largely been neglected (Hodson and Marvin 2009). Only very recently, attention has also been drawn more generally to the importance of spatial dimensions for understanding transitions, such as place-specific impacts, territorial institutional embeddedness and in general, a multi-scalar conception of transitions which avoids simple spatial hierarchies and recognizes the interrelatedness of different scalar levels (Coenen and Truffer 2012). Still, so far only a few studies have dealt with the governance of energy infrastructure change from a socio-technical point of view in cities (Graham and Marvin 2001; Hodson and Marvin 2009; Coutard and Rutherford 2010; Rohracher and Späth 2009; Bulkeley et al. 2011) and in regions (Smith 2007; Späth and Rohracher 2012). In their analysis of the cities of Graz and Freiburg, Spath and Rohracher have built on this strand of research highlighting the importance of spatial perspectives and the crucial role of cities and regions in transition processes; focusing on the particular local dynamics of energy systems change: which instruments and strategies are used to make cities' or regions' energy production and use more sustainable? Which logics of action, which motivations, visions and actor coalitions shape these place-related strategies? How is local action and capacity to change, interlinked with and dependent on multi-scalar relations, such as globalization processes, and national frameworks? Through this analysis, ways in which a recognition of the important role of cities and regions in energy transitions has been taken up in a multi-level perspective on socio-technical transitions: Are cities really just locales for niche experiments? Are local actions mediating between the niche and regime level and have they a particular function in facilitating and stabilizing change processes? Or are they particularly important for embedding such transitions into broader socio-political dynamics beyond the energy system?

The production, distribution and consumption of energy and emission of greenhouse gases are entrenched in and conditioned by large infrastructure systems—of energy, of transport or of our built environment. They are a constitutive part of our societies' metabolism with nature—the flow and exchange of resources—and are tightly interlinked with the social organisation of production and consumption in a growth-oriented economy. A substantial reduction of carbon emissions as urgently demanded in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2013) inevitably requires the radical restructuration of these sociotechnical systems of energy, transport and the built environment. Increasingly, cities are recognised as important arenas for innovative policies and action to reduce greenhouse gases and energy consumption. Many initiatives and programs for sustainable transport, sustainable buildings, energy efficiency or the use of renewable energies are crafted and implemented at the urban level of cities. However, what ambitious greenhouse reduction targets and related infrastructure policies require is nothing less than an 'energy transition'—i.e. a radical reconfiguration of the way we generate and use energy in cities and beyond. Given the global reach and interdependency of infrastructure systems—technologically, politically and economically—the capacity to achieve energy transitions primarily at an urban level can look questionable. However, the distributed nature and specific socio-technical dynamics of such processes, nevertheless makes cities an important arena of infrastructure transformation and a crucial nexus between different levels of governance and strands of socio-political discourse. Therefore, the critical questions that will determine the impact of city dynamics on global energy transitions should answer the following;

- To what extent can local infrastructures and socio-technical constellations be shaped independently from general patterns of provision and consumption, global or national market dynamics and higher-level policies?
- Can such deviations even influence the transformation of dominant, large, highly integrated infrastructures which (materially and institutionally) reach far beyond city boundaries?

- To what extent can alternative urban energy visions be implemented and stabilised at a local level and how is this process shaped by socio-political and sociotechnical contexts at different spatial scales?

2 The Role of City–region Planning in the Energy Transition

Although energy systems are defined and conceptualized mainly on national and supranational levels, overlapping contexts of liberalized markets, borderless climate change, fiscal crises in the public sector, etc. mean that environmental/energy governance is being consistently rescaled, downwards as well as upwards, within a multi-level governance framework (Bulkeley 2005; Bulkeley and Betsill 2005). Some work has begun therefore to explore the possible or actual roles that cities and regions can play in this systemic transformation process (Marvin and Guy 1997; Hodson and Marvin 2009; Monstadt 2007). In a policy context where urban areas are often held to be responsible for a high proportion of energy consumption and CO_2 emissions many city and regional governments are strategically positioning themselves in this policy domain as major actors in 'energy transitions'. Even a quick look at the current urban and environmental policy documents of many European city regions reveals an apparently renewed enthusiasm and engagement of local and regional actors for playing a major part in any transformation of unsustainable energy systems. It is also clear that as centers of population, business, industry and innovation, cities have strategic 'weight/value' both in terms of their environmental 'importance' and the potential they offer for developing and experimenting with sustainable solutions. There is then increasing recognition of the need for action at the level of the city/region, a policy level which is closer to users/consumers and more attuned to local conditions, rendering the stakes more pertinent and contextualised, and thereby offering the possibility of more effective policies. From an analytical angle, an urban/regional perspective offers the benefit of situating processes and practices of socio-technical change.

The literature is abundant with perspectives that allow for a more 'co-evolutionary' understanding of how the 'social', the 'technical' and the 'environmental' are intertwined through the multiple practices of, and relations between, different actors.

Coutard and Rutherford (2010) have argued for the (re)politisizing of transitions research, discussing energy transition policy, which can be defined as the policies aimed at fostering radical/systemic change to sustain energy–climate objectives and stating that transitions at whatever scale (Global, European, national, regional, local) cannot just be concerned with bringing about a socio-technical transition within the energy sector, whether it be, for example, increasing the market share of photovoltaic electricity or biomass, or promoting a 'hydrogen economy'. Social practices and the structural factors and policies which shape these practices (forms of urban organization, 'green taxes', housing and transport policies, etc.) are central to how energy transitions play out in any given context.

This change in focus from socio-technical to energy transitions implies that the policy issues at stake are also changed. Energy transition policies may include, for example, the promotion of energy efficiency in existing or new buildings, the articulation between transport and land use, as well as the coordination and division of ‘labour’ between all kinds of institutions. Thus, the key actors, processes, priorities, conflicts and issues involved in this ensemble of policies differ to a significant extent from those involved in, for example, technological niche management aimed at promoting the diffusion of geothermal technologies. Radical transformations and innovations are required across social, economic, political and cultural, as well as technical domains (Giddens 2009). In light of this, the conceptualization of the energy transitions changes to a political process, through which ideas and interests diverge, socio-technical choices can never be unanimous, and the policies which are decided upon and implemented always necessarily produce ‘losers’ as well as ‘winners’. This focus may well be one way of moving between socio-technical transition and energy transition perspectives, thus going beyond concern for technological innovation and diffusion to concentrate on the socio-economic and political factors at play in systemic sustainability transformation processes.

3 The Energy Transition with Respect to Urban Governance

Utility networks—such as energy, water, sanitation, transport and telecommunication systems—support the economic, social and environmental performance of cities and regions. They are the basic infrastructure grids that provide the fundamental conduits through which modern cities and regions operate. Among the most important utility sectors are electricity, gas and district heating networks. These energy networks are the prerequisite for urban and regional sustainability in three ways. Firstly, energy infrastructures have become increasingly critical for the functioning of nearly all production, services and infrastructure sectors, as well as for politics, public health and even individual social practices. The spectacular power blackouts in North America and Europe have dramatically demonstrated that failure of these systems is one of the most important vulnerabilities of modern societies. Secondly, energy systems occupy a key role in the performance of urban and regional economies: energy utilities have long been among the largest regionally based companies, employers and landowners, launching major capital investment programs for a city or region (Monstad 2007, 2009). The type of infrastructure network, the quality of service provided and tariff levels have major implications for the performance of local economies.

Moreover, energy utilities have often established regionally based R&D facilities and have traditionally been major purchasers and promoters of technologies and skills in a regional context. Additionally, energy systems structure a major part of the urban material metabolism. They are among the most important ‘material mediators between nature and the city' (Kaika and Swyngedouw 2000). Apart from the air, water and soil pollution and nuclear risks involved, energy systems are the largest emitters of greenhouse gases. They therefore represent key sectors for climate protection and the whole ecological modernization of societies.

Many changes have taken place over the last two decades in the institutional structures of energy systems altering the dramatically the regional and urban governance of energy systems. To summarize briefly;

1. The provision of energy services by the state (or in close association with the state) and the organization of energy systems in regional monopolies are no longer sacrosanct. As a consequence of the poor performance of public monopolies—their lack of productive efficiency, their failure to identify consumer demands, and their inertia in socio-technological innovation—and driven by the influence of neoliberal ideas, the European Commission as well as governments all over the world have been initiating the competitive restructuring of the energy markets. Liberalization and Privatization have diminished the control of the states and local governments over prices, losing out to corporate policies of the utilities.
2. Environmental policies, especially climate policies, have accelerated the *ecological modernization* of energy systems and have created new market niches for 'green' energy industries. Climate protection has become an overarching policy priority and a host of new interventions have been developed (Bulkeley and Betsill 2003; Bulkeley and Kern 2006).
3. Innovative technologies of power generation, system control and energy end use have become competitive. The existing centralized supply structure is gradually being supplemented by decentralized systems of heat and power generation, network supply and energy storage (Monstadt 2003). These co-evolving transformation processes have led to new market structures, essential changes in the framework for innovation and in the functions and institutional structures of state involvement. Considering the cumulative effects of these developments for both the supply and the demand sides, it is not exaggerated to diagnose a 'new logic of infrastructure provision' and a paradigm shift in energy policy' (Helm 2005). These developments are having a major impact on the planning, supervisory and provider functions of local and regional authorities, especially in Europe. Despite their significance for urban and regional sustainability the utility sectors have attracted little attention in the debate on urban and regional policy and planning. As Marvin et al. (1999) point out, in the debates on urban and regional development and regional infrastructure policy, the delivery of utility services still seems to be taken for granted and to be left to engineers, network operators and often (supra-)national utility regulators.

Consequently, there has been little research on the urban and regional impacts of utility restructuring and the changing environment for urban and regional governance. This is surprising since the supply of network-based services has traditionally been a major responsibility of local and regional governments, and therefore an indicator of their capacity to implement public policies. Therefore, if urban energy transitions are going to go anywhere, the traditional (but later defunct) role played by local or territorial governments, not only in the regulation and provision of utility services, but also in the promotion of socio-technical innovations in the energy sector needs to be critically acclaimed. New challenges to multi-level governance are stressed frequently enough in debates, but the transformation of local and regional governance has until now remained underexposed to lay out the driving role of these actors in restructuring and regional and urban development.

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The Holy Triangle of Science, Technology and Industry for Photovoltaic Solar Energy Conversion

Şener Oktik

1 Introduction

1.1 The Quest to Convert Solar Energy into Electricity

Science is the quest to gain better insight into the natural and social world by following a systematic methodology based on evidence, objective observation, experimentation, measurement and data collection where mathematics is used as a tool. Technology, on the other hand, utilizes scientific knowledge, skills and competences to design and manufacture tangible or intangible products for industrial and commercial value and human comfort. Collaborations and co-creations within the "Holy Triangle of Science, Technology and Industry" have been governing the unprecedented progress in each and every part of the value chain of the photovoltaic solar energy conversion sector since the first discovery of the photovoltaic effect in 1839 by French physicist Alexander Edmond Becquerel (Becquerel 1839). A nineteen year old Becquerel simply observed the voltage between two platinum electrodes in an electrolytic cell containing silver chloride under light. Willough Smith, an electrical engineer on the other side of the pond, in the laboratory of the Guetta Percha Company in London, England, discovered that the conductivity of selenium rods increased significantly when exposed to sunlight (Smith 1873). William Grylls Adams and Richard Evans Day from Kings College in England had shown that solar energy could be converted directly into electricity without any moving parts or heat, which in turn led to the modern solar cell (Adams et al. 1877). These intentionally or accidentally discovered effects leading to converting solar energy directly to electrical

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energy were initiated innovation cycles in the value chain of the photovoltaic power industry aimed at delivering workable, economically feasible products to serve end users. The first working, but unfeasible, photovoltaic modules with ~1% efficiency were fabricated in 1883 (Fritts 1885). They employed selenium coated copper plates with semi-transparent thin gold leaf front contacts (Fritts 1885). German inventor and entrepreneur Werner von Siemens took on board the results of the Fritts' PV module and presented the results to the Royal Academy of Prussia, expressing photoelectricity to be "scientifically of the most far-reaching importance" (Siemens 1875). To take advantage of emerging photovoltaic technologies Edward Weston, an English-born American chemist and engineer, secured two patents in 1888; the "*Apparatus for Utilizing Solar Radiant Energy*" and the "*Art of Utilizing Solar Radiant Energy*" (US389124 and US389125). Before the end of the nineteenth century there had been several patents secured for converting and storing solar energy (Severy 1894, US527377 and US527379, Reagan 1897, US588177, Bowser 1899, US598177).

Despite the growing interest in photovoltaic conversion in the Holy Triangle of Science, Technology and Industry, the level of scientific understanding of interaction between light and matter had been somewhat unclear. The photoelectric effect had been subject to studies at global scale. In 1887 Heinrich Hertz discovered in experiments with a spark gap generator (where a very small spark is jumped between two small metal electrode spheres) that receiver sparks are stronger when the electrodes are illuminated with ultraviolet light, however Hertz did not give any scientific explanation for the observed phenomenon (Hertz 1893). Similarly, Russian physicist Alexander Stoletov showed that intensity of light is directly proportional to the induced photoelectric current (Stoletow 1888). In 1897 British physicist Joseph John Thomson discovered the existence of electrons and called them "corpuscles". In 1899 Thomson explained that the increased "spark density" in Hertz's experiments, was the result of UV light pushing on corpuscles (electrons) and causing emission of electrons (Thomson 1897). Amongst continued efforts to understand atoms, a model describing the atom as a small positively charged core (nucleus) containing most of the mass, and negatively charged particles (electrons) circulating around a nucleus was proposed by New Zealand physicist Ernest Rutherford (1871–1937), who is considered the father of nuclear physics (Rutherford 1911). Albert Einstein (1879–1955), a German-born theoretical physicist explained the photoelectric effect in his famous 1905 paper by proposing that light beams are energy packets (quanta) which are related to the wavelength of light (Einstein 1905). Gilbert Newton Lewis (1875–1946), an American physical chemist, introduced the "photon concept" in 1920 as a new kind of atom as an alternative to Einstein's quanta proposals (Lewis 1926). Since then despite differences between the Einstein and Lewis concepts, the term "photon" has been in use as a suitable synonym for the light quantum. The frontline of scientific and technological developments in the field of converting solar energy directly to electrical energy were pushed forward continuously in the early twentieth century, with the better understanding of light and matter interaction combined with the discovery of the electron and nucleus. While the science corner of Holy Triangle was maturing through theoretical understanding of photovoltaic energy conversion, progress was slow on the technology and industry corners during the early twentieth century. Photovoltaic conversion efficiencies remained around one percent in the first couple of decades of the twentieth century, despite the low efficiency, technologists and entrepreneurs kept their faith in the emergence of a commercially feasible device to convert solar energy to electricity. William Weber Coblentz (1873–1962), an American physicist with an entrepreneurial vision, registered a total of ten patents during his lifetime, the first being “a solar cell invention to convert sunlight to electricity” in 1913 (Coblentz 1913, US1077219).

1.2 The Science, Technology and Industry Triangle

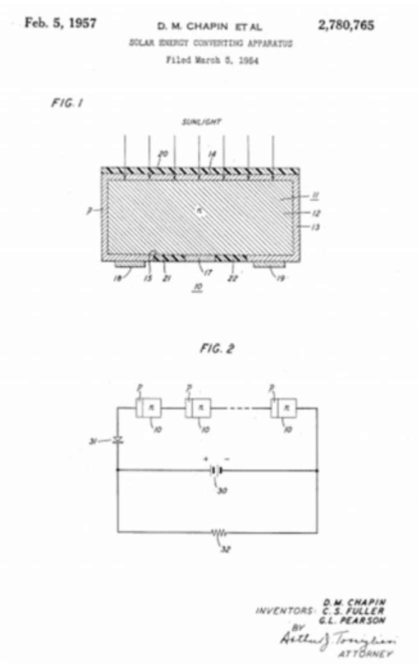
At the beginning of the second half of the twentieth century, the research branch of the Bell Telephone Company in Murray Hill, New Jersey USA, (the Bell Telephone Company eventually became AT&T) was considering replacing conventional “dry cells batteries” with an alternative power source. The research physicist Daryl Muscott Chapin (1906–1995) undertook the task to look into “wind machines”, “thermoelectric devices” and “steam engines” as replacements for a power source in telecommunication systems. In his assessment, Chapin suggested that to improve the existing ~1% efficiency, 5 Wp/m^2 selenium based photovoltaic module technologies might be a better alternative to others. In the same period Russell Shoemaker Ohl (1898–1987) and his team, which were based in the same laboratories, were conducting research on an improved method for making light-sensitive electric devices on high purity fused silicon. The patented results of their work (US2402662) are considered the start of silicon solar cells (Ohl 1941). As a part of industrial research and technological development, scientists Gerald L. Pearson (1905–1987) and Calvin Souther Fuller (1902–1994) from Bell Labs were engaged in controlling the properties of semiconductors by introducing impurities for silicon rectifiers. They discovered that illumination of a p-n heterojunction constructed between silicon containing gallium impurities and lithium creates a current in the external circuit. Pearson and Fuller, with the advantage of working in a multidisciplinary industrial laboratory, took their observation to Chapin and proposed silicon as a replacement for selenium for photovoltaic device development. Initial theoretical calculations showed that an ideal silicon based solar cell could convert 23% of sunlight into electricity (Chapin et al. 1954). Following this new direction Pearson, Chapin, and Fuller focused their effort to improve the properties of silicon semiconductors and fabricating a solar cell based on silicon p-n junctions. Throughout this journey, the innovation ecosystem at Bell laboratories surrounding fundamental research and development, technological progress as well product development to fulfill the demand of industry, had been favored to increase the speed of progress. In a short time they had overcome scientific and technological problems through a better understating of the problems initially faced, such as stable ohmic contacts to silicon and migration of lithium shifting the p–n junction from the front surface of the solar cells. Following these improvements, in 1954 they designed a “solar battery” by serial connection of a solar cell to power the radio transmitter (Chapin et al. 1954). The theoretical calculations published on the relationship between the band gaps of semiconductors and efficiencies under the solar spectrum opened up new horizons and encouraged future research and development activities to identify new potential semiconductor materials for solar cells (Twich 1953).

In 1954, Bell Laboratories published their results for the first practical solar cells based on silicon with a 6% efficiency (Chapin et al. 1954). The patent for the "*Solar Energy Converting Apparatus*" was granted in 1957 (US2780765) (Fig. 1). This significant improvement in solar cell efficiency was a milestone and is commonly considered a turning point in scientific, technological and industrial communities. At this milestone power industries were drawn to take a position in the photovoltaic conversion value chain. In 1955 Western Electric had acquired a license for producing commercial solar cells. The Semiconductor Division of Hoffman Electronics manufactured commercial solar cells with a 2% efficiency for $25/cell or $1785/watt. As the industrial research and technological development activities increased, progress accelerated. Hoffmann Electronics announced 8% solar cells in 1957 and 10% solar cells with the introduction of a grid contact for reduced cell resistance in 1959 (Perlin 2013). On the basic research and development front the use of dielectric surface passivation to reduce the concentration of electronic states at the silicon surface by the formation of a thermally grown SiO_2 layer was reported for the first time in 1959 by M.M. Atalla (1924–2009), a physical chemist at Bell Laboratories (Atalla et al. 1959). Over the years there has been a significant effort to understand the properties of silicon-dielectric interfaces with new perspectives hoping to improve silicon based solar cell efficiencies (Black 2016).

These concentrated efforts gave an unprecedented impetus to the technological readiness level of new and ever developing silicon solar cells. However, in the 1950s, the level of cost for photovoltaic electricity was not attractive enough for the power industry thus the industry, the third corner of the triangle, was not effectively involved.

In 1952, British author Arthur C. Clarke, in his science fiction novel "*Islands in the Sky*" had described the idea of three space stations to provide a worldwide communications network and the vision of converting solar energy into electricity was introduced as a continued power source in space (Clarke 1952). In 1954 the US military had started a satellite project and they considered the developments on solar cells at Bell Labs as an opportunity to secure a power source for their space program. The United States Army Signal Corps (USASC), the unit in charge of powering most military operations, took on the task of designing "a solar electric power system" for the "*Project Vanguard*" satellite program.

The demand coming from the space industry was another milestone in improving the speed of progress in the scientific and technological development of photovoltaic power conversion. In the 1950s the Hoffman Electronics Corporation was the only American company producing silicon based commercial solar cells with a license from Bell Laboratories. Hoffman Electronics got involved in the Vanguard I projects and initial tests of solar cells for satellites started in 1955. In 1958 Hoffman Electronics developed the first 100 cm^2, 0.1 Wp working photovoltaic module with a 9% efficiency. These modules were used in the fabrication of "solar converter cluster



AT&T assignors (Gerald L. Pearson, Daryl M. Chapin, and Calvin S. Fuller) receive patent US2780765, "Solar Energy Converting Apparatus." They refer to it as the "solar batteryUnited States Patent Office 2,780,765 atterated Feb. 5, 1957

The p-n silicon PV cell, Power 55Wp/m2

Fig.1. shows in cross section a p-n silicon body suitable for serving as a photovoltaic cell in accordance with the invention

Fig.2. shows schematically a plurality of cells of the kind shown in Fig.1 connected serially for charging a storage battery in accordance with this aspect of the invention

(11) a silicon body (a rectangular parallel piped)
(12) an inner n-type Si Zone (a resistivity= approximately 0.1 ohm/cm Thickness: 1mm)
(13) p-type boron-diffused Si Zone (a resistivity=y 0.001 ohm/cm, thickness < 2.5µm)
(14) Transparent front contact
(15) The p-type outer layer is etched away along a central portion of the back surface of the body to expose a strip of
the n-type zone for making ohmic contact
(17) Low resistance connections are made to the n- and p-type zones by electroplating coatings of a suitable non contaminating metal(rhodium, in elongated strips)

Fig. 1 Patent for "Solar energy converting apparatus" was granted in 1957 Chapin et al. (1957)

mounting units" to power the radio transmitter of the Vanguard I satellite for more than 6 years (Fig. 2).

Following this important step, the request of the space industry for "a radiation damage resistant solar cell" was met by scientists in the U.S. Signal Corps Laboratories, who fabricated n-on-p type silicon wafers (Mandelkorn 1958). This synergy between science, technology and industry had been a driving force in the implementation of the 2886 solar cell modules in two rings as the electrical power source for the Explorer VI satellite, which was launched in 1959. Despite all these big steps, faith in the utilization of PV power in American and Russian space programs was not strong enough until the late 1960s. The first Nimbus spacecraft of the Nimbus Program used a 470 Wp photovoltaic power system in 1964 (http://nssdc.gsfc.nasa.gov/earth/nimbus.html), then in 1966 the first Orbiting Astronomical Observatory was powered by a 1 kWp solar cell array. The Vanguard I project, with a "milliwatt of solar power in space", opened up the road further and had improved stable efficiencies to over 14%. In the 1970s, unprecedented developments in photovoltaic power industries boosted confidence in the solar cell as a main power source for space applications. Since then multinational space agencies (NASA (United States), Roscosmos (Russia), JAXA (Japan), ESA (Europe), and CSA (Canada)) have installed humanity's largest space solar power installation in the collaborative "International Space Station" (ISS) project. The 120 kWp solar arrays, which are set on four sets of "alpha gimbal" sun tracking systems on the ISS cover an area of roughly 2500 m^2 and were installed over several space shuttle missions (Fig. 3). The first array was installed in 2000 with a 15 years life expectancy and after 20 years the array is still in operation. During this period many new modules were added and replaced, and numerous scientific and technological experiments were carried out. The second, third and fourth arrays were installed in 2006, 2007 and 2009 (NASA 2021).

Despite all the scientific and technological progress made throughout the 1960s, the cost of commercial photovoltaic power installations for terrestrial installations had only been reduced from the initial ~$300 per watt to ~$100 per watt. Thus,

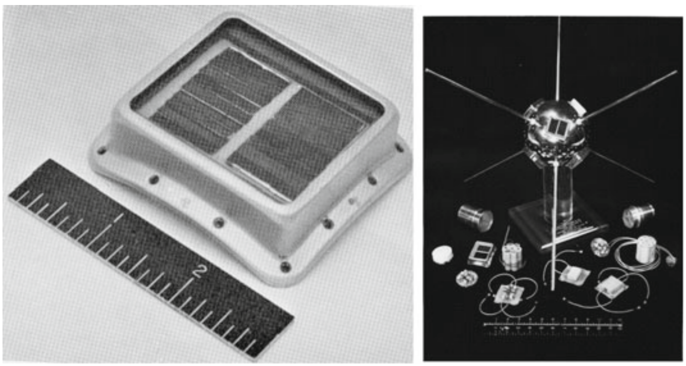


Fig. 2 Solar converter cluster mounting unit and the vanguard satellite with four solar clusters (Perlin 2013)

International Space Station is seen from Space Shuttle Discovery as the two spacecraft begin their relative separation. Earlier the STS-119 and Expedition 18 crews concluded 9 days, 20 hours and 10 minutes of cooperative work onboard the shuttle and station. Undocking of the two spacecraft occurred at 2:53 p.m. (CDT) on March 25, 2009.Credits: NASA (https://www.nasa.gov/mission_pages/station/structure/elements/solar_arrays-about.html). Backdropped by the blackness of space and Earth's horizon, solar array wing panels on the International Space Station are featured in this image photographed by a crewmember while Space Shuttle Endeavour (STS-118) remains docked with the station.

Credit: NASA

Fig. 3 Photovoltaic arrays on the international space station (ISS) (NASA 2022)

the demand for solar cell manufacturing industries was limited to the space power industry, in which the cost factor was not an issue. Efficiency, stability, size and cost were main issues for the terrestrial power industry value chain and photovoltaic power installations were limited to small size demonstrations. On the other side of the world, in Japan, Sharp Corporation produced commercial silicon photovoltaic modules and installed a 242 Wp setup on a lighthouse in 1963; the world largest terrestrial photovoltaic array at the time.

The oil crisis in the 1970s was another milestone for photovoltaic conversion technologies at each corner of the science, technology and industry triangle. Oil companies such as BP, Shell, Mobil and Exon were increasing their interest in renewables and started to invest in research and technological development projects concerning photovoltaic solar conversion, this paved the way in bringing these technologies back down to earth. Exxon, the USA based oil company, established a new research unit headed by Dr. Elliot Berman (a photochemist) with the goal of reducing solar cell cost to $10 per watt. Dr. Berman and his team began searching for an alternative material to monocrystalline silicon and introduced solar grade multicrystalline silicon, bringing the cost of solar cells down to $20 per watt. Based on this development Exxon funded the "Solar Power Corporation" company in 1973 (Fig. 4).

The U.S. Department of Energy had been keeping an eye on progress in the solar energy field and established the "Solar Energy Research Institute" as part of the National Renewable Energy Laboratory in 1977. In spite of all these developments the total global photovoltaic production capacity was only just exceeding ~500 kilowatts per year at the end of 1970s. Yet another milestone in the photovoltaic module manufacturing industry was the acquisition of "Solar Technology International by Atlantic Richfield Company (ARCO)" and establishing "ARCO Solar" in 1977. ARCO Solar had invested significantly in R&D to improve the scientific and technological maturity of the new technology and in 1980, with a one-megawatt production capacity, had become the world's largest photovoltaic solar module manufacturer.

Fig. 4 Elliot Berman tests solar arrays on the roof of solar power corp's office (Perlin 2013)

1.3 The Deployment of Photovoltaic Technologies Within the Science, Technology and Industry Triangle

These developments enabled photovoltaic power systems to be deployed in many off-grid applications such as; warning lights, lighthouses, railroad crossings, remote locations, offshore oilrigs warning systems and remote off grid systems, etc. ARCO Solar installed the first megawatt-scale photovoltaic power system on a 108 dual axis tracker in Hesperia, California, while global PV module production in 1982 was approaching 10 megawatts. The annual photovoltaic market on the global scale had increased from $11 million in 1978 to $150 million in 1983. Starting from the 1980s the accumulated experience in photovoltaic solar energy conversion systems on every corner of the Holy Triangle has been facilitating unprecedented scientific and technological progress in each component of the value chain, which in turn has empowered a significant growth in production volume, together with a sizable cost reduction in the value chain of photovoltaic power industries. In addition to these subsidies, in 1990 Germany pioneered the introduction of a law relating to "feeding electricity into the grid" which was followed by over 50 countries in many forms and has had a significant effect on the deployment of renewable energy across the world. This significant growth in cumulative photovoltaic power on the global scale has in turn accelerated the progress of each corner of the science, technology and industry triangle for the conversion of solar energy into electrical energy.

The progress ratio of technologies is defined as the rate of cost reduction of a product for each time the production volume doubles, with the most common empirical relationship between the production volume and the cost reduction employing a single factor learning curve, as shown in the following equation (Eq. 1).

$$
\begin{aligned}
C_{Cum} &= C_0 \times C_{cum}^{m} \\
\log\ C_{Cum} &= \log C_0 \times \mathrm{m}\ \log \mathrm{C_{cum}}
\end{aligned}
\tag{1}
$$

$$
\begin{aligned}
\text{Progress ratio(PR)} &= 2^{\mathrm{m}} \\
\text{Learning rate(LR)} &= 1 - \mathrm{PR}
\end{aligned}
$$

Where: C_{cum} = *Cost per unit of cumulative production*
C_0 = *Cost of the first unit produced*
m = *experience parameter*.

A single-factor learning curve approach to assess cost reduction in PV technologies has been criticized by several researchers (Nemet 2006; Yu et al. 2011; Grafström and Poudineh 2021). It is suggested that two-or multi-factor models incorporating scientific technological developments and innovative steps at the value chain level might improve shortcomings (Grafström and Poudineh 2021). Nevertheless, for technologies in the photovoltaic value chain, a logarithmic relationship between production volume, which is related to accumulated experience, technical maturity, as well as commercial performance and cost has been valid since the 1980s. The

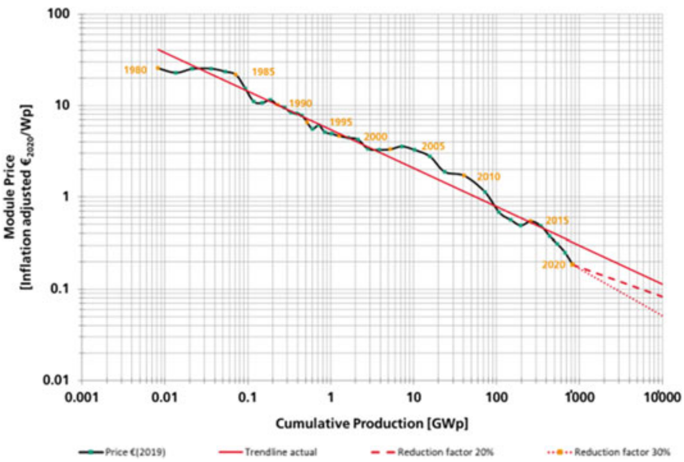


Fig. 5 Module price cumulative module production learning curve (Farunhofer ISE 2021)

~25% price decline in relation to the doubled production volume of commercially available photovoltaic modules is assumed to be a valid assessment for the last four decades, as shown in Fig. 5 (Fraunhofer ISE 2021). Any data given in the photovoltaic value chain is outdated as soon as it is published. However snapshots from "*Photovoltaics Report*" (updated in mid-2021) by the Fraunhofer ISE are as follows: between 2010 and 2020 the Compound Annual Growth Rate (CAGR) of cumulative PV installations was ~34%; in 2020 the global cumulative installation number reached ~710 GWp, producing ~856 TWh (3% of world electricity production) at a competitive cost; 95% of PV modules produced were Si-wafer based (monocrystalline ~ 84%, multicrystalline ~16%); + 600 W per module was possible due to improved efficiencies, increased wafer size and new designs. Further discussion on the parameters of photovoltaic conversion is given in Sect. 2. For large solar energy plants the system cost was well below $1 million per megawatt and the PV market moved from a subsidy driven to a competitive pricing model (Power Purchase Agreements PPA) with unprecedented tenders per kWh (Fraunhofer 2021).

2 Photovoltaic Conversion and Solar Cells

The photovoltaic conversion efficiency of a solar cell is simply defined as the ratio between input and output power. Shockley and Queisser's work reported a calculated theoretical efficiency limit of ~30% for a single junction solar cell under "one-sun" illumination (Shockley and Queisser 1961). To achieve the theoretical single junction efficiency and to improve beyond has been a challenging task over the years. At the global scale, numerous research groups in universities and research centers have been engaged in a significant number of projects adopting new and emerging opportunities

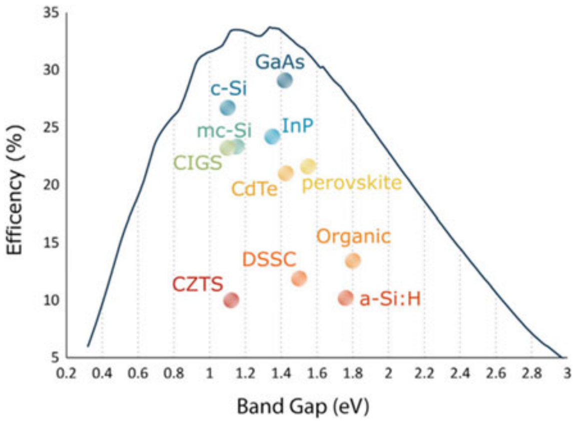


Fig. 6 The Shockley–Queisser efficiency limit as a function of bandgap of absorber materials for a single junction solar cells and best laboratory efficiencies reported for various types of solar cells by the end of 2020 (Green et al. 2020)

in organic and inorganic conducting, semiconducting and insulating materials to be utilized in photovoltaic energy conversion. The Shockley-Queisser efficiency limit as a function of a band gap of selected absorber materials for single junction solar cells are depicted in Fig. 6 (Green et al. 2020).

The Technology Readiness Level (TRL) of many innovative ideas from materials to cell designs, from module fabrication components to module designs have continuously been raised to the commercial level (Gregory et al. 2020). Cell efficiencies are one of the key parameters defining the power and cost of a PV module and are related strongly to the cost of photovoltaic power systems (PVPS) as well as the levelized cost of electricity production (LCOE). However in recent years the share of module cost in the total cost of PVPS has declined below 40% in 2021 and expected to drop further to around 20% in the next ten years (ITRPV 2021). Besides efficiency, power and cost stability of PV modules have been key issues to be tackled in photovoltaic power production industries. The following sections will address the details of these subjects more closely.

2.1 The Solar Spectrum and Photovoltaic Conversion

Almost 55% of solar energy is in the visible region (380 nm–780 nm). Ultraviolet (280 nm–380 nm) and near infrared (780 nm–2500 nm) regions contribute ~4% and ~41% respectively. In the theoretical efficiency calculation limit, several parameters have been under investigation. A matching of semiconducting absorber layer band gaps to the solar spectrum to improve photoelectrical conversion efficiency is one of the major criteria for the selection of absorber materials. There is no contribution to photoelectrical conversion if energies of photons are smaller than the bandgap (no absorption) and if energies of the photon are well above the bandgap full efficiency of photoelectrical conversion cannot be achieved due to charge carrier thermalizations.

Figure 7 shows spectral irradiance at the top part of the atmosphere (air-mass-

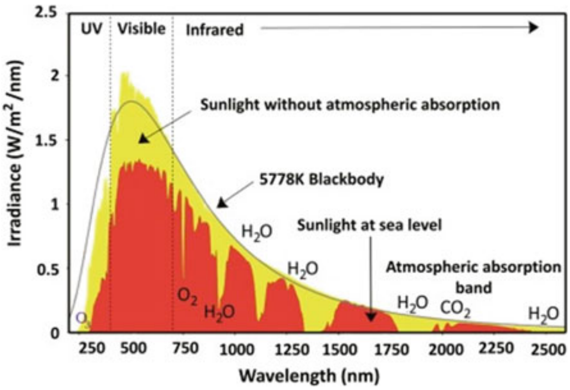


Fig. 7 Solar spectra as a function of wavelength (*Source* Data from United States department of energy, national renewable energy laboratory, reference solar spectral irradiance: ASTM G-173, http://rredc.nrel.gov/solar/spectra/am1.5/ASTMG173/ASTMG173.html)

zero (AMO = 1353 W/m^2)) and the same numbers after being filtered in a clear, dry atmosphere at ground-level (air-mass-one (AM1.5G) = 1000 W/m2). Spectral irradiance is usually given in units of W/m^2/nm. The spectral distribution of the number of photons per second per unit area is defined as photon flux spectra, $\varphi(\lambda)$ and is derived from the spectral irradiance I_λ (W m^{-2} nm^{-1}) using the following relationship:

$$\varphi(\lambda) = I_\lambda / E_{ph} \quad \text{where} \quad E_{ph} = hc/\lambda \quad \text{where} \quad h = \text{Planck's constant} \tag{2}$$

In the AM1.5G terrestrial spectrum ~4.3 × 10^{21} photons impact every sun facing square meter area per second with the spectral distribution of ~5% in ultraviolet, ~22% in visible and ~73% in near infrared regions. The spectral distribution of AM1.5G photon flux and the integrated AM1.5G photon flux as a function of wavelength are shown in Fig. 8.

2.2 *Attempts to Classify Solar Cells*

Along with the power industry, the fields of science and technology have been undertaking ever-growing steps in research and development and, since the petrol crisis-born solar cell milestone of the 1970s, transferring ideas to market activities for numerous innovative photovoltaic materials and devices (Wilson et al. 2019). Thus, the diversity of available and promising solar cell materials and technologies at different levels of technological readiness have become a confusing issue to follow by all stakeholders of the PV value chain (Frass 2014). In an attempt to structure this diversity a "generation concept" for solar cells was introduced at the beginning of the 2000s (Green 2001). The generation concept simply groups the development of solar cells by their cost and efficiencies. The 1st generation solar cells (1G) were based on wafer-based inorganic crystalline silicon materials enabling high conversion efficiency at a high cost, solar cells based on GaAs are also included in the

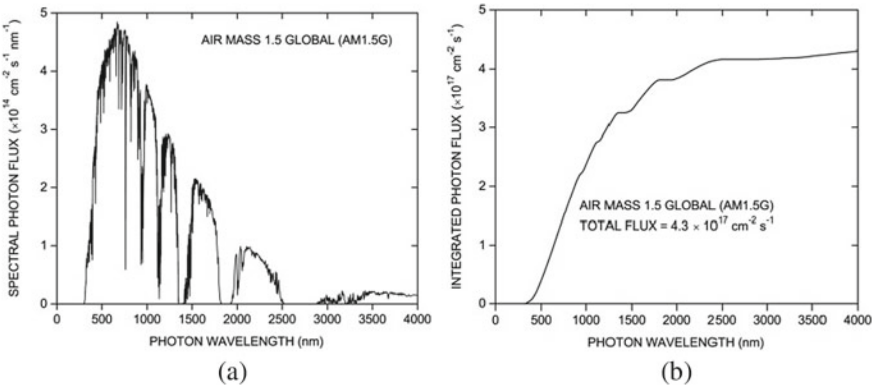


Fig. 8 **a** AM1.5G spectral photon flux (number of photons per second per unit area) as a function of wavelength **b** AM1.5G integrated photon flux as a function of wavelength. (*Source* Data from United States department of energy, national renewable energy laboratory, reference solar spectral irradiance: ASTM G-173, http://rredc.nrel.gov/solar/spectra/am1.5/ASTMG173/ASTMG173.html)

1G classification. The second generation of solar cells (2G) aimed to deal with the cost issue by employing thin film solar cell technologies for low conversion efficiency at a low cost, including amorphous silicon (a-Si) and microcrystalline silicon (µc-Si) thin film solar cells, cadmium telluride/cadmium sulfide (CdTe/CdS) and copper indium gallium selenide (CIGS) solar cells (Oktik 1989). The photovoltaic conversion efficiencies in 1G and 2G single junction solar cells are limited by the Shockley-Queisser (SQ) limit.

Development over the years has shown that the efficiency and the cost gaps between 1 and 2G solar cells have been decreasing. In third generation solar cells (3G), basic concepts of physics such as; multiple energy levels, multiple carrier pair generation from high energy photons, single carrier pair generation with multiple low energy photons and capturing carriers before regenerations combined with low cost thin film deposition processes and employing abundant nontoxic inorganic and organic thin film materials have been implemented. The R&D efforts of 3G cells were initiated by the pioneering work of O'Reagan and Grätzel in (1991). Focusing on technologies based on organic (polymer)-based solar cells, dyed-sensitized solar cells as well as new and emerging compounds such as nano-crystalline films, active quantum dots, tandem or stacked multilayer cells, etc. (Conibeer 2007). Recent developments in nanotechnology, introduced by Richard Feyman as a concept in the 1960s (Feynman 1960), opened the road for manipulating organic or inorganic materials at atomic levels. Discovery of fullerene and fullerene derivatives such as a series of hollow carbon molecules that form either a closed cage ("buckyballs") or a cylinder (carbon "nanotubes", ellipsoid tubes and many other shapes and sizes) might be considered scientific milestones in many other fields as well as photovoltaic conversion (Kroto et al. 1985). Furthermore the discovery of synthesis and controlled doping of polymers (Heeger 2000) and the ability to produce graphene (Novoselov 2004)

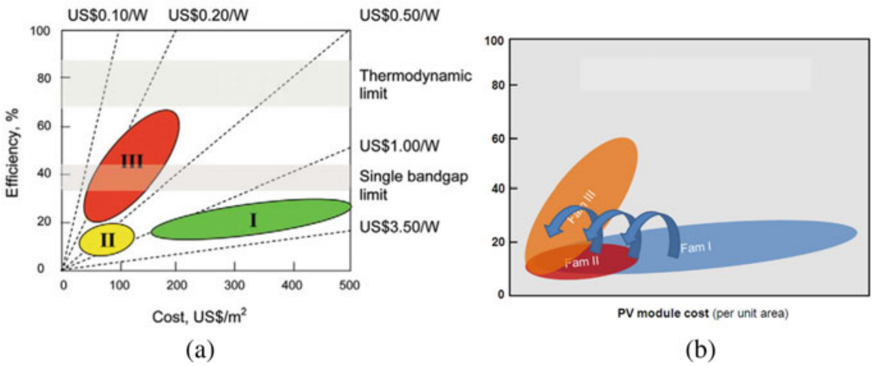


Fig. 9 **a** Efficiency and cost projections for first-(I), second-(II), and third-generation (III) PV technologies (wafer-based, thin films, and advanced thin films, respectively) **b** Reconstruction of the generation approach to a proposed families (FAM) approach (Sinke 2019)

were two big steps enabling improvement efficiencies and stabilities of novel solar cells at lower costs. This was achieved by combining inorganic and organic materials at the nano-scale on nonflexible and flexible substrates. These developments were covered in the classifications of fourth generation of solar cells (4G) (Imalka et al. 2013).

Although many stakeholders use the four-generation approach to define development of the photovoltaic value chain, the shortcomings of these classifications were recently discussed and criticized (Sinke 2019). The main points in these arguments might be summarized as: the problems of generational overlap and merging; crystalline wafer based technologies being increasingly combined with thin film technologies; the notion that materials and technologies do not simply become obsolete and disappear, but follow more complex and evolutionary paths; the parameters of solar cells in one generation not being improved further without using materials and/or technologies from other generations. Figure 9 depicts the merger of technology families in G1 (FAMI) and G2 (FAMII) and incorporation of overlaps of FAMI and FAMII into technology families in G3 (FAMIII) (Sinke 2019).

2.2.1 Science, Technology, Industry and the First-Generation of Solar Cells

First generation (1G) technologies employ wafer-based crystalline bulk materials namely; monocrystalline, multicrystalline silicon and GaAs. Currently more than 95% of terrestrial commercial applications use modules based on crystalline silicon cells manufactured on high-quality high-cost Czochralski monocrystalline silicon (mono-Si) and lower-cost defect-prone crucible-cast multicrystalline silicon (mc-Si). GaAs is mostly used for multi-junction cell designs in high efficiency high power per area applications.

Monocrystalline and Multicrystalline Silicon

The primary steps of the wafer-based mono-Si module supply chain are; polysilicon production, ingots and wafering. Cell manufacturing and module production are shown in Fig. 10.

Polysilicon

Almost 20% of the cell production cost comes from polysilicon and currently over 90% of polysilicon is produced by using the now matured Siemens technologies. The share of the Fluidized Bed Reactors (FBR) technology is only about 5% and is expected to increase to 12% in the next ten years. Other technologies in the market such as upgraded metallurgical grade-Si have not yet been able to compete in the polysilicon market.

Crystalline Silicon Ingots

To achieve higher efficiency and lower cost in the crystallization process of mono and multi crystalline silicon, research and technological development efforts have been continuous in each corner of Holy Triangle (Science, Technology and Industry). Currently the Czochralki (CZ) and the the floating zone (FZ) techniques are the main technologies utilised to grow monocrystalline (single crystal) solar grade silicon. However due to the higher cost of FZ, the Czochralski (CZ) technique is dominating the market and looks to remain the main technology for mono-Si ingoting in the near future (Fornari 2018). New and novel approaches such as the "Continuous Czochralski" (CCZ) process which utilizes recharging and multi-pulling, direct wafering and magnetic CZ for oxygen reduction have been under investigation but the technology readiness levels of these efforts are at too early of a stage to take a share in the monocrystalline market. The 400 kg ingot mass of monocrystalline silicon boules in 2020 is expected to increase in dimensions and weight to about 500 kg within 10 years (ITRPV 2020).

In an attempt to reduce the cost of solar cells a crucible-cast silicon growth, which is a directional solidification of silicon melt to form a crucible bottom, have been in use since the early work of Eliot Berman at Exxon (Perlin 2013). Besides conventional or standard multicrystalline-Si and its derivative "High Performance mc-Si (HPMS),

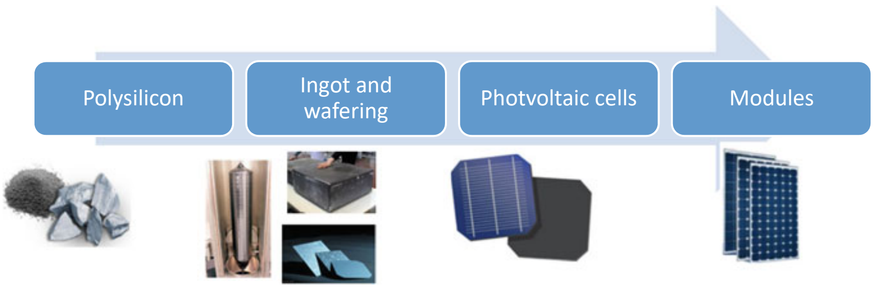


Fig. 10 The primary steps of the wafer-based c-Si module supply chain

novel technologies such as “mono-like silicon” growth, non-contact crucible silicon (NOC-Si) and Kerfless Epitaxial Silicon (KE-Si) have been investigated globally. However these new technologies are in their infancy and their market share is only a few percent (Lana et al. 2018). Currently GEN8 HPMS has ingots of over 1000 kg on the market despite the potential for achieving a 2000 kg ingot mass with current technologies. It is predicted that the ingot cast-Si weight will grow slowly to around 1300 kg within next 10 years (Fig. 11) (ITRPV 2021).

While silicon ingots might be intrinsic, n-type phosphorous doped or boron doped p-type, the industry-standard for p-type boron-doped monocrystalline silicon has been losing its share due to problems related to the combination of boron with interstitial oxygen, which in turn has given rise to Light Induced Degradation (LID) in solar cells. It was shown as early as 1973 that the replacement of Boron with Gallium was effective in the reduction of LID in solar cells (Fisher and Pschunder 1973). In 2020, the market share of Ga doped p-type mono Si was about 70% and it is expected that the boron doping for p-type will be phased out within 10 years.

Crystalline Silicon Wafers

The wafer production process starts with the slicing of the crystal ingot into bricks, then into wafers. The major challenges over the years have been to reduce the wafer thickness towards the theoretical limit while keeping the total thickness variation (TTV) as small as possible. The efficiency of the cutting process with decreased kerf loss and cost have also been under constant investigation. In 2020, as-cut mono-Si wafer thicknesses on the market depending on wafer size varied between 170 and 175 μm for p-type and 160 and 170 μm for n-type, with a TTV of ~20 μm. The ten year projection for as-cut mono-Si wafer thicknesses would be 150–160 μm bands for p-type and 135–145 μm bands for n-type with a TTV of ~10 μm (Fig. 12). The kerf loss is expected to be reduced to ~50 μm from the current value of ~70 μm.

In the wafer industry, 100 mm × 100 mm mono-Si wafers were the most common substrates for Si solar cells between 1980 and the early 1990s. Since then wafer sizes have been continuously increasing due to improved diameters of ingots. 200 mm diameter ingots enabled wafers with a size of 156 mm × 156 mm (M0). Further 5 mm to 10 mm increases in the ingot size allowed the reduction of “pseudo” square

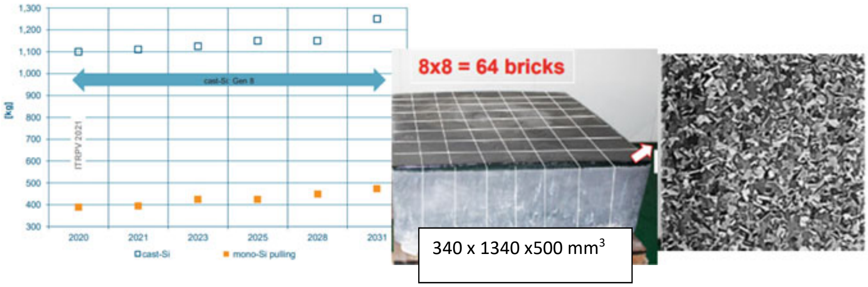


Fig. 11 Ingot mass in mono silicon and crucible-cast polysilicon silicon projections (ITRPV 2021)

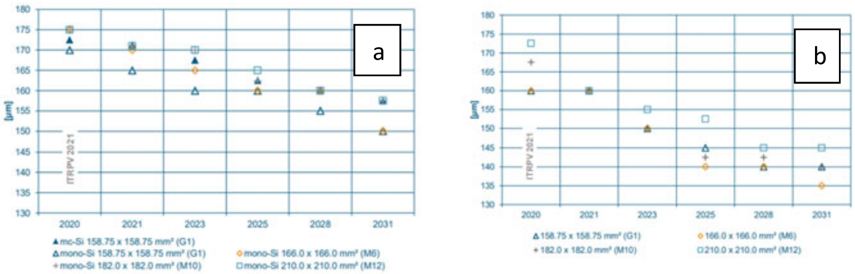


Fig. 12 As cut mono-Si wafer thicknesses and projections up to 2031 for different wafer sizes: **a** p-type **b** n-type (ITRPV 2021)

geometry with a wafer dimension of 156.75 mm × 156.75 mm. These wafers were only ~0.75 mm longer in side lengths but the area of the wafers cut from 205 and 210 mm ingots were 97.33 mm^2 (M1) and 131.33 mm^2 (M2) larger than that of the M0 wafers due to an increase in surface area in the corners. Production infrastructure changes for replacing the M0 wafers with the M2 wafers were negligible and the M2 wafers have been the industry standards for mono-Si up to 2018 (ITRPV 2021). In order to exploit the same cell production lines, multicrystalline silicon wafers have also been cut into M2 sizes. The progress in ingot sizes and cutting technologies have been facilitating production of new sizes of wafers such as; M3 (158.75 mm × 158.75 mm), M4 (161.7 mm × 161.7 mm), M5 (165 mm x 165 mm) and M6 (166 mm × 166 mm) with various thicknesses to supply a demand for novel module designs. In 2010, the concept of a full square mono-silicon wafer with the dimensions of 158.75 mm × 158.75 mm (G1(FSQ)) was introduced, and its market share has been on the rise up to 2020 (Fig. 13). Furthermore, it is expected that wafers with dimensions of 210 mm × 210 mm dimension (M12) will be opening new opportunities to cell and module manufacturers (ITRPV 2021).

Solar Cells on Crystalline Silicon Wafers

Silicon based p-n homojunction photovoltaic solar cells have been the backbone of all PV developments since the early 1950s (Cahpin et al. 1954). Since then several

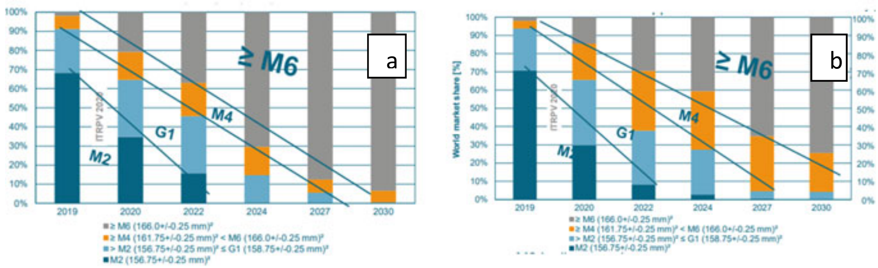


Fig. 13 Market share of wafer sizes **a** monocrystalline Si **b** microcrystalline silicon (ITRPV 2021)

novel cells have been introduced (Tuzun et al. 2006).The most common solar cell fabrication steps on boron doped p type silicon wafers might be summarized in eight distinguishable stages: (i) etching to remove cutting damages and to create textured surfaces, (ii) phosphorus diffusion to form the front n + region and to form p-n homojunctions, (iii) removing of doped regions at the rear and at the edge of the wafers, (iv) coating of an antireflection layer on the front side, (v) printing the finger gridlines connected by busbars on the front side of the wafer (vi) application of metal back contacts to the back side of the wafer, (vii) thermal treatment of the wafers to cure the front and back simultaneously, and (viii) removing unwanted phosphorus-diffused parasitic shunting layers around the perimeter of the wafer through laser ablation. Progress on each step over the years has been dynamically reported but only a few of the milestones are presented here as the greater details are beyond the scope of this review (Wilson et al. 2019, Mercaldo and Veneri 2020).

In 1973, aluminium back surface field (Al-BSF) cells were introduced to reduce back contact recombination losses through creation of an n + pp + structure by alloying screen printed Al back contacts into silicon (Mandelkorn and Lamneck 1973). Al-BSF cells had been a dominant technology up to the beginning of the 2000s when cell efficiencies of around 20% were achieved. However in the journey towards the Shockley-Queisser efficiency limit of 33.7%, new cell design technologies with innovative ideas have been introduced in laboratories, technologically developed and transferred to the production line. The front runner technologies racing for high efficiency solar cells based on crystalline silicon can be summarized as: the passivated emitter and rear cell (PERC) family of solar cells, n-PERT (passivated emitter rear totally diffused) solar cells (Chai et al. 2016), n-TOPCon (tunnel oxide passivated contact) solar cells (Glunz and Feldmann 2018), interdigitated back contact (IBC) solar cells (Mulligan et al. 2004) and heterojunction solar cells (HJT) (Taguchi et al. 2000).

The first silicon solar cell with PERC technology was reported by Green (1984) with a reported efficiency of over 22% in 1989 (Blakers 1989). In the PERC family of solar cells the rear surface recombination is reduced further by a combination of a dielectric surface passivation layer and a reduced metal/semiconductor contact area together with rear surface reflection by employment of a dielectrically displaced rear metal reflector (Green 2015). The cost effective process for PERC was not available immediately, nevertheless synergy between science, technology and industry managed overcome all barriers and delivered PERC cells commercially in 2016. It is calculated that the theoretical efficiency limit of a PERC cell is around 24.5%. At the end of 2019 efficiencies very close to the theoretical value were achieved at the laboratory scale. The 24.06% lab efficiencies lead to a 23% efficiency in the mass production scale in the middle of 2020 (Mercaldo and Veneri 2020).

SunPower reached a major boost in efficiency (above 25%) by applying passivating contacts. IBC structure combined with heterojunction passivating contacts delivered an efficiency of 26.7% (Yoshikawa et al. 2017). In the race for efficiency n-PERT and IBC were left behind due to lower efficiency potentials compared to the other contenders, together with complex fabrication steps and related high costs.

Currently TOPCon and HJT are the leading candidates for further efficiency improvements each with related pros and cons. It was reported at the Silicon PV 2019 conference that the TOPCon and HJT theoretical efficiency limits were about 28.7% and 27.5% respectively, approaching the theoretical limit of crystalline-silicon based solar cells (PVMagazine 2021). The next main stream silicon solar cell designs are being evaluated and optimized at each corner of the Science, Technology and Industry triangle. A chart of the highest confirmed conversion efficiencies for research cells for a range of photovoltaic technologies are updated dynamically at the NREL website (https://www.nrel.gov/pv/cell-efficiency.html) (National Renewable Energy Laboratory 2020).

2.2.2 Science Technology Industry and the Second Generation Solar Cells

As it is stated in the Sect. 2.2 the second-generation solar cells (2G) aimed to employ thinner layers of material using a fully automated in-line thin film technologies and reducing manufacturing cost. The main contenders in the 2G have been amorphous silicon (a-Si) and microcrystalline silicon (μc-Si) thin films solar cells, cadmium telluride/cadmium sulphide (CdTe/CdS) and copper indium gallium selenide, Cu(In, Ga)Se2 (CIGS) solar cells. In the 2G single junction solar cells conversion efficiencies are also limited by the Shockley-Queisser (SQ) limit. In the beginning of 1980's "the commercial readiness level (CRL)" for the 2G solar cells was at market competition. However the years expectations and the shares in the market for thin film solar cells have ben fluctuating significantly reaching the biggest share above 30% just before 1990's. The current share in 2020 is only 5%. Amongst the main thin film solar cells contenders, CdTe and CIGS cells are still in the race for large area applications. In 2020 global thin film module production was about around 7.7GW and this was shared by; of CdTe ~6 GW; CI(G)S ~1.5 GW and a-Si ~0.2 GW (Burger et al. 2021).

Cadmium Telluride Based Solar Cells

Cadmium telluride (CdTe), compound semiconductor has a direct energy band gap of ~1.5 eV which is an ideal match with the solar spectrum (Fig. 7.). Thus CdTe is one of the ideal absorber materials for a single junction solar cells (Fig. 6). Photon energy above ~1.5 eV (the wavelengths below 855 nm) would be totally absorbed within 1 μm thickness of CdTe due to high optical absorption coefficient. It is calculated that a theoretical maximum efficiency is close to 30% with an achievable photocurrent over 30 mA/cm^2 under Standart Test Conditions (STC: 100 mW/cm^2 solar irradiance at 25 °C cell temperature in air mass equal to 1.5, and ASTM G173-03 standard spectrum). Furthermore CdTe compound semiconductor has a simple chemical structure to work with outstanding stability under high irradiations for space applications. It is a general practice to form a heterojunction solar cell between CdTe and a large band gap n-type compound semiconductor as a window. The most common window material is n-type cadmium sulphide (CdS), since the pioneering work in 1972 (Bonnet and Rabenhorst 1972), However alternative window materials have also been also under investigations such as In O_2 (Nakazawa 1987) and ZnO (Aranovich et al. 1980, Oktik et al. 1996). Deposition techniques of CdTe thin films have a strong influence on the quality of the grown layers. Deposition temperature is inversely proportional to the grain size of thin films and the post deposition chloride treatments are usual practice for recrystallization (Paudel et al. 2011). Deposition techniques such as electrodeposition (Barker et al. 1992; Cunningham 2020), sputtering (Nowell et al. 2015), thermal evaporation (Kranz et al. 2012), metal organic chemical vapour deposition (2007) and close space sublimation (Major et al. 2010, 2017) have been taken CdS/CdTe solar cells to technology readiness levels of TRL9 "actual system proven through successful operations", but only close space sublimation technique has been successful to take the CdTe based solar cells to the commercial readiness index of "Bankable Asset Class, CRI 6). The 10% efficiency target for CdTe based solar cells was passed in the beginning of 1980's when the heat treatment process in chlorine atmosphere introduced to cell fabrication steps (Turner 1991, 1994; Tyan et al. 1982). Yet another milestone was reached by combining Cu diffusion with the heat treatment process in chlorine atmosphere and 15% cell effiency was achived (Britt and Ferekides 1993). Versatile collaboration within the triangle of science, technology and industry through 2000's the cell efficiencies were improved towards 17% by employing numerous ideas such as using novel alternative front contacts and back contacts (Wu 2004; Wu et al. 2001). In 2010's the scientific and technological developments through optimization of thin films and interfaces, selection the most suitable substrates, antireflection coatings had improved efficiencies towards ~20% band (NREL Chart 2021). In an attempt to increase the efficiency of CdTe cells, the concept of reducing the band gap as well as improving the lattice match at the junction of absorber layer CdTe(1-x)(S, Se)x mixed compound introduced and 22.1% efficiency was achieved by First Solar in 2016 (First Solar 2016; NREL 2021).

In spite of an environmental concern related to cadmium during cell and module production, modules life as well as module recycling together with skeptical view on the limit in material resources for Cd and Te, CdTe based cell and module production have exhibited continuous progress at the corner of the science, technology and industry triangle over 40 years. The current (2020) commercial status might be summarized as ~6 GWp CdTe based stable modules with STC efficiency of 19% were produced at the competitive cost in fully automated large capacity production lines with mature technologies (Baines 2018).

Cu(In, Ga)Se2 (CIGS) Based Solar Cells

The direct band gaps value of the group I-III-VI chalcopyrite (Cu)(In, Ga)(S, $Se)_2$ semiconductor alloys starts from 1 eV and goes up to 2.6 eV (Fig. 14). High absorption coefficients together with high minority carrier lifetime due to intrinsic defect properties make them one of the most favorable absorber for photovoltaic applications. Photovoltaic modules based (Cu) (In, $Ga)Se_2$ are one of the main contender in the race of the commercial second generation solar cells (Upadhyaya 2007). The theoretical efficiency limit for CIGS solar cells for the bandgap of 1.14 eV is calculated to be ~33.5% (Choi et al. 2011) and the reported small area CIGS efficiencies in 2020 were still below 24%. (Farunhofer 2021).

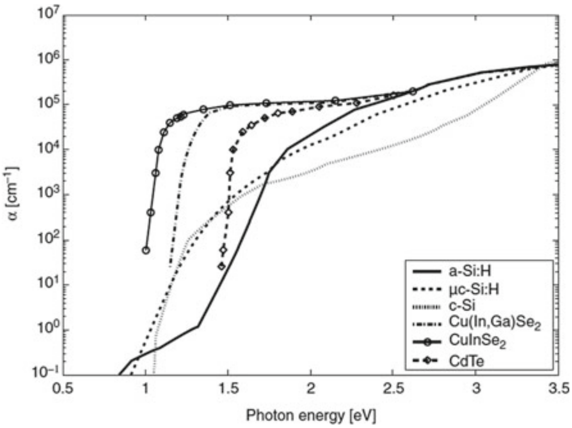


Fig. 14 The optical absorption (a) versus bandgap (Eg) spectra of the c-Si and other prominent lightabsorbing materials that are used in thin-film solar cells (Upadhyaya 2007)

The last couple of decades the efficiencies of CGIS cells and module have been improving by a strong cooperation between science, technology and industries, new innovations have been transferred from laboratory benches to production lines since 1980's. Major steps in CIGS deposition technologies in the progress of efficiencies can be summarized as; evaporation of the compound CIS; reactive elemental codeposition of bilayers; selenization of sputtered metal precursors; chemical bath deposition of CdS with ZnO:Al as the emitter; gallium alloying; sodium alkali incorporation; three-stage co-deposition; alkali heavy-ion-exchange post-deposition treatment; sulfurization-after-selenization Fig. 15 demonstrates the record CIGS cell

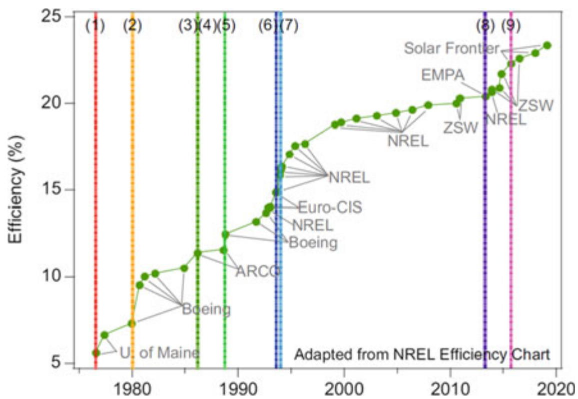


Fig. 15 CIGS record cell efficiencies and technological innovations: (1) evaporation of the compound CIS; (2) reactive elemental codeposition of bilayers; (3) selenization of sputtered metal precursors; (4) chemical bath deposition of CdS with ZnO:Al as the emitter; (5) gallium alloying (6) sodium alkali incorporation; (7) three-stage codeposition; (8) alkali heavy-ion-exchange post-deposition treatment; (9) sulfurization-after-selenization (SAS) (Wilson et al. 2019)

efficiencies over the years and innovative technologies employed throughout the progress.

Despite a significant progress in the small area efficiencies, the efficiency gap between small area cells and the module is still too large. In 2020 total CIGS module production was about ~1.5 GW and the reported efficiencies of 841 cm^2 modules were about just over 19%. At the each corner of the Holy Triangle of Science, Technology and Industry, the efforts on manufacturing cost, efficiency, energy yield together with durability have been continuous to stay in the race. Tasks at the each corner are still fairly big. In the recent studies, novel approaches have been reported on: improving intergrain homogeneity; utilizing Sulphur substitiuon in the Group VI lattice; the buffer/CIGS interface; utilizing passivated back contacts to reduce recombination; to incorporate light management features increasing radiative recombination emission reabsorption etc. (Wilson et al. 2019).

It is claimed that CIGS based photovoltaic cells and modules would provide over 25% efficiencies in the near future and much higher efficiencies with tandem structure used together with lower band gap materials. Furthermore it is shown that low degradation rates of CIGS solar cells would deliver stability over decades (Jordan et al. 2016).

2.2.3 Science, Technology, Industry and the Solar Cells Generation Form the Third to the Fourth

Production technologies of third-generation solar cells are based on solution processes with a great potential for low cost large-scale applications. Novel materials and device designs employing basic concepts of physics such as; multiple energy levels, multiple carrier pair generation from high energy photons, single carrier pair generation with multiple low energy photons and capturing carriers before regenerations have been subjects of numerous R&D studies in academia and in industries (Ma 2002). The several scientific and technological milestones contributing development of the 3G and the 4G solar cells might be summarized as: following the introduction of the concept of nanotechnology for manipulating organic or inorganic materials at atomic levels by Feyman (1960); discovery of fullerene and fullerene derivatives (a series of hollow carbon molecules that form either a closed cage ("buckyballs") or a cylinder (carbon "nanotubes"), ellipsoid tubes and many other shapes and sizes Kroto et al. 1985); discovery of synthesis and controlled doping of polymers (Heeger 2000); introduction of graphene production technologies (Novoselov et al. 2004). These steps opened up new horizons in the scientific, technological and industrial development of photovoltaic conversion.

Historically the R&D efforts of 3G cells were initiated by the pioneering work of O'Reagan and Grätzel (1991). They focused on dyed-sensitized solar cells (DSSC) and employed nanoporous TiO_2 electrodes to increase the roughness of the surface and increasing the number of dye molecules attached to the surface. R&D effort on DSSC has continued by the same group and the efficiency of 12.3% for a zinc–porphyrin cosensitized DSSC was reported in 2011 (Yella et al. 2011). Efficiency improvement has exhibited a slow progress reaching over only 13% in 2019 for DSSC based on a triazatruxene-based sensitizers (Zhang et al. 2019). Introduction of nanomaterials into photovoltaic device design was an important mile stone for the future of the single-bandgap solar cells to overcome efficiency limit of 30% reported by Shockley and Queisser (Shockley and Queisser 1961). New and emerging concepts such as nano-crystalline films, active quantum dots, tandem or stacked multilayer cells have undertaken by many researchers across the world (Conibeer 2007; Chen et al. 2013; Wu et al. 2020). Physical and chemical properties of nanomaterials with a larger surface area and volume ratio are considerably different that of the bulk materials. The advantageous for nanostructured film in photovoltaic conversion via nanoparticles and quantum dots might be summarized as: the larger optical paths for absorption due to multiple reflection; reduced recombination losses (due to short distance that electron–hole pairs need to travel); a reduced thickness of absorber layers. Furthermore, nanoparticles as sensitizing agent in the 3G and the 4G solar cells enable to tune the bandgap by changing the size of nanoparticles. As the size of nanoparticles increases the energy band gap moves from blue to red region of the spectrum (Chen et al. 2013). In Many combinations of nanoparticles at different sizes have been under investigation to harvest the large portion of solar spectrum such as titanium dioxide crystals in DSSC and the lead halide in perovskites (Chen et al. 2013; Wu et al. 2020).

Initial solid-state quantum dot sensitized solar cell exhibited efficiencies less than 1% (Plass et al. 2002), however through a progress in the science corner of the holy triangle, the efficiency of 16.6% was reported in 2020 by combining quantum dots and perovskites (Hao et al. 2020). The 4G solar cells have emerged to benefit “the best of both worlds”, large scale manufacturability and the flexibility of the organic materials (synthesis and controlled doping of polymers) and the stability of inorganic materials (the stable nanostructures). Furthermore employing nanostructures in the thin film device designs enable to improved charge transfer (Nismy et al. 2010), optical coupling and the extended life time (Gilot et al. 2007). These in turn have been attracting a measurable interest in each corners of the holy triangle. The scientific, technological and industrial progresses on the 4G solar cells have been continuously revived (Gershon 2011; Bouniox 2012; Gan et al. 2013; Yang et al. 2013; Imalka et al. 2013; Akinoglu 2021).

In an attempt to address the demand for transparent solar cells in variety of industries such as; construction, transport, electronics, display technologies etc., a new roadmap has been followed through the progresses in 4G technologies. Almost 55% of solar energy is in the visible region (380 nm–780 nm). Contributions of ultraviolet (280 nm–380 nm) and near infrared (780 nm–2500 nm) regions are ~4% and ~41% respectively. Thus at the first glance the idea of “converting solar energy by photovoltaic process via transparent solar cells” might seem to be a bit controversial. Initially Schottky-type potential barriers at the metal/ the p-type or n-type photoactive semiconductor polymer layer interfaces with different work functions were employed for single-layer organic photovoltaic cells to utilize the insulating nature in organic semiconductors, short exciton diffusion length and the recombination of the excited charge carriers. The nature of molecular orbitals in organic semiconductors differs from inorganic semiconductors and results in the discontinuous absorption spectra. Solution-processable fullerene/no fullerene derivatives used in the form of small molecules with broad absorption in the visible and near-infrared portion of the electromagnetic spectrum and polymers. Derivative of fullerenes/non fullerens polymers with wavelength selective properties are long-chained molecular systems can be obtained as p-type organic semiconductor as a donor and as n-type organic semiconductor as acceptor. The discontinuous absorption spectra opens up possibilities to design a "spectra selective active layers" in fullerene and non-fullerene polymer solar cells exhibiting transparent, semi-transparent, and translucent properties (Chang et al. 2018). However progress towards transparent organic photovoltaic had been fairly slow through the first decade of 2000's (Chu et al. 2006; Baily-Salzman et al. 2006). The cutting-edge research and technological development efforts on transparent polymer solar cells have shown that this new field has a great potential to change the game in photovoltaic industries. Following the introduction of bulk heterojunction (BHJ) polymer solar cell in 2011 (Yu et al. 2011), technology readiness levels and efficiencies of the 4G a tunable absorption spectrum polymer solar cells have been increasing towards to the level to attract the interest of photovoltaic industries. The progress in transparent photovoltaic solar cells has been exponential and dynamically reviewed (Husain et al. 2018, Vasiliev et al. 2019).

Figure 16 demonstrates the progress in fullerene base and non fullerene base organic photovoltaic solar cells (IDTechEx Research 2020). In 2020 single-junction non-fluerene organic solar cells with $\eta = 18.22\%$ was reported (Liu et al. 2020). Despite the encouraging progresses at the science and technology corner of the holly triangle the industry corner is still in the demand of the 4G solar cells and modules which can be compete with an existing modules in the market in terms of efficiency, stability and cost.

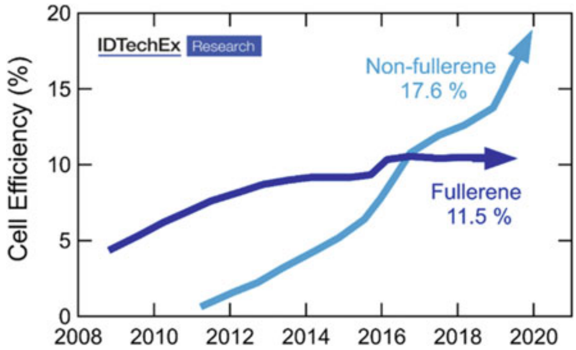


Fig. 16 Trends in OPV cell efficiencies for fullerene and non-fullerene based cells ((IDTechEx Research 2020)

3 Comments on Future of Science, Technology, Industry for Photovoltaic Conversion

Since the first discovery of the photovoltaic effect, collaborations and co-creations within the "Holy Triangle of Science, Technology and Industry" have been governing the progress in each part of the value chain of the photovoltaic solar energy conversion industry. The sustain progress in the basic research and development front has been continuously taken up by technologist to push the discoveries and innovations towards the higher level of technology readiness. However, the photovoltaic industry needs to provide conversion technologies to compete with conventional power production technologies as well as other clean energy technologies. The extensive basic research and technological development efforts have been offering innovative solutions for all generation of solar cells in efficiency, stability and manufacturing cost. In reality, generations have been overlapping and crystalline wafer based technologies are increasingly combined with thin film technologies. The progress in the each corner of the holy triangle follow more complex and evolutionary road maps and the parameters of solar cells, modules and systems have being improved using materials, devices, technologies of all generations in different combinations. At the end of 2020, the market share of crystalline silicon based technologies, thin film technologies were about 95% and 5% respectively, and the technology roadmap prepared by 56 leading actors in the value chain of photovoltaic industry scientist suggests their ratio would stay the same in near future (ITRPV 2021). The innovative module designs have been employing mono crystalline silicon cells due to a significant decline in cost and a better performance of half cell interconnects modules with bifacial mono crystalline cells. Furthermore using larger wafer format showed that the learning rate in the historical module price cumulative module production learning curve (Fig. 5) increased to 23.8%. The strong collaboration in the holy triangle will continue to be the driving force for improvement of the learning rate by reducing manufacturing cost through innovative and improved approaches in polysilicon technologies, wafer technologies, cells front and rear sides, bifacial cell concepts, cell layout in module designs as well as in other components of modules (ITRPV 2021). Future topics to be addressed in wafer based crystalline silicon solar cells might be summarized as: new and improved polysilicon production technologies; reduction of silicon consumption per wafer; novel cell concepts and designs employing tandem approaches with increased efficiency and stability at competitive cost; novel materials and processes to improve quality as well as to reduce cost throughout the value chain; integrated manufacturing to improve the yield and throughput; the last but not the least, development of environment friendly processes and technologies.

Low cost large area thin film deposition processes for solar cells and employing abundant nontoxic inorganic and organic thin film materials have been being reviewed over the years (Oktik 1989, Dutter et al. 2014, Ramanujam et al. 2020) for assessing competitiveness in efficiencies, stabilities and manufacturing costs. In recent years promising developments have been evolving by combining these technologies with physical and chemical properties of nanomaterials together with band gap tunability of flexible polymers. In the roadmap to overcome the Shockley-Queisser (SQ) limit (Shockley and Queisser 1961) for single junction solar cells, the basic concepts of physics such as; multiple energy levels, multiple carrier pair generation from high energy photons, single carrier pair generation with multiple low energy photons and capturing carriers before regenerations has been successfully implemented in photovoltaic conversion. In the film solar cells, CdTe and CIGS based modules are leading with only 5% market share. The emerging and novel technologies have been advancing in the technology readiness level (TRL) index. From the 3rd generation to 4th generation cells progress and supports by technology developers and power industry changes according to TRL from blue sky research (TRL1) to actual system demonstration over the full range of expected conditions (TRL9). In the near future, some of the new and emerging technologies combining the best of all materials and technologies available are expected to progress towards the TRL9 and move to the commercial readiness level to share the emerging several terawatt market along the wafer based crystalline solar cells and existing thin film solar cells.

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Integration of Renewable Energy Sources to Power Networks and Smart Grids

Bilal Gümüş

1 Introduction

Electrical power network systems used around the world have changed in recent years due to the new concept of energy supply. This new concept of energy supply is based on three key issues, decarbonize, decentralize, and democratize (Hirsch et al. 2018). Global climate change forces governments to reduce carbon emissions. The widespread use of electricity from renewable energy sources has led to an increase in Distributed Energy Resources (DERs), resulting in decentralization of the energy supply (Lasseter 2007). The use of off-grid systems has proven to be a suitable solution for regions with no access to electricity. Thus, democratization in energy access has increased. All these developments have resulted in the change of electrical power network infrastructure and the emergence of microgrids (Mariam et al. 2016). With microgrids and distributed energy resources, traditional power grids have transformed into smart grids with the increase of sensing and decision-making capabilities.

Smart grids have become a good alternative to traditional power grids because they are flexible in design, traceable, controllable, and allow bidirectional energy flow (Salkuti 2020). The unidirectional flow of energy in traditional power grids and the understanding of generation in large power plants had to change due to distributed generation systems (DGSs). Add to this the need for change in outdated grids, the Internet of Things and blockchain, and it is clear that smart grids have a bright future (Zhuang et al. 2021).

While its flexible structure and advantages have raised interest in smart grids, problems have occurred due to the structure of smart grids. The integration of renewable energy resources into the grid at different scales has made it necessary to control

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some parameters in terms of grid stability and quality. The most important of these parameters are voltage, frequency, and reactive power control. On the other hand, the management of smart grids is a very important issue for customers and distributors.

In this chapter, introduction to the smart grid and associated challenges are presented. The chapter is organized as follows. Section 2 presents smart grid architecture, smart and traditional grids comparison and challenges of smart grids. Section 3 discusses problems related with the integration renewable energy sources to power networks and the management of smart grids. Section 4 concludes the chapter.

2 Smart Grids

Smart grids differ significantly from traditional power networks. DER, which is becoming more and more widespread, has changed the network structure and created the concept of microgrid. Monitoring and control structures of microgrids have caused these networks to be defined as smart grids. However, the smart grid concept allows the monitoring, communication, and management of the entire power grid. Smart grids naturally include DER and microgrids. Advancements in DER and microgrids enable the development of smart grids. In this section, first, the traditional network structure will be examined, and the differences of smart grids from traditional grids will be revealed. Then, information will be presented regarding the smart grid concept, architecture and development.

2.1 Traditional Power Grids

The electric power grid consists of generation facilities, transmission lines, and distribution lines that connect consumers and producers. The commercial power generated in large power generation plants is delivered to the consumers with the help of transmission and distribution network (Gupta et al. 2021). In the conventional power grid, the flow of energy is unidirectional. The design of the grid, protection and communication systems are designed accordingly. The electromechanical nature of power generation systems and the strong moments of inertia of these systems create a secure structure against power fluctuations in the grid. On the other hand, the transmission and distribution of large power leads to an increase in electrical losses. Additionally, a large number of consumers fed by a main line can be affected by a fault on this line. The traditional power network structure is presented in Fig. 1.

Traditional power grids consist of large power plants, step-up and step-down transformers, transmission and distribution lines, protection, and communication equipment (Gupta et al. 2021; Dileep 2020a). Electricity generation in traditional power grids mostly relies on fossil fuels. Power grids operate at different voltage levels. While transmission lines operate at high voltage, distribution lines operate at

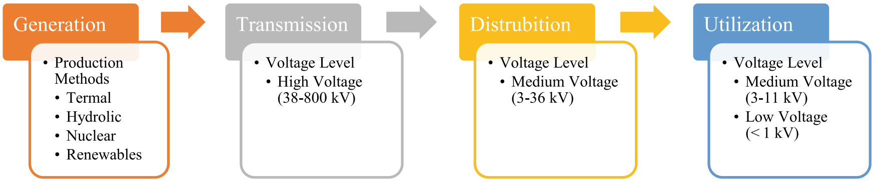

Fig. 1 Traditional power grid structure

medium voltage. The consumers connected to the power grids use low and medium voltage levels depending on their function (industrial, domestic, commercial, etc.).

The transition of energy resources from fossil fuels to renewable energy resources forces to change the structure of traditional grids. The most important change in power grids is the bidirectional flow of electricity and the widespread use of distributed generation systems.

2.2 Smart Grid Concept

A smart grid can be defined as an advanced electrical network based on a bidirectional, secure communication infrastructure and power exchange between suppliers and customers (Worighi et al. 2019). The smart grid structure differs from the traditional power networks in two fundamental ways: structurally and administratively. Bidirectional power flow causes structural change of power network. The protection and communication equipment have to be compatible with bidirectional power flow. On the other hand, the management of the power grid should be more advanced with smart capabilities. Smart grids are built on these two main constituents. Comparison of the traditional power networks and smart grids is presented in Table 1.

The features of smart grids such as the diversity of production resources, consumer participation, observability, controllability, transparency in data access and sharing are more advanced compared to conventional grids (Gupta et al. 2021; CEDEC, E.DSO, Eurelectric, and GEODE 2021). For the development of these features, it needs a more complex structure, bidirectional secure communication systems, more sensors, and measurement systems. As a result, smart grids have flexible and controllable management systems and a self-healing restoration system and use more renewable energy resources.

2.3 Conceptual Model of Smart Grid

The conceptual model of smart grids consists of seven domains which are generation including DER, transmission, distribution, costumers, market, operations and service providers (Nist 2014; Gopstein et al. 2021). Smart grid conceptual model

Table 1 Comparison of traditional power network and smart grids

Feature	Traditional network	Smart grid
Power flow	Unidirectional	Bidirectional
Power generation	Centralized	Centralized and DER
Energy resources	Focuses on traditional resources	Focuses on renewable energy resources
Management system	Limited	Smart and flexible
Communication	One way	Two way
Complexity	Less	More
Consumer participation	Impossible	Possible
Distribution system	Passive	Active
Observability	Less	More
Controllability	Less	More
Transparency in data access and sharing	Less	More
Restoration system	Manual	Self healing
Monitoring	Manual	Automatic (self, smart and remote)
Sensors	Limited use	Extensive use
Metering system	Traditional	Advanced (electronic and remote)

is presented in Fig. 2. Bidirectional power flow is between generation including DER, transmission, distribution, and costumers. Bidirectional data flow of domains is also presented in Fig. 2. Data flow refers to secure communication flows between domains.

Each Smart grid domain has its own specific tasks and roles. In addition to the transmission and distribution of electrical energy from generation to the customer, it is necessary to transfer the electricity generated by the customer to the grid with the changing power network structure. While the transfer of electrical energy takes place between the domains of generation, transmission, distribution and consumer domains, the domains of market, operator and service provider domains have roles during these transactions. The definitions and roles of the domains are shown in Table 2. Due to developments in Smart Grid, the roles and definitions of domains are updated from time to time. With the February 2021 release by the National Standards Institute of the United States, the domain roles have been updated from the previous version (Gopstein et al. 2021).

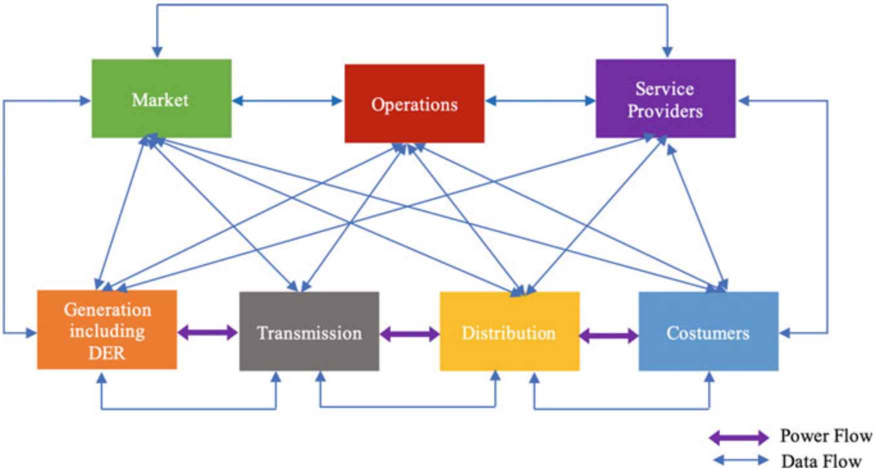

Fig. 2 Conceptual model of smart grid

Table 2 Definitions and roles of domains in smart grid conceptual model

Domain	Definition and roles
Generation including DER	This domain refers to producers of electricity. Generation includes traditional generation sources such as thermal generation, large-scale hydro generation, utility scale renewable installations and distributed energy resources (DERs). The generation domain may also store energy.
Transmission	This domain refers to carriers of high voltage electricity over long distances.
Distribution	This domain refers to distributors of electricity to and from customers.
Customers	This domain refers to end user of electricity that may also generate, store, and manage the use of energy. There are residential, commercial, and industrial customers.
Markets	This domain refers to electricity markets where the facilitator and participants drive action and optimize system outcomes.
Operations	This domain refers to processes that enable the movement of electricity.
Service provider	This domain refers to providing services for electrical customers and utilities.

2.4 Challenges of Smart Grids

Due to the smart grid structure, it should offer the energy generated by the consumer for the use of the main grid. The integration of distributed energy sources into the grid presents some challenges. These difficulties can be listed as synchronization of distributed generators with the grid, reorganization of protection systems, reactive power control and power quality problems such as harmonics, voltage and frequency changes. In addition to the challenges related to the electrical system, other challenges include issues of cybersecurity and data protection, database management, establishing a competitive pricing system, and legal and normative regulations (Mariam et al. 2016; Colak et al. 2016; Tuballa and Abundo 2016; Dileep 2020b; Aleksic and Mujan 2018; Alonso et al. 2020).

The integration of distributed generation systems (DGS) into the power grid has led to the development of the microgrid concept. The technical challenges in the field of power network integration are also the challenges of micro grids. The problems encountered in the grid integration of distributed generation systems and proposed solutions are discussed in detail in the following section.

Cybersecurity is one of the most important challenges of smart grid systems (Zhuang et al. 2021; Shrestha et al. 2020; Ansari et al. 2019). Vulnerabilities in the security system can compromise both security of the customers and security of the grid. Smart grid data can be stored in cloud servers. Security vulnerabilities in cloud servers can lead to cyber threats. Taking precautions against these threats is also very important for managing the power network. There is a need for regulation in relation to smart grids. There is a need to regulate many issues, such as regulating the sale of electricity by customers, setting the rules in this market, selecting the suppliers of the other customers, setting the electricity sale prices and incentives (Lasseter 2007; Dileep 2020a; Alonso et al. 2020; Yoldaş et al. 2016). Real-time pricing mechanisms are required to meet energy demand during customer demand periods. The disadvantages of the intermittent nature of DERs can be eliminated through forecasting tools and dynamic pricing (Farmanbar et al. 2019; Zafar et al. 2018).

3 Problems Associated with Integration of Renewable Energy Sources to Power Networks and Solution Methods

Renewable energy sources play a key role in avoiding greenhouse gas emissions. However, the integration of renewable generation units into the grid as a distributed generation system can lead to grid stability difficulties with respect to the intermittent nature of these resources. To overcome this difficulty, electrical storage systems need to be integrated into the grid. Renewable energy systems with different generation characteristics and electricity storage systems ensure a smooth transition from conventional grids to smart grids. The power generation of conventional grids is based on electromechanical energy conversion, which can be tolerated since the effect of a possible load change in the grid can be absorbed by the inertia of the mechanical system. Since there is little or no mechanical inertia in renewable energy generation by inverter coupling, the effect of a possible load change on the grid is higher. Therefore, the development of methods to solve the problems of voltage and frequency changes in the networks to which renewable energy sources are connected is an important area of research. The presence of energy storage systems is very important to ensure stability and power quality in grids with a high penetration of renewable energy sources (Nazaripouya et al. 2019). In addition, the management of microgrids is also important for system stability.

In this section, in addition to voltage and frequency stability, which are the most important problems in the integration of microgrids and distributed generation resources into the power grid, energy storage and management systems of smart grids are presented.

3.1 Energy Storage Systems

Energy storage system (ESS) plays a significant role in network stability in connecting distributed energy sources to the grid (Gupta et al. 2021; Yoldaş et al. 2016; Nazaripouya et al. 2019). ESS acts as a regulator that provides power quality after sudden power changes. Intensive development works have been conducted on energy storage systems in recent years. Decreased costs enable the widespread use of these systems. In the future, there will be a network structure where ESS is widely included in the network. ESS is also one of the key technologies of electric vehicles. The proliferation of electric vehicles will also cause ESSs in electric vehicles to become an important mobile storage unit of the grid. ESS Technology is divided into four main groups (Gupta et al. 2021; Nazaripouya et al. 2019) (Fig. 3):

– Electrical ESS
– Mechanical ESS
– Chemical ESS
– Thermal ESS.

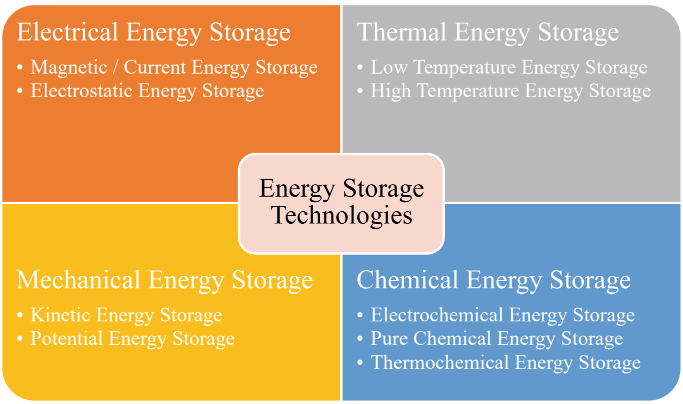

Fig. 3 Classification of energy storage technologies

Electrical energy storage (ESS) can be divided into two subgroups: magnetic/current-based energy storage and electrostatic energy storage. Superconducting magnetic energy storage devices, supercapacitors, are examples of electrical energy storage devices. Mechanical energy storage can be divided into the subgroups of kinetic energy storage such as flywheels and potential energy storage such as pumped storage power plants. Chemical energy storage is one of the most widely used storage areas. This group is comprised of three separate subgroups such as electrochemical energy storage, chemical energy storage and thermochemical energy storage. Examples of these groups are conventional and flow cell batteries, fuel cells and solar hydrogen. Thermal energy storage can be defined with two subgroups called low temperature energy storage and high temperature energy storage. Cold aquifer thermal storage systems are examples of low thermal energy storage systems, while steam or hot water accumulators are examples of high temperature energy storage systems. The appropriate storage system is selected by considering the rating characteristics, space requirements, and dynamics of the ESS (Fig. 4). Rating characteristics express the power and energy ratings of the storage system, such as the charge/discharge rate and the discharge duration. The storage system efficiency is also an important criterion to be considered in the selection process.

When generation and unpredicted power demand do not match in grids where DES is integrated, storage systems are a powerful solution. In addition, storage systems play an important role in ensuring system reliability, stability, and power quality.

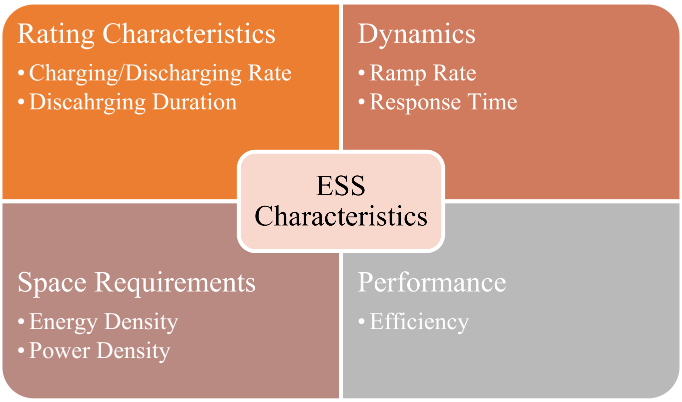

Fig. 4 Characteristics of energy storage systems

3.2 The Problems to Overcome in the Integration of Distributed Generation Systems to the Grid

The increasing integration of distributed generation into transmission and distribution networks leads to difficulties in voltage, frequency, and reactive power control with respect to grid stability. The spread of distributed generation has also accelerated the transformation of the grid structure into microgrids. An important part of the future smart grids will consist of microgrids. Therefore, the problems that occur in microgrids and their solutions are important. Microgrids are a sub-grid with DERs, own loads and own control (Hirsch et al. 2018; Lasseter 2007; Mariam et al. 2016). They operate in islanded and on-grid mode. Multiple DERs are connected to a point of common coupling (PCC) to power a microgrid (Fig. 5). In this section, the problems of voltage, frequency, and active reactive power control in microgrids are briefly discussed.

3.2.1 Voltage Control in Microgrids

The increasing integration of wind/photovoltaic (PV) power plants into transmission grids and distributed generation (DG) into distribution grids leads to significant problems in voltage regulation of the power grid. There are many problems with voltage

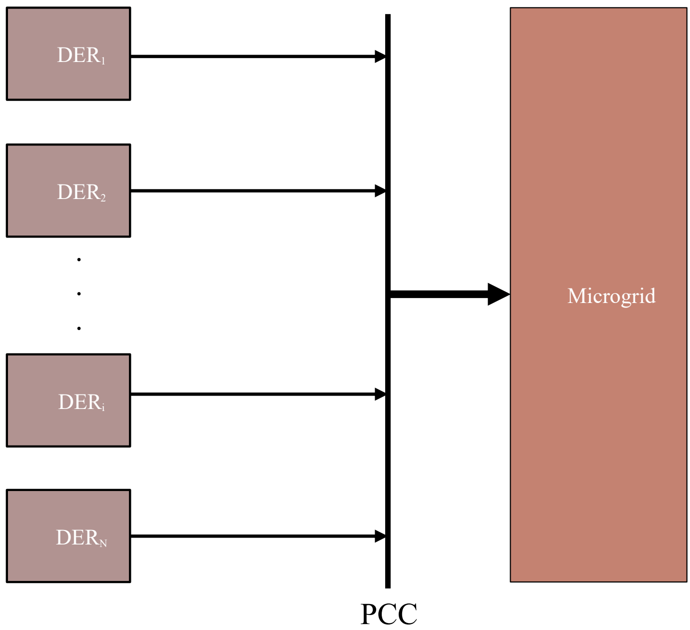

Fig. 5 DERs connection to a microgrid

stability in the transmission network (TN), such as voltage fluctuations, cascading faults, and fault-induced delayed voltage recovery (FIDVR) (Sun et al. 2019).

High penetration of wind and solar power plants in the transmission network increases the risks of voltage fluctuations and cascading trips (Bollen et al. 2017; Yang et al. 2015). Three basic voltage control methods are used to regulate voltage in transmission lines. These control methods are voltage control mode, corrective control, coordinated control and preventive control (Guo et al. 2015). Corrective control is used to maintain the terminal voltage of the distributed generations at the desired value within the operating limits. Coordinated control follows the set point and reduces the voltage fluctuation within the operating limits. The preventive control ensures that the voltages on the high voltage side of the DGs remain within a certain range with the faster reacting dynamic reactive power (DRP) control (Vittal et al. 2010). Model Predictive Control (MPC), heuristic dynamic programming, PI control, reactive current division algorithm and online supervisory coordination techniques are some of the methods used for voltage regulation (Zhao et al. 2017; Tapia et al. 2007; Qiao et al. 2009). The purpose of all these methods is to maintain the voltage at a certain value under operating conditions. Since the voltage change is related to the reactive power change, the voltage can also be controlled using methods that provide dynamic reactive power response. Cascading trips occurring in the system may cause the voltages of the DGs to increase. To prevent this, control methods based on the voltage security region approach, which is a preventive method, are used (Niu et al. 2016; Ding et al. 2016).

Distribution networks with a high degree of penetration DER present challenges in terms of voltage regulation when the load pattern changes. One of the most important of these difficulties is to ensure the coordination of voltage regulation devices. In addition, low and medium voltage level regulations are required for power quality. Voltage problems in distribution networks are categorized into four types: as voltage drop, voltage rise, voltage fluctuation, and reverse power flow impact problems, as shown in Fig. 6.

The main reason for the voltage rise problem in distribution systems is the high PV power generation. The high R/X ratio of the distribution system in low voltage (LV) systems makes the voltage sensitive to the active power (Carvalho et al. 2008; Tonkoski et al. 2012). This contrasts with the low R/X ratio in high voltage transmission lines, which makes the voltage sensitive to reactive power. Increasing the active power transmission of the PV generation towards a constant voltage substation causes an increase in the terminal voltage. Negative reactive power injection is used to prevent this rise. In cases where the reactive power injection cannot regulate the voltage, the active powers of controllable loads such as electric vehicles, energy storage devices can be changed (Cheng et al. 2015; Zeraati et al. 2019). Voltage irregularity can be limited by PV inverter and demand side control (Acharya et al. 2019).

Voltage drop is a common problem in distribution systems. Overloads and connection of electric vehicles to the grid cause voltage drops, especially during peak loads. The increase in the number and deployment of electric vehicle charging stations has highlighted the impact of these loads on voltage drop (Clement-Nyns et al. 2010).

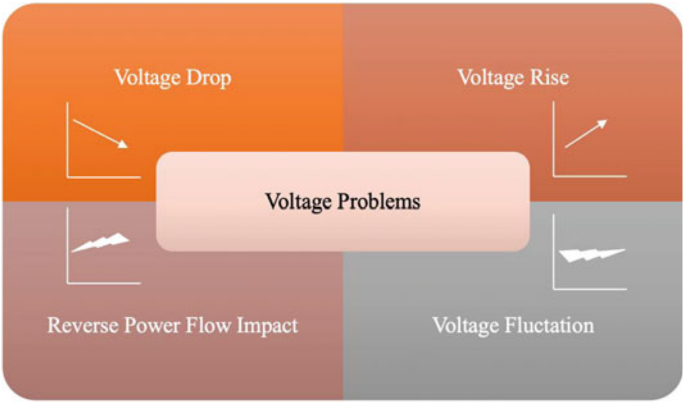

Fig. 6 Common voltage problems in distribution networks

Therefore, optimization and control of battery charging is effective to prevent this problem.

Conventional Distribution systems are designed and operated on the principle of unidirectional power flow. DER allows power to flow from the consumer to the grid. In this case, voltage rise may occur in the grid if the grid voltage regulators are not set appropriately. The problem is solved by voltage verification and coordination between line voltage regulators and DER (Sun et al. 2019).

Voltage fluctuations due to various reasons are an important power quality problem. With smart inverters in microgrids, voltage fluctuations can be kept within specified limits. For this, methods such as conservation voltage reduction (CVR) and Volt-Var control (VVC) are used for this purpose (Divan et al. 2016).

Voltage control methods can be divided into four different categories as shown in Fig. 7, which are local voltage control, decentralized voltage control,

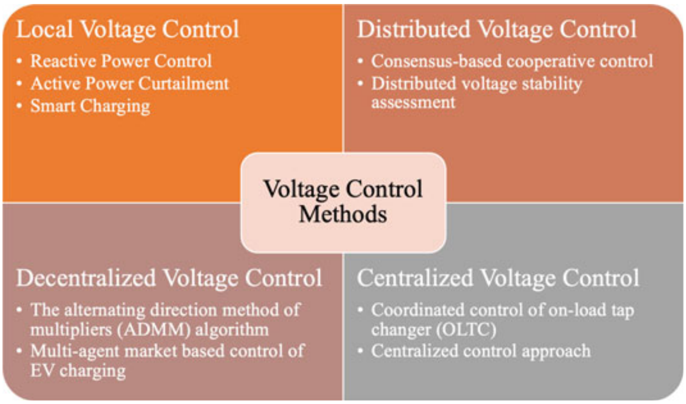

Fig. 7 Voltage control methods of microgrids

distributed voltage control and centralized voltage control (Yang, et al. 2015). Local current/voltage measurements are made in the Local Voltage Control Method. No communication is required in this method. Voltage control is done by reactive power control, active power curtailment and smart charging techniques (Martinenas et al. 2017; Al-Awami et al. 2016; Chalise et al. 2016). In distributed voltage control technique, local measurements and calculations are performed and there is limited communication with neighboring nodes. In this control method, techniques such as consensus-based cooperative control and distributed voltage stability assessment are used (Cheng et al. 2015; Li et al. 2018). In Decentralized Voltage Control, local control is performed with little communication. The alternating direction method of multipliers algorithm and multi-agent based control techniques (Zhao et al. 2020; Gao et al. 2018) are used for decentralized voltage control. With decentralized voltage regulation, flexible, efficient voltage regulation is possible. Centralized voltage control performs voltage regulation from a single control center with an advanced communication system. The control of on load tap changers (OLTC) is one of the control methods that use a centralized control approach (Valverde and Cutsem 2013; Juamperez et al. 2014). Centralized voltage control optimizes resources and outperforms decentralized control techniques.

3.2.2 Frequency Control in Microgrids

In conventional power systems, the grid frequency remains constant during load changes due to the large grid power and the inertia of electromechanical generators. In distributed generation systems, on the other hand, the system frequency fluctuates during load changes due to the lack of sufficient inertial support. In addition, the connection of electric vehicles to the grid can pose a significant problem with frequency fluctuations. When the load is suddenly connected or disconnected, the system needs more time to reach a new power equilibrium and short frequency fluctuations occur during the recovery process (Kilic et al. 2018). Figure 8 shows the deviation on the grid frequency caused by the load change that occurs when the electric vehicle is connected to a microgrid. In microgrids consisting of distributed power systems, similar load changes cause frequency fluctuations. Various control methods are used to keep these fluctuations within the ranges allowed by the standards. Some of these methods are the use of secondary control method and virtual synchronous generator (Long et al. 2021).

3.2.3 Active-Reactive Power Control in Microgrids

Microgrids can operate in islanded mode and grid-connected mode, and in both cases, they must provide the active and reactive power required by the load. Grid-connected microgrids can cover the active and reactive power deficits from the grid to which they are connected. However, since the required power in microgrids operating in islanded mode has to be provided from their own sources, they become more sensitive to power

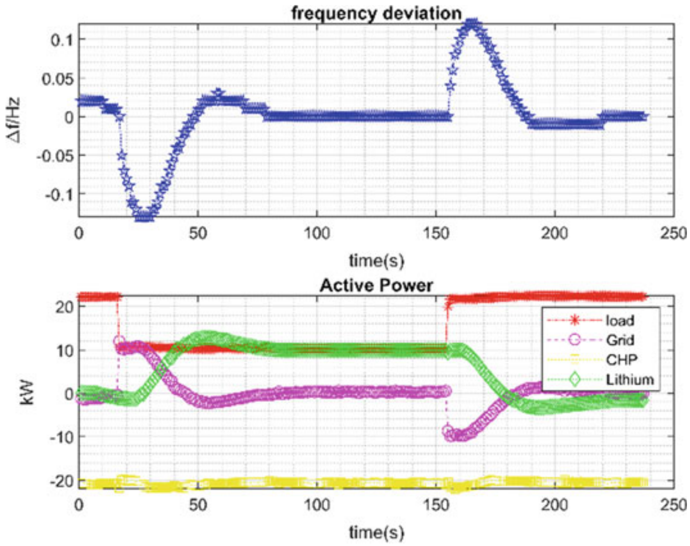

Fig. 8 Frequency deviation in microgrids during EV charging process

changes and are expected to have an appropriate management system. Active/reactive power control becomes more difficult when the DERs are connected to the grid with inertia-less power electronic devices.

According to the standard IEEE 1547 (Lydic and Baldwin 2019), inverters connecting DERs to a microgrid can operate in three operating modes (Fig. 9) which are Grid-Forming operating mode, Grid-Supporting operating mode, and Grid-Feeding operating mode. (Guo et al. 2015). Grid-forming inverters are controlled in microgrids operating in islanding mode to operate as an AC voltage source with

Fig. 9 Operating modes of DERs and its properties

constant amplitude and frequency. In grid-forming mode, power is shared among multiple inverters. Inverters in Grid-Supporting mode of operation are controlled to help regulate voltage and frequency in both grid-connected and islanded micro-grids (Tuckey et al. 2018; Fathi et al. 2018; Kimpara et al. 2018). Inverters in Grid-Supporting operation mode can participate in frequency and voltage regulation without any Grid-forming inverter (Vasquez et al. 2009; Guerrero et al. 2009). Inverters in Grid-Feeding operating mode are controlled to inject a specified active and reactive power into the grid. Therefore, these inverters are normally used in microgrids in both on-grid and islanded configurations to support DERs-connected inverters and regulate the grid voltage frequency (Anand et al. 2014; Serban et al. 2017). Of these modes, the Grid-Supporting mode is the most common. The purpose of controlling the inverters in Grid-Supporting mode is to provide voltage and frequency stability as well as optimal distribution of active reactive power when operating in parallel with other DERs.

Power control in microgrids is handled under two main categories: active power frequency control (P/f) and reactive power voltage control (Q/f) (Han et al. 2017). Methods such as droop control, hierarchical active power management (Ghazanfari et al. 2012), active power sharing control (Ahn et al. 2010) are used for active power control in microgrids.

Reactive power control in microgrids is another method for voltage control. A great deal of research has been conducted on this method, which is called Q/V control. Primary Q/V control has two main parts: communications-based and communication-free control. Communications-based Q/V control requires an advanced communications technology infrastructure. Although this control method works efficiently, it faces security vulnerabilities in broadband communications. Integrating a new DER into the microgrid is more complex because this control method does not support plug-and-play. For a new DER integration, the communication and control structure is designed accordingly. The communication-free control method uses local measurements and is more difficult as it does not communicate with other DERs. However, it supports plug-and-play functionality, which facilitates the connection of DERs to the grid. In addition to using the droop approach for reactive power sharing (Han et al. 2015), alternative solutions such as virtual impedance (Gu et al. 2015) or extended hierarchical control (Zhu et al. 2013) have been proposed for the communication-free control method.

3.3 Management of Smart Grids

Today, traditional electricity consumers are able to generate electricity with the help of DERs. On the one hand, this leads to the development of smart grids with bidirectional power flow and communication; on the other hand, it requires an energy management system (EMS) to balance generation and consumption (Hussain et al. 2021). Demand Response Management (DRM) is used as one of the most common Energy Management Systems. It takes control towards the desired goal by using the

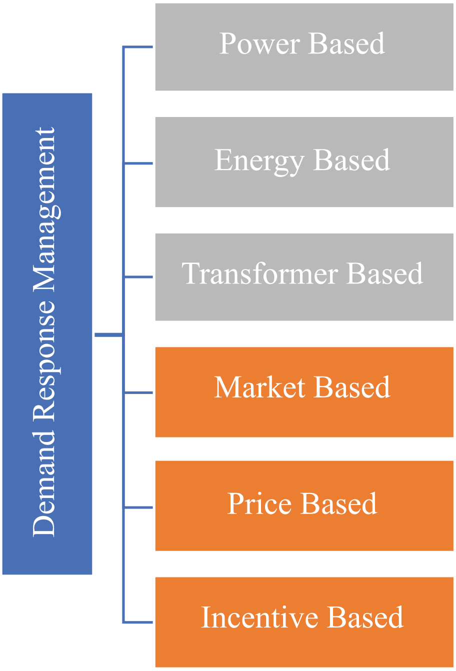

Fig. 10 Demand response management classification

flexibility of distributed energy sources and controllable loads. DRM is a management system that takes into account economic and technical aspects (Setlhaolo and Xia 2016). DRM can be used both on technical basis like power, energy, transformer based and on economic basis like price, market, incentive based (Fig. 10).

Energy management is performed at two different levels: home level and grid level (Hussain et al. 2021). Energy management at home level is called Home Energy Management System (HEMS) which utilizes the flexibility of loads at home, reduces the cost and controls the generation resources by the consumer. Energy management at the grid level is referred to as Grid Energy Management System (GEMS), which focuses on technical aspects such as power losses, voltage/frequency and power control, and economic aspects such as reducing operating costs (Hussain et al. 2021). GEMS controls output power and voltage using DERs and voltage regulators. With the integration of energy management systems at different levels in the grid, the system becomes more complex.

Home Energy Management System is a management system that takes into account the existing constraints to achieve the desired objectives. This management system controls loads like appliances and air conditioners in homes and does home scale energy management. This management also considers power generation, such as home-scale PV system, and energy storage systems including electric vehicles. Depending on the management purpose, it makes the necessary connections for energy exchange with the distribution system. In addition to the necessary software

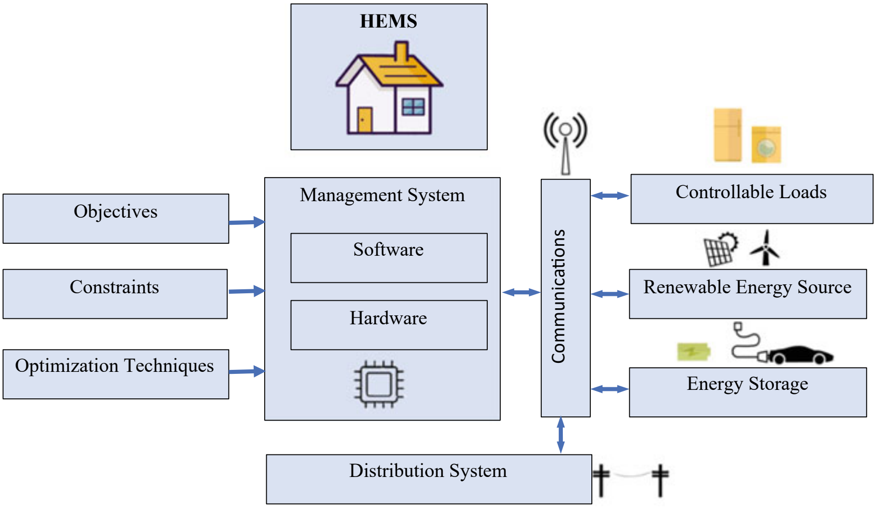

Fig. 11 Structure of home energy management system (HEMS)

and hardware for implementing the management system, various optimization techniques are also used. The Home Energy Management system needs a communication system to perform these operations. HEMS will be an important solution to manage energy consumption in residential buildings in the future. Evolving technological capabilities and increasing smart grid applications are expanding the global HEMS market (U.S. EIA 2020) (Fig. 11).

Electric vehicles (EVs) are used as transportation for only a very small portion of the day. In addition to loading the power grid, electric vehicles can also be used as mobile storage when not in use. Electric vehicles can be connected to the grid as unidirectional and bidirectional charging systems. In both cases, it is important in terms of demand response management. In unidirectional charging, the most convenient and economical connection to the grid is important. In bidirectional charging, the EV also acts as a storage system where electricity demand is met. Thus, EV charging is an important component in HEMS and influences the way HEMS is managed (Kamankesh et al. 2016).

The grid energy management system (GEMS) is used to ensure power quality of the grid and optimal use of the generation resources in the grid. Therefore, a management system is required to monitor and control the power flow. GEMS is a management system based on techniques such as power loss reduction, peak shaving, voltage/frequency regulation and power flow control. It uses a communication system that includes DERs, EESs, and loads, as well as distribution and transmission systems for these transactions (Hussain et al. 2021; Joo and Choi 2017). To take advantage of power generating consumers, an additional unit called an aggregator is required to manage the flow of power between the grid and the power generating consumers.

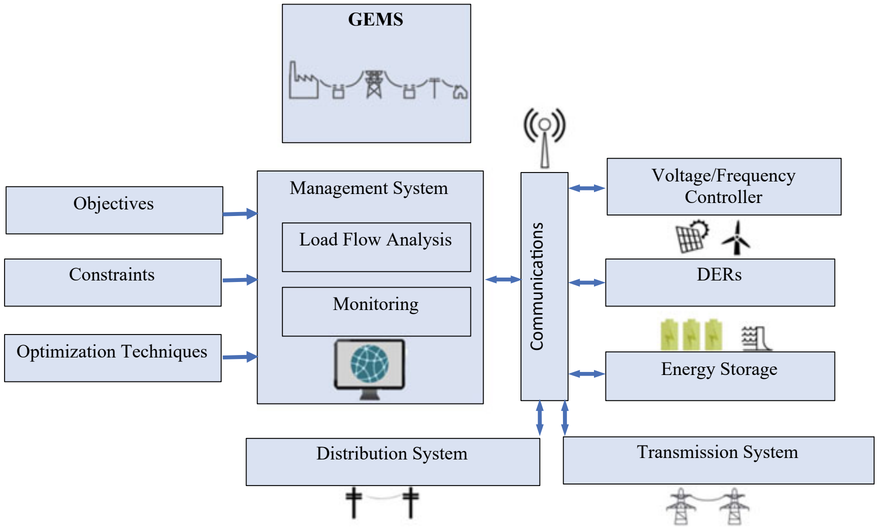

Fig. 12 Structure of grid energy management system (GEMS)

The control methods used for GEMS have been presented in the previous sections (Fig. 12).

The electrical management system architecture is formed based on economic and technical aspects. The economically oriented management system, ignoring the technical constraints and objectives, may experience the worst situations, such as blackout; that is, it may face technical problems although it provides the best economic solution. Therefore, technical and economic objectives must be considered together, leading to a more complex management architecture. Demand-based management alone cannot achieve unified objectives. For example, in a price-based program, a high number of electric vehicles that tend to charge at low rates can cause technical problems in the grid. The electric management system uses three control architectures: centralized, decentralized, and hierarchical (Cheng et al. 2017).

The centralized control architecture manages the system centrally with a single controller and an advanced communication network. It is preferred for optimizing charging loads in networks with a high penetration of vehicle charging stations. Although it has advantages in terms of reduced operational cost and optimal performance, it has disadvantages such as high risk of single control point and difficulty in expansion. This system is more commonly used in conventional power grids and requires central aggregators (Elmouatamid et al. 2020).

The decentralized EMS manages each asset with its own control unit and communicates with neighboring management units (Pourbabak et al. 2018). Control units communicate with neighboring management units and exchange information. There are three types of decentralized control systems: fully dependent, partially dependent, and fully independent. In a fully dependent decentralized control system, the local controller makes decisions and communicates only with the central controller.

In a partially dependent decentralized control system, the local controller partially communicates with other local controllers, while in a fully independent control system, the local controllers communicate directly with other local controllers. A decentralized control architecture has advantages over a centralized control system, such as expandability, flexibility, distribution of computational overhead, and reduction of the risk of failure. This makes it more reliable.

Increasing the geographical area of the system to be controlled makes centralized control impossible because of the increased processing and communication overhead. Moreover, when there are a large number of local controllers, coordination among them becomes difficult with decentralized EMS. Hierarchical EMS architecture provides solutions to these problems. In the hierarchical control architecture, the system is divided into different levels with their own goals and constraints. The controllers of the levels manage the energy according to their own constraints and goals and send the solution to the controller of the next level (Xu et al. 2016). The higher level controller acts as a central controller that collects the data from the lower level controllers and sends the necessary commands to the lower level controller to achieve an optimal overall solution. Three-level and two-level hierarchical control models are the most commonly used models. While HEMS is at the lowest level, DERs and aggregators are at the middle level and GEMS is at the highest level (Fig. 13). The advantages and disadvantages of centralized decentralized and hierarchical EMS are shown in Table 3.

The classification of the energy management system according to its objectives is shown in Fig. 14. EMS objectives are classified into three main groups: technical, economic and other objectives. While technical objectives include power quality, voltage/frequency control, technical loss reduction and load balancing, economic objectives include cost reduction, stakeholder economics and investment planning. Environmental objectives, overall system stability and social benefits are other objectives (Hussain et al. 2021).

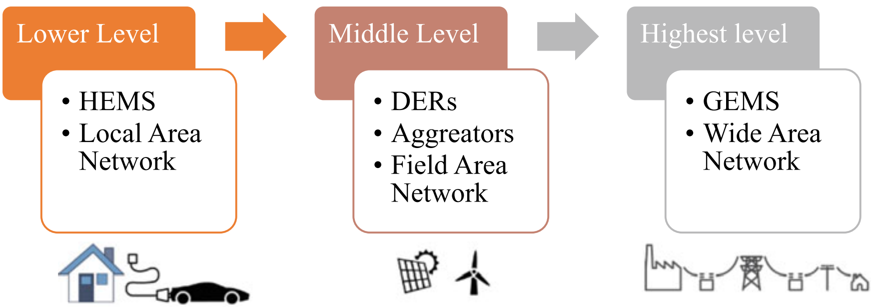

Fig. 13 Architecture of three level hierarchical EMS

Table 3 Advantages and disadvantages of energy management systems

Architecture of EMS	Advantages	Disadvantages
Centralized EMS	Simple architecture Optimal performance Low operation cost Optimal global solution Secure communication	One controller Computation burden Single point failure risk expanding difficulties Don't support plug and play Real-time application difficulties
Decentralized EMS	Enhance expandability Support plug and play Flexible Distributes computation burden Prevent single point failure Has several controllers	Single objective control Provide optimal local solution More than complex to centralized control Need synchronization and communication other local controllers
Hierarchical EMS	Allows level side optimal solution Increases accuracy, reliability More flexible Prevent single point failure Distributes computation burden Less processing times Provides optimal global solution	Requires different level coordination Has communications faults risk Has different levels of privacy and data security Requires complex architecture

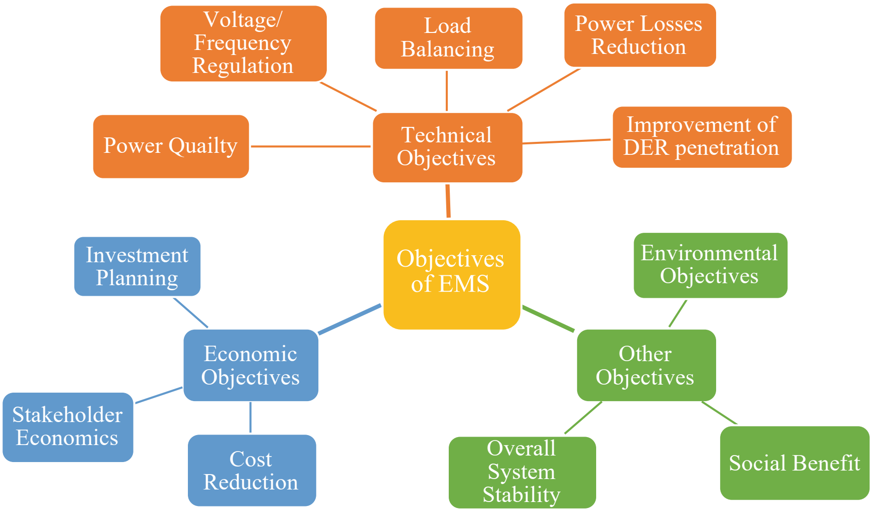

Fig. 14 Classification of EMS according to objectives

4 Conclusion

In this section, we discuss the integration of DERs into power grids, which is an important part of the energy transition. In this context, the emerging concepts of microgrid and smart grid are explained. Voltage/frequency control, active/reactive power control issues that arise in grid integration of DERs and microgrids are presented. The impact of energy storage systems on grid stability where DERs are located is discussed. Finally, energy management systems (EMS) in smart grids are presented. The designs of home energy management systems (HEMS) and grid energy management systems (GEMS) are explained. The advantages and disadvantages of centralized, decentralized and hierarchical management systems are presented. In this section, an attempt has been made to introduce the problems that need to be considered especially when integrating renewable energy sources into the grid.

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Renewable Energy Integration and Zero Energy Buildings

Hasan Alpay Heperkan, Büşra Selenay Önal, and Tanay Sıdkı Uyar

1 Introduction

Today, efficient use of energy and energy saving are becoming more and more important. As a result of the destruction of the ozone layer, the consumption of fossil fuels that provide most of the world's energy needs, the increased consumption in industrial processes, the increase in greenhouse gas concentration in the atmosphere to levels dangerous for human health have put energy production and efficient use of energy among the most challenging issues of today.

The concept of energy efficiency is the reduction of energy consumption per unit or amount of product without causing a decrease in the quality of life and service in buildings and in production quality and quantity in industrial enterprises (Heperkan et al. 2020). Efficiency is provided in every operation where the same product output is obtained with less energy input.

Buildings account for about a third of global energy consumption. During this consumption, it is important to use renewable energy resources and to ensure sustainable energy performance in buildings. In this context, smart buildings represent an important stage of energy efficiency. Improvements are made in the areas of heating,

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cooling, ventilation, lighting, CO_2 emission and hot water depending on the climatic conditions, architectural design and insulation standards for buildings.

According to the Energy Performance in Buildings Directive, all new buildings are planned to be in the zero-energy class. Heat pumps, cogeneration, renewable energy, condensing combi boiler and boiler systems can be given as examples of energy efficiency technologies in buildings. BEP-TR software, HAP (Hourly Analysis Program) software, Energy Plus software are also used to evaluate the energy performance of buildings. As a result of the studies, it has been observed that the energy performance has increased with the use of new energy technologies in buildings.

2 Renewable Energy Integration and Electrification

2.1 Renewable Energy Integration

With continuous economic development and population growth, the world's electricity consumption has increased. Despite the growing interest in renewable energy, fossil fuels continue to be the primary energy source in electricity generation. The increasing demand for energy worldwide is putting tremendous pressure on energy supply and the environment. The environmental costs associated with extracting, transporting and burning fossil fuels have reached enormous proportions. It is estimated that the electricity generation sector alone accounted for 28% of total CO_2 emissions in the USA in 2017. Since the consumption is expected to increase in the near future, renewable energy is being introduced as an important alternative to meet the increasing electricity demand reducing environmental impact.

Renewable energy, which is obtained from resources in nature and defined as having the potential to be continuously reinforced by nature, forms the future of the world. Renewable energy sources have started to gain importance with their never-ending existence, minimum damage to the environment and less cost than fossil fuels. While 22% of the energy produced in the world is renewable energy, it is seen that this rate has reached 29% in Turkey recently (http://termoklimadergisi.com/img/9fubbOs9.pdf). This ratio shows that the use of renewable energy is gradually increasing and that it can have various integrations. The types of renewable energies include geothermal energy, wind energy, solar energy, hydroelectric, hydrogen, wave and biomass energy.

Solar energy is the result of the sun's rays being converted into heat and electricity with the help of solar panels. Solar energy, which is among the natural energy sources, can be obtained without any harm to the environment. Wind energy is a type of energy obtained from the pressure created by the differences in the angle of incidence of the sun rays coming to the earth's surface and the angles of the winds formed by the rotation of the earth. Wind energy obtained from wind turbines installed in intense winds is among the renewable energy sources.

Hydroelectric energy is produced by transmitting the kinetic energy generated by the water flow to the turbines through the channels. Geothermal energy is the type of energy that is obtained directly or indirectly where geothermal resources are located. This type of energy, which serves different purposes such as heating, cooling, electricity generation and mine production, also helps the tourism sector with the help of hot springs (Özkara 2018).

Hydrogen energy is an energy source produced by processes and conversion of hydrogen gas, which is found in nature as compounds. Although it is not a natural energy source, it is among the sustainable and alternative energy carriers. Wave energy is the type of energy obtained from the ripples in the sea and the pressure created by the waves. Biomass energy is the type of energy obtained by burning biomass wastes or using them with different processes (Özkara 2018).

Advantages of renewable energy:

- It is important for the environment as it reduces the use of fossil fuels,
- It is of great importance in the development of domestic resources,
- Reduces dependency on external resources,
- It is suitable for international agreements,
- Provides new employment and reduces unemployment,
- Provides electricity usage in geographical areas where electricity distribution is difficult.

Renewable energy is used in the building sector, transportation, industrial sector and power generation.

Renewable energy met less than 14% of the total energy demand in buildings in 2017. In 2018, renewables contributed an estimated 10.1% of heating and cooling demand in buildings. Modern bioenergy still represented the largest renewable heat source in the buildings sector, followed by renewable electricity for heat, solar thermal and geothermal heat. The majority of renewable electricity in buildings was provided by utility-scale, grid-connected renewables with a growing share from rooftop solar photovoltaic (PV) systems (https://www.ren21.net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf).

Direct policy action to stimulate renewable energy uptake in buildings was lacking in 2019, although more local and national governments have introduced bans on fossil fuels for heating. Global efforts to decarbonize buildings through net zero carbon/net zero energy buildings have promoted the uptake of renewable energy in the sector (https://www.ren21.net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf) (Fig. 1).

As can be seen in Fig. 2, from 2013 to 2018, there was an increase of 21.5% in the consumption of renewable energy resources.

In Fig. 3, renewable energy has a share of 10.1% in thermal, 3.3% in transportation and 26.4% in power generation.

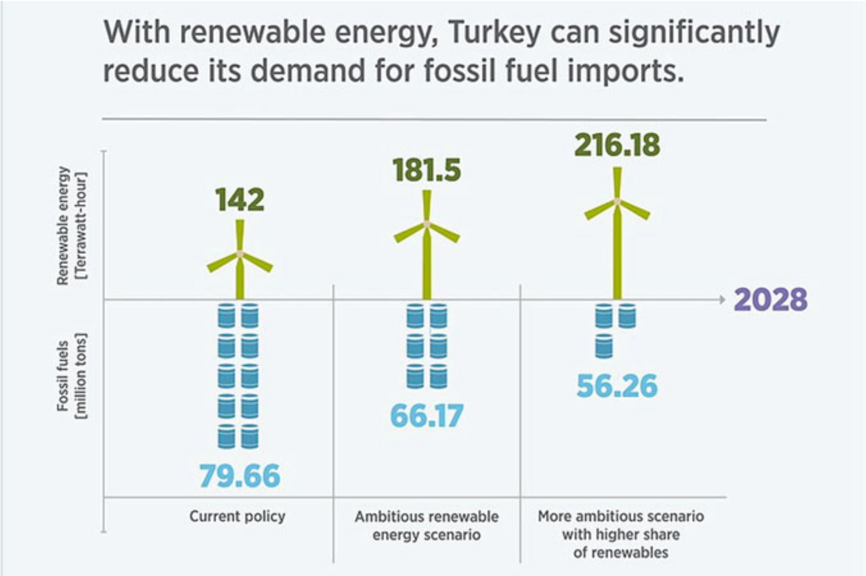


Fig. 1 Renewable energy in Turkey (https://www.ren21.net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf)

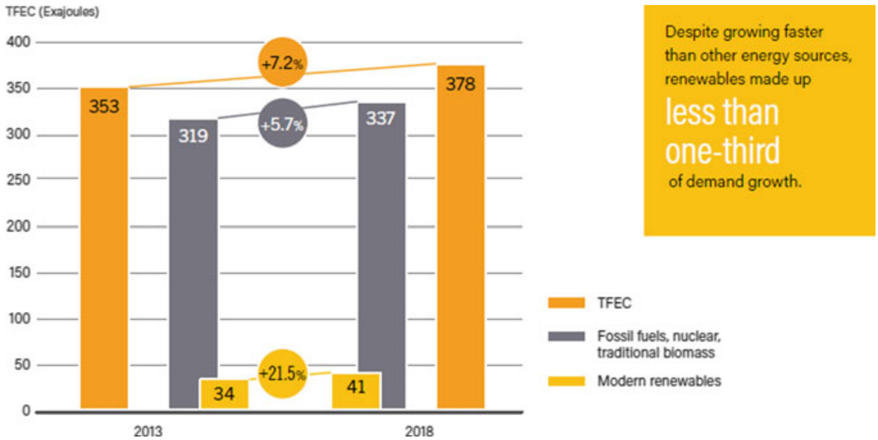


Fig. 2 Estimated global growth in renewable energy compared to total final energy consumption, 2013–2018 (https://www.ren21.net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf)

2.2 *Electrification*

The share of electricity generated by variable renewable electricity (wind and solar PV) continued to rise in several countries around the world. While VRE contributed

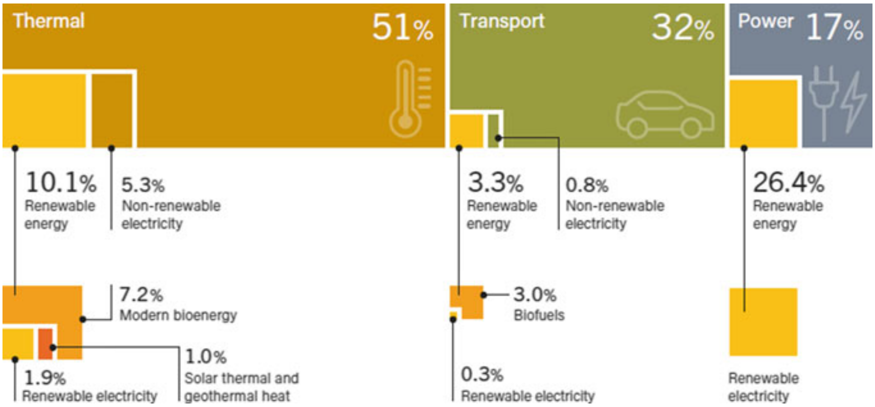


Fig. 3 Renewable share of total final energy consumption, by final energy use, 2017 (https://www.ren21.net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf)

an estimated 8.7% of global electricity production as of the end of 2019, during the year it met much higher shares of generation in some countries, such as Denmark (60%), Uruguay (33%), Ireland (32%), Germany (30%) and Portugal (29%).

Overall, at least nine countries produced more than 20% of their electricity from VRE in 2019. In recent years, some countries have made efforts to increase the flexibility of their energy systems in order to integrate rising shares of VRE. Expanding or modernizing grid infrastructure can help achieve higher levels of flexibility needed to maximize VRE integration.

Many countries (including Australia, Brazil, Chile, China, Colombia, Germany, India, South Africa and the United States, among others) are establishing or investing in transmission infrastructure specifically to accommodate rising shares of variable renewables.

Figure 4 shows the estimated renewable energy share of global electricity generation by the end of 2019.

As seen in Fig. 4, the share of electricity generation from renewable energy sources in global electricity generation is 27.3%. Electricity from renewable energy; obtained by wind, biomass, solar PV and geothermal, CPS and ocean power. Figure 5 shows estimated renewable energy share of global electricity investments by the end of 2018.

Figure 5 shows that, the share of electricity investment from renewable energy sources in global electricity investment is 65.4%. Figure 6 shows solar PV global capacity additions, share of top 10 countries and rest of world 2018.

In Fig. 6, the highest rate of solar PV global capacity is China with 45%, while Turkey is among the top 10 countries–with 2%. Figure 7 shows, wind power global capacity and annular additions between 2008 and 2018.

As seen in Fig. 7, wind energy capacity was 121 Gigawatts in 2008, and reached 591 Gigawatts in 2018. Figure 8 shows CSP global capacity and annular additions between 2008 and 2018.

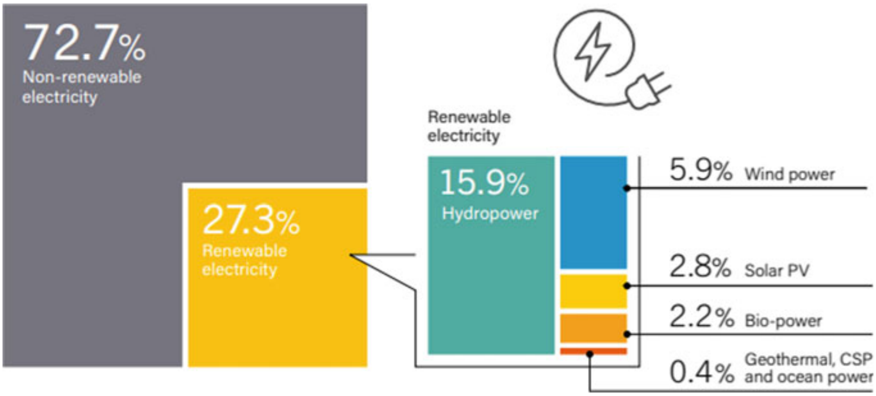


Fig. 4 Estimated renewable energy share of global electricity production, end-2019 (https://www.ren21.net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf)

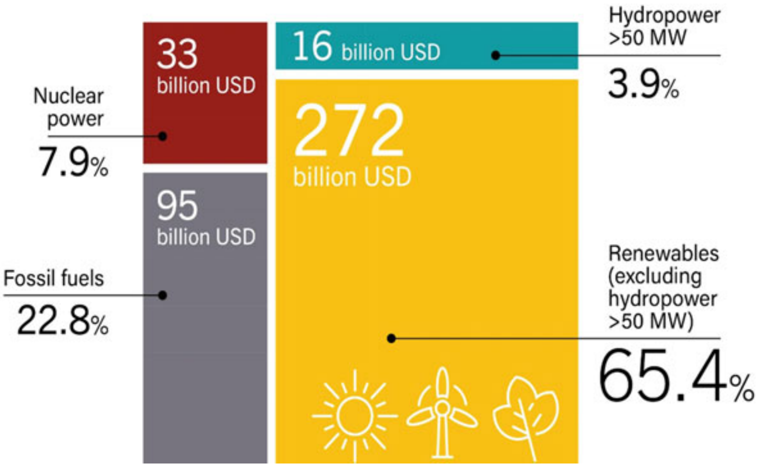


Fig. 5 Estimated renewable energy share of global electricity investments, end 2018 (https://www.ren21.net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf)

As seen in Fig. 8, CPS reached 16.6 Gigawatts-hour in 2018, reaching the highest value.

3 Use of Renewable Energy in Buildings and Legislation

Commercial energy consumption in the world depends on approximately 81% fossil fuels, 5% nuclear, 2% hydraulic, 5% biomass and 7% renewable energy sources. Electricity is produced by 80% from non-renewable sources (coal, natural gas, petroleum

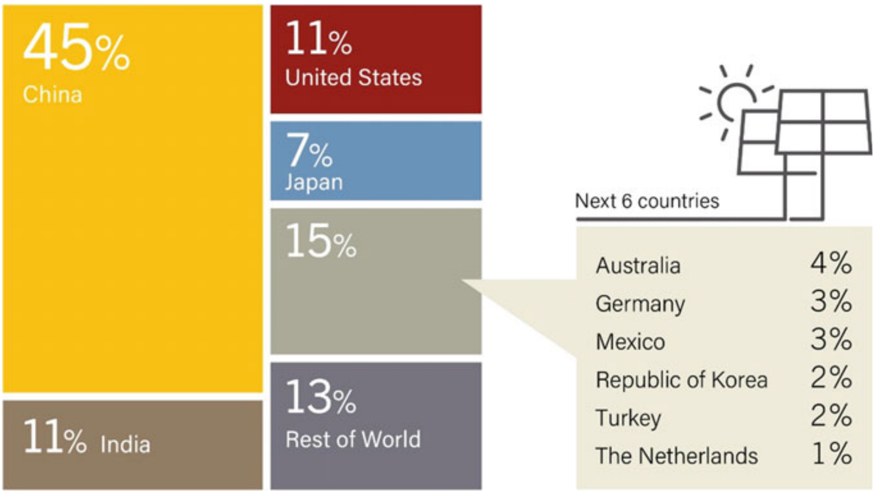


Fig. 6 Solar PV global capacity additions, share of top 10 countries and rest of the world 2018 (https://www.ren21.net/wpcontent/uploads/2019/05/gsr_2020_full_report_en.pdf)

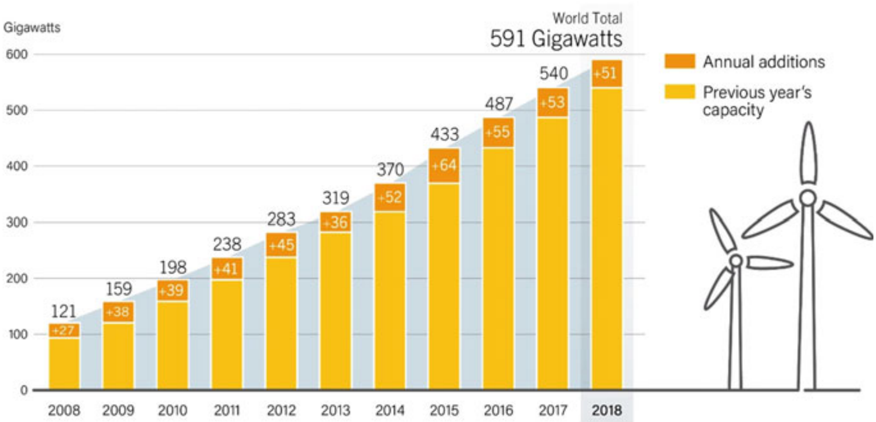


Fig. 7 Wind power global capacity and annular additions, 2008–2018 (https://www.ren21.net/wpcontent/uploads/2019/05/gsr_2020_full_report_en.pdf)

and uranium). The rest use renewable resources. Hydraulic energy accounts for 19% among them. The building sector is responsible for approximately 50% of global electricity demand and 25% of global greenhouse gas emissions; About 30% of this is direct emission (e.g. space heating and hot water production) and 70% indirect emissions (e.g. electrical appliances and lighting).

Although Turkey has various energy resources, it imports more than half of the total energy it produces. When we look at electricity generation, natural gas is mainly used. On the other hand, looking at the situation in the world, it can be seen that the use

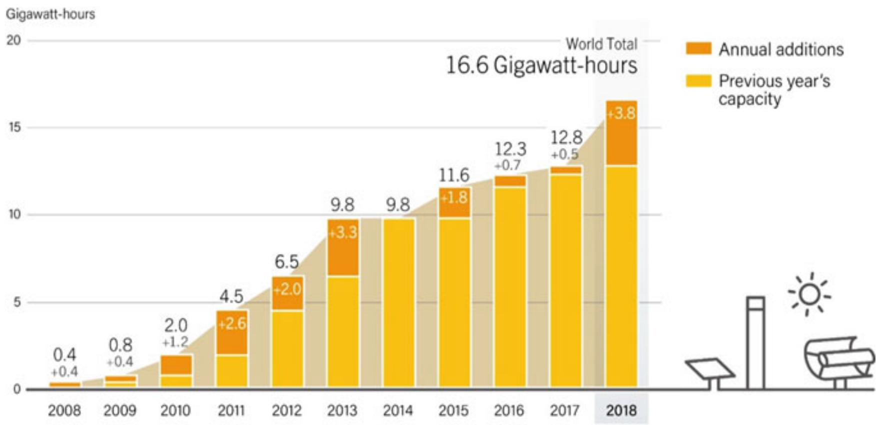


Fig. 8 CSP global capacity and annular additions, 2008–2018 (https://www.ren21.net/wpcontent/uploads/2019/05/gsr_2020_full_report_en.pdf)

of gas in electricity generation is not that high. When Turkey's energy consumption is examined on a sectoral basis, 25% is used in residential buildings, 24% in the industry, 20% in transportation, 3% in agriculture, 23% in conversion technologies and 5% for other purposes. Electricity consumption is 21.8% in residences, 46.8% in the industry and 26.9% in commercial buildings (http://www.teias.gov.tr).

However, Turkey has various renewable energy sources and a great potential. For example, geothermal potential constitutes about 8% of the world total. Due to its geographical location, the solar potential is also quite high. Measurements show that it receives an average of 3.6 kWh/m^2 day solar radiation. It also has many water resources that can generate hydraulic energy. Wind energy potential is estimated to be 160 TWh.

As the current fossil fueled energy model is no longer suitable, a paradigm shift is required to shift energy strategies and policies towards a low carbon society. The International Energy Agency has explored the benefits and challenges of various electrification scenarios, for example in all economic sectors, under the IEA 2017 Energy Technology Perspective. In this context, special attention was given to the role of the building industry due to its great potential in terms of electrification.

The increasing use of electricity and electronics in air conditioning technologies also offers interesting opportunities for the integration of renewable energy sources into buildings. In this framework, the role of HVAC systems is very important and if they are used optimally, integrated with local renewable energy sources, reduction of greenhouse gases and air pollutant emissions, and a balanced electricity grid can be achieved (Crespi and Bompard 2020).

The key to sustainable development is that the balance between energy supply and demand is that the environment is clean, healthy, and free of pollutants. At the same time, the energy performance of buildings must be sustainable. In this context, smart buildings represent an important stage of energy efficiency and constitute the basic element of the smart micro grid. Large amounts of data must be stored and processed during the planning, implementation, control and management of air conditioning and mechanical systems. A network structure consisting of wireless sensors and micro control elements is used to ensure energy efficiency in buildings (Heperkan et al. 2020).

After the industrial revolution that started in the 1750s, the concentration of greenhouse gases in the atmosphere started to increase, the carbon dioxide concentration increased by 40%, reaching from 280 to 394 ppm. According to the Intergovernmental Panel on Climate Change (IPCC), the increase in carbon dioxide is mainly due to the use of fossil fuels. The second notable factor is land use change, particularly deforestation. The Intergovernmental Panel on Climate Change has shown that global average temperatures have increased as a result of the impact of human activities in the atmosphere (https://www.wwf.org.tr/ne_yapiyoruz/iklim_degisikli give enerji/iklim_degisikligi).

The results of a scientific study conducted by the IPCC show that global average warming should be kept below 1.5 °C. More efforts are needed to become carbon neutral or decarbonized and potential disasters are planned to be prevented by keeping global warming below 1.5 °C (https://www.semtrio.com/cop24-birlesmis-milletler-iklim-degisikligi-konferansi). Although their share in global greenhouse gas emissions is only 10%, EU countries have acted responsibly and adopted it as a policy to bring these levels to 85–90% of the 1990 level by 2050.

Member states have long promoted renewable energies and energy efficiency in individual state policies. They also play a leading role in the international arena. The reflection of these policies has led to the establishment of zero-energy buildings. These buildings have no net energy consumption and do not generate carbon dioxide. According to EU targets, public buildings by 2018/2019 and all other buildings by 2020/2021 should be zero or close to zero.

To serve this purpose, the EU has published the Energy Performance Directive EPBD (2002/91/EC) for Buildings. These directives are grouped into the Hot Water Boiler Directive (92/42/EEC) Construction Materials Directive (89/106/EEC) and the SAVE Directive (93/76/EEC).

The energy performance regulation in buildings aims to reduce energy consumption by considering all kinds of energy use such as heating, lighting, cooling, air conditioning, ventilation as well as outdoor weather and local conditions, indoor air quality and cost effectiveness. It encourages the use of energy efficiency technologies and renewable energy in both new and existing buildings to ensure a more rational use of energy resources. Among the ways to achieve these, these measures are mandatory for major renovations, including changes to the building envelope (such as sheathing), issuing energy certificates to buildings and auditing boilers and air conditioning systems.

The legislative proposal “Clean Energy for All Europeans” published by the European Commission in November 2016 includes energy efficiency and the use of renewable energy for buildings. This proposal proposes amendments to both the “Energy Performance Directive”, EPBD, and the “Renewable Energy Directive”, RED. These changes have an important place in achieving the 2050 targets for decarbonizing the economy. The European Union aims to increase the use of renewable energy until 2030. In order to achieve this goal, the Building Energy Performance Directive, EPBD, requires all new buildings to be nearly zero-energy buildings after 2021. RED's goal is to promote energy generation from renewable sources. The recommendations focus on the technical systems of the buildings.

Since the signing of the Paris Agreement, the energy performance of new and existing buildings has been on the agenda. Limiting global warming and reducing CO_2 emissions are among the goals. Europe has consumed half of its energy for heating and cooling, as thermal energy. Most of this energy is produced from fossil fuels (natural gas and oil). Renewable energy share is around 15% (http://heating-and-cooling-in-europe.eu/). Only 12% of thermal energy consumption in buildings is provided by renewable sources. Most buildings in Europe were built before 1960 and their heating systems are inefficient (about 75%). Buildings in Turkey have increased their energy performance with urban transformation projects implemented in recent years. The energy consumption of old buildings is much higher than that of new buildings. Energy consumption for buildings built in the last 20–25 years is around 34–125 kWh/m^2 (Hogeling 2015).

In order to minimize the energy, need of buildings, it is necessary to support HVAC systems with renewable energy generation and to ensure higher energy efficiency. In the first stage, the energy consumption of the buildings should be reduced. For this purpose, measures such as insulation, passive solar energy measures and increasing energy efficiency can be applied. The second stage is increasing the use of renewable energy produced in the construction site or facilities established in its vicinity and finally decarbonization of the energy generation network. ISO 52000-1 contains clues as to how and to what extent these measures will affect.

The smart building is a building that is efficient in terms of energy use and meets very low energy demand with renewable energy sources on site or in its immediate vicinity. Intelligent building technology accelerates the transition to carbon-free energy consumption by balancing the energy system thanks to energy storage and demand-side flexibility. Intelligent building technology empowers users to control the flow of energy and thus provide rapid response by recognizing comfort, health, indoor air quality, safety and operating requirements.

The EU's Directive on Promoting and Supporting the Use of Renewable Energy Sources (2009/28/EC, RES Directive, Article 2) defined renewable energy sources. Energy obtained from renewable energy sources; It is energy that does not rely on fossil fuels such as wind, solar, aero-thermal, geothermal, hydrothermal and ocean energy, hydraulic, biomass, gas from buried garbage, gas produced in treatment plants and biogas. Aerothermal energy is the energy stored in the form of heat in the air, geothermal energy, energy stored under the ground surface in the form of heat.

In Fig. 9, the share of renewable energy in the total energy consumption of the buildings is 13.6%. This ratio includes modern bio-heat, renewable electricity, solar and geothermal heat.

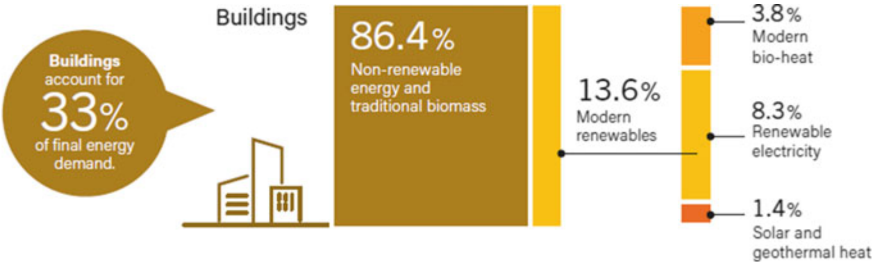


Fig. 9 Renewable share of total final energy consumption in buildings, 2017 (https://www.ren21.net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf)

Modern bioenergy represented the largest source of renewable energy use in the building sector and directly provided around 4.6% of total heat demand in buildings in 2018. However, bioenergy use in buildings is growing only slowly and its share has remained relatively stable, bio-heat consumption has grown at the same rate as the building's thermal energy demand. Renewable electricity supplies the second largest renewable heat demand. Solar thermal and geothermal heat together contributed some 2.0% of thermal energy demand in buildings in 2018. Renewable energy delivered by district heating and cooling networks supplies a minor share of building heat demand worldwide. Nevertheless, some European countries have achieved high shares of renewables in the district heat supply (more than 50% in at least six countries as of 2017) (https://www.ren21.net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf).

Figure 10 shows that the estimated share of renewable heating and cooling in buildings is 10.1%. It includes space heating, space cooling, water heating and cooking. Modern bioenergy includes heat supplied by district energy networks.

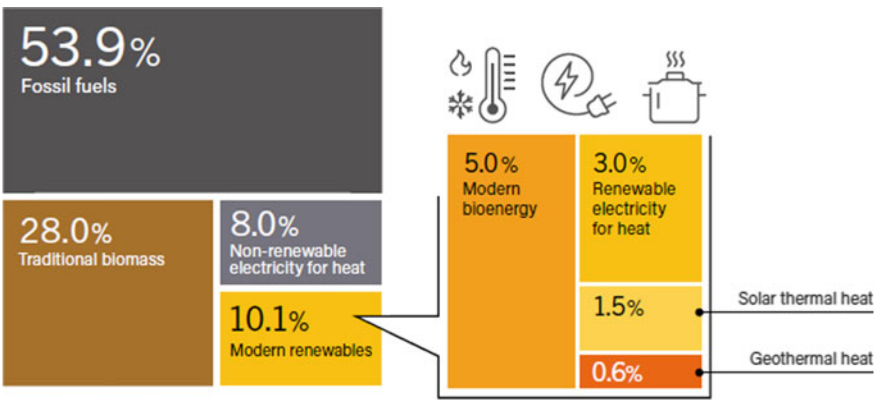


Fig. 10 Estimated renewable share of heating and cooling in buildings, 2018 (https://www.ren21.net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf)

Compared to heating and cooling, renewable energy supplies a higher share of electricity end-uses in buildings, at around 26%. (see Fig. 3.) This share continues to grow, with most of the electricity provided by utility-scale, grid-connected renewables and a growing share by rooftop solar PV systems. In some places, solar PV self-consumption grew and met high shares of building electricity use throughout the year.

At the same time, global efforts to decarbonize buildings, specifically through net zero carbon/energy buildings are simultaneously promoting the uptake of renewables in the sector. As of early 2020, 6 states and regions, 28 cities, and 48 businesses and organizations have signed the Net Zero Carbon Buildings Commitment (https://worldgbc.org/thecommitment). In 2019, the EU's Energy Performance in Buildings Directive mandated that new public buildings in the region be "nearly zero energy buildings", and the standard was set to apply to all new buildings starting from 2021 (https://ec.europa.eu/energy/content/nzeb-24_en).

As seen in Fig. 11, renewable energy capacity has increased to over 200 GW in 2019 by technology.

Additionally, the "European Green Deal" of 11 December 2019 is a roadmap that aims to re-adjust the previous commitments of the European Union (EU) in tackling climate and environmental challenges in a broader and more effective way. New strategies will be determined to achieve economic growth (decouple) while reducing natural resource consumption and to achieve the targets of zeroing the net emission value of greenhouse gases (carbon neutral) in 2050. The EU has initiated some efforts to direct large public investments and private capital towards climate and environmental actions, especially since reducing greenhouse gases requires great effort. The

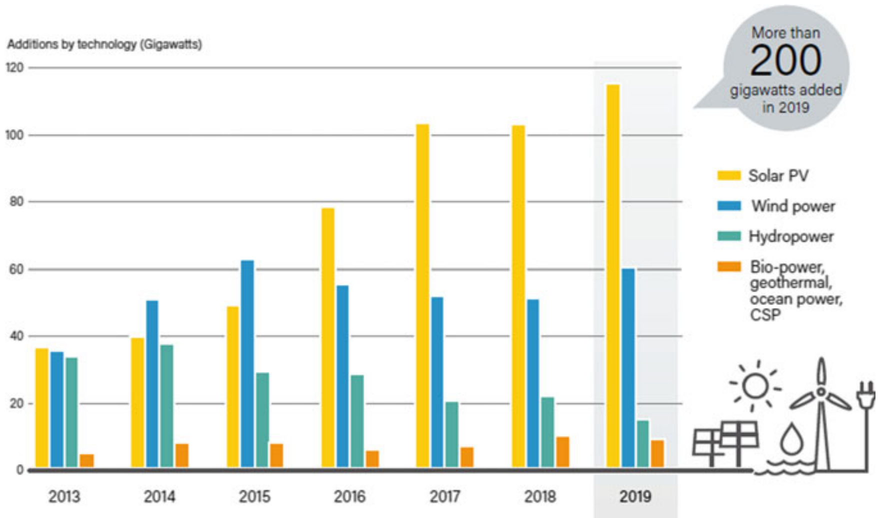


Fig. 11 Annual additions of renewable power capacity, by technology and total, 2013–2019 (https://www.ren21.net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf)

main policies in this growth strategy are; clean energy, sustainable industry, construction and renovation, farm-to-table, pollution elimination, sustainable mobility, and biodiversity.

The European Green Consensus is focused on tackling important climate problems such as global warming and the sustainability of water resources. In this context, it has designed the Border Carbon Regulation to prevent carbon leakage and ensure that this process is adopted by commercial stakeholders. The EU has developed some plans and mechanisms that will serve as a roadmap and tool for the realization of the targeted transformation under the Reconciliation.

They are;

- To include sustainability in all EU policies,
- Ensuring a fair transition, taking into account green finance and investment,
- Greening national budgets and sending accurate price signals,
- Mobilizing research and encouraging innovation,
- Enabling education and training,
- Green oath—Do no harm,
- European climate agreement,
- EU global leader.

The ultimate target of the Green Deal is to ensure that the EU becomes a "carbon neutral" (zero-emission) continent by 2050. Articles 1 and 2 of the Climate Law provide for the reduction of emissions in the EU gradually and irreversibly until 2050, and the achievement of the targets regulated in the Paris Agreement. Article 2 of the Climate Law regulates the reduction of emissions in the EU by 50–55% by 2030 in comparison to the emission levels of the EU in 1990. In accordance with this target, Article 2 of the Climate Law, provides that the Commission will make an assessment by 30 June 2021, as to which pieces of legislation will need to be amended in the EU to achieve the reduction of emissions by 55% until 2030; the "Fit for 55%" initiative.

Considering all the policies and enablers of the Green Deal including circular economy to a fair adjustment mechanism, a sustainable finance action plan to Carbon Border Adjustment Mechanism, one can easily predict that Turkish economy and trade with EU will be affected in a lot of ways (https://www.lexology.com/library/detail.aspx?g=478d57c8-01ef-44c5-80f1-6c7817df74f4):

- Companies that export raw materials, intermediate products, or final products to the EU may be subject to some form of a carbon tax for the products they export pursuant to a carbon border adjustment mechanism to be introduced by the Commission by 2023
- Turkish companies, which are in the supply chain of the EU companies, will be required by their EU customers to adopt their activities to sustainable and green businesses as Green Deal will set forth regulations that will require companies operating in the EU to align their supply chains with Green Deal. Carbon footprint of the products will be assessed by considering the carbon footprint of all materials used for its production and its transportation;

- Subsidiaries of EU-owned companies in Turkey will be required to align their businesses with Green Deal.

Ministry of Environment and Urbanization, Ministry of Commerce, and other relevant government agencies in Turkey are following up and working on the developments in the EU with respect to the Green Deal and are expected to propose a roadmap for Turkey within 2021.

4 Energy Efficiency in Buildings

As energy efficiency applications in buildings, the exterior insulation made according to the climate zone of the building directly affects the efficient use of energy. For example; Insulation applied to a building with the same architectural and mechanical system features in two different thicknesses at the same location causes a big change in the energy performance of the building. When the insulation thickness is increased at appropriate levels, energy losses decrease (Heperkan et al. 2020). Roof insulation comes first in order of importance in terms of insulation. According to the principle of the rise of heated air, the insulation properties of the roof should be taken into account in order to warm the indoor air in winter. It is important that windows and doors do not leak ambient air. For this reason, the use of insulating glass and insulating glass is becoming widespread today and heat losses are reduced.

The suitability of the mechanical systems for the project to be applied should also be taken into account. For example, the use of condensing boilers instead of standard combi boilers reduces the fuel consumption used in heating and reduces the energy consumed for heating. Using the fuel used in central heating systems as natural gas instead of coal, increasing the use of renewable energy sources such as solar energy, wind energy and thermal energy are among the studies aimed at increasing energy efficiency (Heperkan et al. 2020).

Apart from these, in order to meet the lighting requirement of the buildings with minimum consumption, appropriate energy saving lighting systems should be selected. The compliance of the architectural design of the buildings with energy efficiency standards is also among the important data. The time and angle at which the building can see the sun during the day are among the issues to be considered in this regard (Heperkan et al. 2020).

Heat pumps, cogeneration, renewable energy, condensing combi boiler and boiler systems can be given as examples of energy efficiency technologies in buildings. Heat pumps are devices that transfer heat from one heat source to a different heat source. As known from thermodynamic rules, an external energy source must be used to transfer energy from a low temperature environment to a higher temperature environment. The majority of heat pumps used in conventional systems include electrically powered compressors. Heat pumps are named according to the environments from which they draw and transfer heat. Heat can be extracted air, water and soil and transmitted to air or water (https://midori.com.tr/isi-pompasi/isi-pompasi-nedir.html). Air conditioners are essentially' air to air' heat pumps. In industrial applications involving larger systems, the preferred devices are soil-to-air and water-to-air heat pumps.

In energy applications, cogeneration, that is combined heat-power generation systems (CHP, Combined Heat and Power), are systems where steam and electricity are produced together. In these systems, more energy is used compared to conventional systems by increasing energy efficiency by utilizing waste heat. Since energy is produced where it is consumed, it eliminates the losses in transmission and distribution lines and provides uninterrupted and high-quality electricity supply without being affected by the network (Pravadalioğlu 2011).

Renewable energy is energy that continuously utilizes natural processes for its production and renews itself in a shorter time than the depletion of the resources it uses for production. Renewable energy types include geothermal energy, wind energy, solar energy, hydroelectric, hydrogen, wave and biomass energy (Özkara 2018).

5 Zero Energy Buildings and Digitalization

5.1 Zero Energy Buildings

The Paris Agreement brought universal consensus to strengthen global climate action with the aim of keeping the global temperature rise this century well below 2 °C above pre-industrial levels. Nationally determined contributions, commitments to help reach this goal have been developed. The building sector is responsible for approximately 50% of global electricity demand and 25% of global GHG emissions, from which roughly 30% are direct emissions (e.g., space heating and hot water production) and 70% are indirect emissions (e.g., electric appliances and lighting).

Technological solutions are available and cost-efficient to reduce emissions. Examples include increased thermal insulation; double/triple glazing windows; energy efficient heating, cooling, ventilation, lighting, and appliances; integrating renewables. Proper insulation reduces thermal losses and help to minimize the energy needed to keep the indoor air temperature at comfortable levels. Increasing the energy efficiency of water and space heating and cooling devices has a major impact on the energy consumption of buildings (e.g. Condensing gas boilers, Heat pumps, Absorption chillers, Tri-generation). Heat pumps are also a valuable element of "nearly Zero Energy Buildings".

Ventilation provides indoor areas with fresh air and helps keep internal temperatures and humidity at comfortable levels. The constant exchange of indoor air reduces moisture, odours, and pollutants (e.g. Mechanical ventilation with heat recovery). Lighting accounts for nearly 10–15% energy consumption in the residential and 15–30% commercial building sector (e.g., Energy efficient solid-state lighting, Light

Emitting Diodes). Retrofitting of the existing building stock plays a key role in reaching climate targets; countries can increase green employment significantly, while saving billions of Euros.

Nearly zero energy buildings (nZEB) are accepted as highly energy efficient buildings supported by renewables to compensate for their energy demand. This method is used by the European Parliament Building Energy Performance Directive (EPBD) [Directive (EU) 2010/31/EU]. The directive states that, buildings that need to be cooled or heated according to their purpose, should be built as zero-energy buildings after December 31, 2020.

The purpose of calculating energy performance in buildings is to determine the annual total energy demand given in net primary energy corresponding to energy for heating, cooling, ventilation, hot water and lighting. Therefore, high-energy consuming buildings should be supported with renewable energy. For residential buildings, most Member States aim to have a primary energy use of no higher than 50 kWh/(m^2 y). In our country, the energy performance of buildings is determined using the calculation method within the scope of the National Energy Performance of Buildings Method and using BEP-TR software. The method followed in this study is based on BEP-TR software and calculations. The Turkish Standards Institute study method (TSE/TSI) begins with the determination of the reference specifications for each building type, using the available architectural data. The share of renewable energies in the total energy supply is required for the net zero energy building concept, taking into account active systems such as photovoltaic panels, hot water collectors and heat pumps.

As a result, net zero energy buildings, supported by renewable energy, are being implemented in Turkey as well. The location of the buildings, the number and density of the building occupants provide a useful flexibility to reduce the performance deficiencies that may be experienced due to the design features and to achieve the nZEB targets.

Interest in energy-efficient buildings is increasing, mainly in developed countries where the implementation and updating of energy codes, certification policies and energy performance requirements for construction and renovation at the national level are influencing energy use in the sector. Numerous building standards emphasize a high commitment to energy efficiency, ensuring that the energy performance of buildings is as efficient as possible, and often interlinking efficiency with on-site and/or off-site renewable generation (mostly through solar PV) to cover residents' remaining energy use.

The European Union took the first step with the Energy Performance in Buildings Directive (2002/91/EC), EPBD. The directive, which was revised in 2010 (2010/31/EU), introduced concepts such as "reference building", "optimum cost" and "nearly zero energy buildings". The last revision of EPBD was approved in 2018. The new revision includes the strengthening of indoor environment quality, proper maintenance and effective inspection and setting more ambitious energy efficiency targets in line with the opinions of the stakeholders and REHVA. Encouraging the use of information and communication technology (ICT) and smart technologies (smart meters, building automation and control systems) to ensure efficient operation of buildings, energy storage and the definition of "smart readiness indicator" that shows how ready the buildings are for compliance with the distribution network, requests the renovation of existing and old buildings.

In December 2021, the European Commission proposed a revision of the directive (COM (2021) 802 final). It upgrades the existing regulatory framework to reflect higher ambitions and more pressure on climate and social action, while providing EU countries with the flexibility needed to take into account the differences in the building stock across Europe. The energy required should be covered to a very significant extent from renewable sources, including sources produced on-site or nearby. Spain has adopted (not yet official) nearly zero-energy buildings (NZEB) in the legislation.

As concrete numeric thresholds or ranges are not defined in the EPBD, these requirements leave room for interpretation and thus allow Member States to define their nearly zero-energy buildings (NZEB) in a flexible way, taking into account their country-specific climate conditions, primary energy factors, ambition levels, calculation methodologies and building traditions. This is also the main reason why existing nearly zero-energy buildings (NZEB) definitions differ significantly from country to country.

The EU-project ZEBRA2020 sets a clear methodology for how nearly zero-energy buildings (NZEB) are defined in the context of market tracking: the nearly zero-energy buildings (NZEB) radar graphic*. The nearly zero-energy buildings (NZEB) radar allows combining qualitative and quantitative analysis of building standards in a specific region. The nearly zero-energy buildings (NZEB) radar clusters energy efficiency qualities in 4 different categories that have been defined at national level by experts:

- Net zero energy buildings/Plus energy buildings
- Nearly zero-energy buildings (NZEB) according to national definitions
- Buildings with an energy performance better than the national requirements in 2012
- Buildings constructed/renovated according to national minimum requirements in 2012

Article 9 of the EPBD requires that "Member States (MS) shall ensure that (a) by 31 December 2020 all new buildings are nearly zero- energy buildings; and (b) after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings". MSs shall furthermore "draw up national plans for increasing the number of nearly zero-energy buildings" and "following the leading example of the public sector, develop policies and take measures such as the setting of targets in order to stimulate the transformation of buildings that are refurbished into nearly zero-energy buildings".

The Concerted Action, CA EPBD activities on the topic Towards 2020—Nearly Zero-Energy Buildings' support the MS through the exchange of experiences regarding already existing high performance buildings, ranging from low energy buildings to passive houses, zero-energy and zero-emission buildings, and even to

Fig. 12 Two NZEBs visited by CA EPBD: on the left, a single-family demonstration house in Berlin (Germany); on the right, a renovated multifamily house in Graz (Austria) (Hinton 2020)

buildings with an energy surplus. Figure 12 shows two NZEBs in Germany and Austria visited by CA EPBD.

Several countries including Germany, France, Spain, Canada, and Ireland have introduced targets to achieve net zero energy emissions by 2050, according to the International Energy Agency. The truth is that, there is no one way to achieve energy efficiency; since there are so many strategies that can help you to attain net zero, such as considerations related to lighting, HVAC and windows. It can be hard to know where to start.

As seen in Fig. 13, the Sustainable Energy Fund (SEF) office building lies in a former apple orchard in Schnecksville, Pennsylvania and it is greener than ever. Inspired by Passive House projects, the building was positioned to take maximum

Fig. 13 The sustainable energy fund office building (Hinton 2020)

advantage of the sun and shade, including windows sized and spaced for optimal daylight and to minimize energy loss (Hinton 2020).

The office, which is the first energy-positive building in the Lehigh Valley, also includes a photovoltaic array on the roof that generates all the necessary energy for the building's operation to help it achieve net zero office design. The design is just as pleasing to the eye as it is eco-friendly to the earth: 12,000 square feet of leasable office space, bright colors, open concept spaces, and wooden accents make up the modern interior. The SEF building plans to reduce its energy consumption by 75% while generating more than 130% of the energy it requires (Hinton 2020).

With timber craftsmanship throughout, Schwaikheim housing and workshop includes six apartments and a workshop in rural Germany is made almost entirely of reusable materials. In this building, architects used conscientious windows, heating, and electricity to make it a net zero energy building. Photovoltaic panels on the roof and a heat pump that complies with the energy efficiency standards also help to meet the building's energy goals (Hinton 2020) (Fig. 14).

"State-of-the-art" meets "sustainable" with this eye-catching net zero home in historic Lexington, Massachusetts. Sitting on top of the family's three-car garage roof are 40 solar panels enough to cover the home's annual energy use. The 4200 square-foot house is also entirely electric from appliances to heating with double wall construction and triple-glazed windows for tight insulation, all making it 58% more energy-efficient than a standard home (Hinton 2020) (Fig. 15).

In the hopes of achieving carbon neutrality by 2050, the John J. Sbrega Health and Science Building at Bristol Community College in Massachusetts is using energy-efficient practices in every possible way. Designed by Sasaki, the building's biggest

Fig. 14 Schwaikheim housing and workshop (Hinton 2020)

Fig. 15 Historic Massachusetts contemporary home (Hinton 2020)

Fig. 16 Bristol Community College's John J. Sbrega health and science building (Hinton 2020)

challenge was breaking even on the amount of energy used versus produced each year.

Technological solutions and green building strategies were set into place to accommodate everything needed to train medical professionals without the heavy loads and high energy devices while achieving its mission of zero net energy. These solutions included, reducing lighting and plug loads, using no fossil fuels for heating or cooling, and having fume hoods that filter chemical fumes. Daylighting for solar heat gain and air-tight windows and doors were also critical when it came to be paving the way for a net zero future for Bristol Community College (Hinton 2020) (Fig. 17).

Fig. 17 The Joyce Centre for Partnership and Innovation (Hinton 2020)

Doubling as a laboratory and teaching tool for a sustainable future, The Joyce Centre for Partnership and Innovation at Mohawk College's Fennell Campus is the largest net zero energy institutional building in the Southern Ontario region, making it the perfect example how to turn net zero buildings into positive teaching tools (Fig. 17).

The team to implement green tactics by sticking to a budget to ensure their energy targets would succeed. A few of those green tactics include solar panel "wings" on the roof, geothermal heat sourcing, and a high-performance, triple-glazed curtain wall for the least amount of leaked air exposure (Hinton 2020).

5.2 Digitalization

In modern economies, it is very difficult to do business without ICT, information and communication technology and internet connection. More and more devices contain communication modules that connect them to the internet or a similar network. These products are referenced by IoT, Internet of Things, a network of interconnected cyber-physical objects that bring society closer to digitalization. The increasing importance of cyber security in these technological changes attracts great attention.

Digitalization is a good opportunity to increase the share of various renewable energy sources to meet the demand for heating and cooling. Approximately 19% of Europe's heating and cooling consumption is met by renewable energy (mostly solid biomass) (EEA 2018). Renewable energy technologies used to heat, and cool buildings can be placed in individual units of small capacity or in DHC, district heating and cooling systems with larger capacities. Digitization, by optimizing implementation, planning and business models, reduces the total cost of decarbonization by connecting heat and cooling device manufacturers, users, local stakeholders and energy markets. It is a driving force for smart buildings, smart communities, smart cities, local energy and district heating and cooling (DHC). In many buildings today, control is limited to at most one room thermostat. Even though thermostats are programmable, many building occupants do not know their existence or do not know how to do it. The benefits of digitization for heating and cooling, even the existence of technologies, are little known. However, heating and cooling are vital for comfort at home and at work.

Using devices that analyze and process large amounts of data, digital technologies provide a new data layer that can be energetically and socially utilized, helping to better manage the building energy system and increase energy efficiency. For example, when digitization and electrification are used together, direct communication between the building and the main grid can be achieved and both generation and demand sides can be optimized through some innovative approaches. “Internet of Things” solutions create greater interaction between HVAC systems and building occupants; consumers can become more aware of energy waste and make their own energy choices more consciously. Advanced HVAC technologies are actually ready for this environment; the main challenge is to show that they are economically and financially sustainable through cost–benefit analysis.

Internet of Things (IoT), provides the interconnection of smart objects within a widely spread large computing environment (https://proente.com/akilli-bina-nedir/).The term Internet of Things refers to this internet-based structure which facilitates the exchange of information and data between numerous objects that are smart within themselves (Miorandi et al. 2012) (Fig. 18).

The Internet of Things, IoT, is a term that reflects the growing number of intelligent, connected products and emphasizes new opportunities they can represent. What

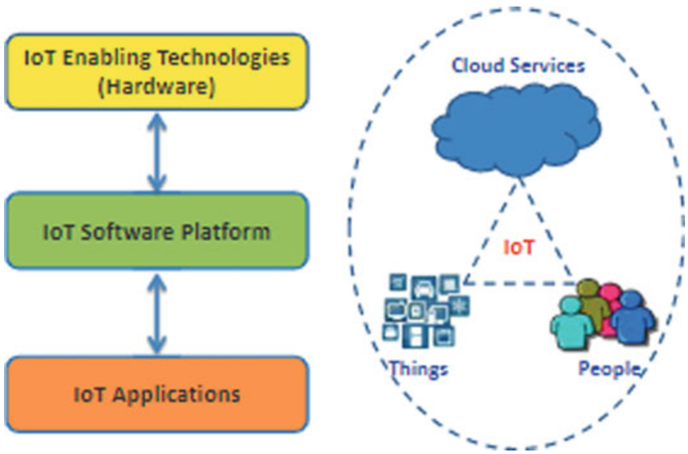


Fig. 18 The IoT architecture model (Khajenasiri et al. 2017)

makes these smart, interconnected products fundamentally different is not particularly the Internet, but the change in the nature of objects (Porter and Heppelmann 2015).

Zero energy building Technologies are considered as an important tool towards the reduction of greenhouse gas emissions. However, realization of comfort conditions without degrading them is possible with the correct design of mechanical and air conditioning systems (Heperkan 2018).

Digital Control Systems (DDC) and BIM technologies are also used in intelligent building applications. These technologies are very useful in the design, operation, control, management and monitoring of air-conditioning and mechanical systems of intelligent buildings. DDC systems can be used effectively in many areas. These include residential automation, air conditioning systems of commercial buildings and building automation and industrial applications (PLC, SCADA, etc.). Modern DDC, Direct Digital Control Systems, applied to a building can be considered in 4 stages. Sensors, field elements, integration, operation and management (Heperkan 2019).

Sensors measure the variables of an automation system (temperature, humidity, flow rate, pressure). Signals are electronic or pneumatic. RTDs, thermocouples, room thermostats are examples. CO_2 sensors are used commonly to measure air quality. Field elements receive the signal from the sensor and create an output signal through a logic function. Then operate a valve or damper. Integration: Data collected from several sources are matched through a standard platform like TCP/IP, BACnet, LON and are processed by a computer. Management: collected data can be used to save energy, improve comfort conditions or secure the building.

6 Energy Performance Software for Buildings

Some of the software used to evaluate the energy consumption and performance of buildings are as follows:

- BEP—TR Software
- HAP Software
- Energy-Plus Software
- Izoder TS-825 Program.

6.1 BEP—TR Software

It is the energy performance evaluation software that enables to evaluate the energy consumption of the building and issues the Energy Class Certificate. National building energy performance calculation methods (BEP-TR) for Turkey have been developed to determine the energy performance class to evaluate the energy consumption, energy efficiency and the impact of all parameters of the building. BEP-TR is an internet-based software. It calculates the annual energy consumption and CO_2 emissions per m^2 of buildings within the scope of the BEP regulation (Korkmaz 2020).

In the BEP-TR software, the method for calculating the amount of net energy for heating and cooling buildings is a simple hourly calculation (EN 13790). This method requires the determination of the heating and cooling seasons. It also allows the calculation of the net energy amount during the transition seasons (Korkmaz 2020).

Energy identity certificate is valid for 10 years from the date of issue. It can be rearranged according to a report to be prepared at the end of this period. BEP—TR is a modular software that consists of the following components.

- Geometry and Material Properties
- Net Energy: ISO 13790
- Lighting: EN 15193 (Pre-standard)
- Solar Benefits: EN ISO 13790: 2004, EN ISO 13790: 2008, EN ISO 15255: 2007, EN ISO 13792:2005
- Ashrae Foundations: 2009 Internal
- Loads: EN 15316, EN15241, EN 15243, EN 15193
- Ashrae: 2009 Mechanical
- Installations: DIN V 18599: 2007.

It has four main modules. The first determines the building's geometry, material properties, zones and the heat loss and gain of the building on an hourly basis. Geometry is defined in a hierarchical flow associated with component properties. It also provides the opportunity to read data from CAD software (Korkmaz 2020).

Properties of building elements can also be introduced in a hierarchical model. The objects that hold the geometry together (building, floors, regions, rooms, walls, windows, etc.) are defined relative to each other. The drawing can be performed using a professional CAD program or an existing CAD software output can be adopted.

The second module, the building's net energy demand, includes several parameters, both active and passive. It is based on the ISO 13790 standard. The components of the structure are interrelated on an unsteady basis using an electrical network analogy (Korkmaz 2020). The third module processes the lighting, and the last one processes the mechanical system serving the building. The system has heating, cooling, ventilation, domestic hot water, cogeneration and photovoltaic elements.

6.2 HAP Software

The Hourly Analysis Program provides powerful energy analysis to compare the energy consumption and operating costs of versatile features and designs alternatives for designing HVAC systems in commercial buildings. Results obtained from input data and system design calculations can be used directly in energy studies (https://www.carrier.com/commercial/en/us/software/hvac-system-design/hourly-analysis-program/).

HAP performs a real hourly energy analysis using measured weather data for all 8760 h of the year to calculate the building's heat transfer and loads, air system operation and plant equipment operation. It performs detailed clock-hour simulations of the thermal and mechanical behavior of air handling units for both system design and energy analysis (https://www.carrier.com/commercial/en/us/software/hvac-system-design/hourly-analysis-program/).

6.3 Energy-Plus Software

Energy-Plus is a complete building energy simulation program that engineers, architects and researchers use to model energy consumption - for heating, cooling, ventilation, lighting, and plug and process loads—as well as water usage in buildings (https://energyplus.net/).

Integrated, simultaneous solution of thermal zone conditions and HVAC system, heat balance-based solution of radiant and convective effects generating surface temperatures, thermal comfort and condensation calculations, user-defined time steps for sub-hourly interaction between thermal zones and environment, combined description of inter-zonal air movement Heat and mass transfer model and lighting and glare calculations for reporting visual comfort and driving lighting controls are among the features of Energy-Plus.

6.4 Izoder TS-825 Program

With this calculation program based on the TS 825 standard, the insulation material and thicknesses to be used in the design of energy efficient building elements are determined. Properties of the building elements forming the building envelope, such as walls, floors, roofs and window systems should be supplied. The building is designed to remain within the permitted energy requirement, it is considered as a whole and is not calculated by dividing it into volumes (Atmaca 2016).

In order to make calculations with this program, the following information should be known for the building to be calculated:

- Architectural design
- The location of the building
- Building information.

The factors that determine the heating requirement of the building in this program are as follows (Atmaca 2016):

- **Building features**: Heat losses through conduction, convection and ventilation (heat recovery, if any) and thermal capacity,
- **Features of the heating system**: Especially the control systems and the reaction time of the heating system to changes in the heating energy need,
- **Internal climate conditions**: the temperature value desired by the building users, changes in these temperature values in different parts of the building and at different times of the day,
- **External climatic conditions**: Outside temperature, direction and intensity of the prevailing wind,
- **Internal heat recovery sources**: Various devices and persons used for purposes such as internal heat sources that contribute to heating, cooking, obtaining hot water, lighting and radiating heat to the environment other than the heating system,
- **Solar energy**: It is the amount of solar energy that directly reaches the space that is heated from transparent structural elements such as windows.

In the defined calculation method, the annual heating energy need is found by summing the monthly required heating energy needs covering the heating period. Thus, it is possible to evaluate the thermal performance of the building in a more realistic way. In addition, it provides the designer with the opportunity to evaluate the solar energy capacity of the proposed design. In the calculation method, the boundaries of the heated environment consist of walls, floors, roofs, doors and windows that separate this environment from the external environment and if any, from the unheated environments. External-to-external dimensions are used in calculations. If the whole building is heated to the same temperature, an average internal temperature value is calculated for the whole building and the building is considered as a single volume and the heating energy need is calculated according to 5 methods. If there are other areas with high temperature difference in the building, these sections are calculated separately by taking them into the closed volume.

7 Case Study: Determining the Energy Performance of a Selected Building with Three Different Energy Software

In our study, a theoretical model was developed to evaluate the energy efficiency in buildings. The heat loss of a building used in this model calculates and compares results for the provinces of Istanbul, Antalya and Erzurum, using three different methods. The first calculation method is TS 825; the second is with the calculation methods from the "Design of Heating Installations" book of the Chamber of Mechanical Engineers and finally with the BEP-TR software, which is releted to the new energy technologies in buildings. The results obtained with the three methods were compared in terms of energy performance. In order to see the heat loss occurring in the building more clearly, provinces from three different climatic zones were selected. According to Figs. 19 and 20, Antalya is located in the 1st climate zone,

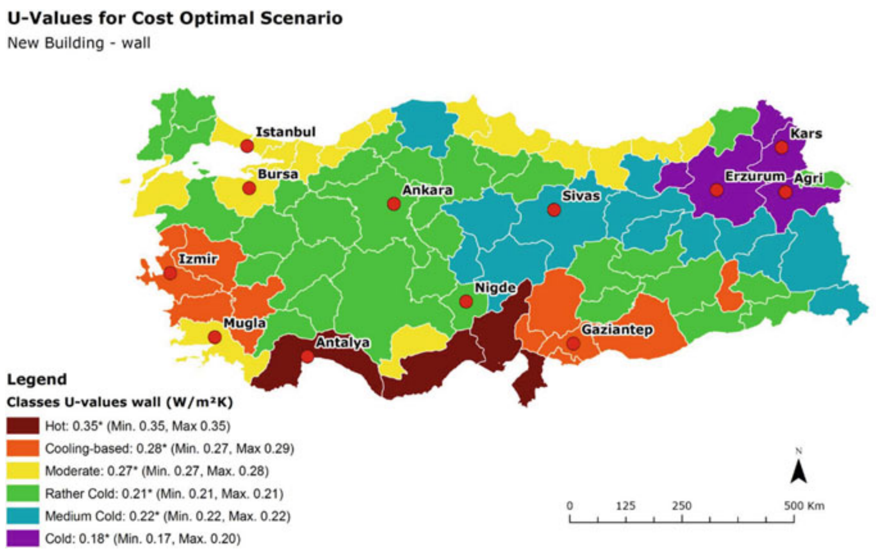


Fig. 19 Climate Zones and U-values According to Cost-Optimality (https://www.izoder.org.tr/dosyalar/haberler/Turkiye-U-degerleri-haritasi-raporu-2016-Ingilizce.pdf)

Region	Climate classification	HDDs (acc. to ASHRAE)	CDDs (acc. to ASHRAE)	Number of Turkish provinces in class	Climate region according to TS825
1	Hot	<1000	>1000	4	1
2	Cooling-based	1000-2000	>=1000	10	1-2
3	Moderate	<2000	<1000	17	2
4	Rather cold	>=2000	<1000	32	3
5	Medium cold	>=3000	<1000	13	4
6	Cold	>=4000	<1000	5	4

Fig. 20 U-Values According to TS-825 (https://www.izoder.org.tr/dosyalar/haberler/Turkiye-U-degerleri-haritasi-raporu-2016-Ingilizce.pdf)

İstanbul in the 2nd climate zone and Erzurum in the 5th climate zone.

The selected building is a single house with 1 floor and 1 basement floor. The entrance door faces the north facade. The total gross area is 615.73 m^2 and the total volume is 1721.96 m^3. Areas are determined according to the facades and underground walls, exterior surfaces, columns, windows and brick areas are given on each facade. In line with these data, heat loss calculations were made with three different methods. The architectural plan of the selected building is shown in Figs. 21 and 22.

These six regions allow a more detailed analysis of recommendable U-values based on different climate conditions (Figs. 19 and 20).

Table 1 shows the total gross area, brick, column, window, outer door and the total area under the ground. The basement floor of the building is 236.28 m^2, the ground

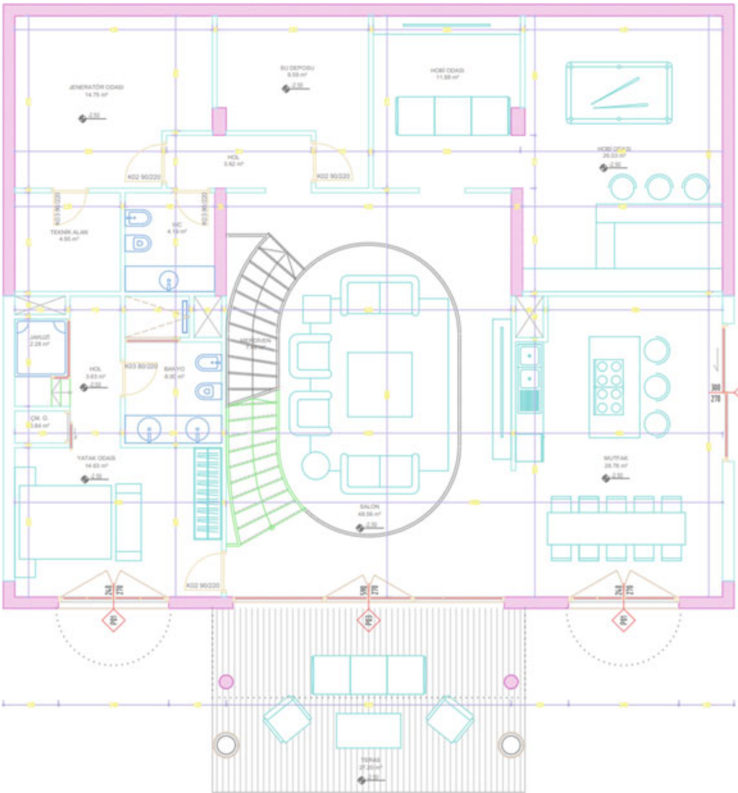


Fig. 21 Basement floor plan

floor is 199 m^2 and the first floor is 180 m^2. U value requirements according to TS 825 are given in Table 2.

7.1 *Heat Loss Calculation with Izoder TS-825 Program*

Heat loss calculations of the selected architectural plan using the Izoder TS-825 program were made for Istanbul, Antalya and Erzurum, respectively. While determining the annual heating energy need, specific heat loss, temperature difference for each month, heat losses, internal heat gain, solar energy gain, gain loss ratio, gain utilization factor are determined and the heating energy need for each month was obtained. The total area was 991.1 m^2 and the gross volume 1722 m^3. Table 3, shows the details for the calculations related to the annual heating energy requirement of the building for Istanbul province.

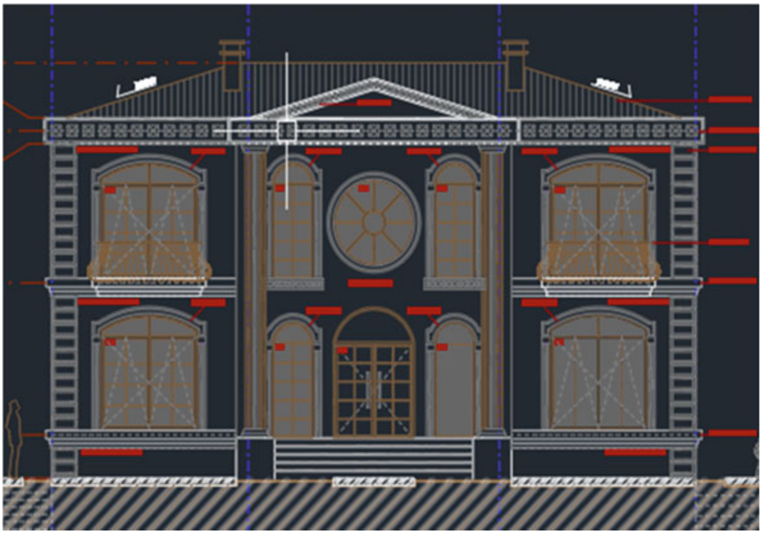


Fig. 22 North facade of the building

Table 1 Total areas of the building

Areas	Amount (m^2)
Total gross areas	615.73
Total brick area	256.66
Total column area	112.3
Underground wall space	100
Total window area	147.4
Outer door area	4.4

Table 2 U value requirements according to TS 825 (https://www.izoder.org.tr/dosyalar/haberler/Turkiye-U-degerleri-haritasi-raporu-2016-Ingilizce.pdf)

TS 825 Climate zone	Wall (W/m^2 K)	Roof (W/m^2 K)	Floor (W/m^2 K)	Window (W/m^2 K)
1	0.7	0.45	0.7	2.4
2	0.6	0.4	0.6	2.4
3	0.5	0.3	0.45	2.4
4	0.4	0.25	0.4	2.4

The heat transmission coefficient is determined according to the degree day regions of Turkey. Istanbul province is in the 2nd region, Antalya province is in the 1st region and Erzurum is in the 3rd region.

While calculating, the building surfaces have been selected in accordance with the heat permeability coefficient (U) determined according to these regions.

According to Table 3, the annual heating energy requirement calculated for the building in Istanbul is 55.12 kWh/m^2. Since Istanbul is located in the 2nd region, the highest heat loss allowed for the building is 65.01 kWh/m^2. Since the annual heating energy calculated for the building is below the required maximum value, this project complies with the standards according to this calculation method. The total heat loss is 30.37 kWh.

According to Table 4, the annual heating energy requirement calculated for the building in Antalya is 29.28 kWh/m^2. Since Antalya is located in the 1st region, the highest heat loss allowed for the building is 35.99 kWh/m^2. Since the annual heating energy calculated for the building is below the required maximum value, this project complies with the standards according to this calculation method. The total heat loss is 16.13 kWh.

According to Table 5, the annual heating energy requirement calculated for the building in Erzurum province is 98.1 kWh/m^2. Since Erzurum is located in the 3rd region, the highest heat loss allowed for the building is 98.74 kWh/m^2. Since the annual heating energy calculated for the building is below the required maximum value, this project complies with the standards according to this calculation method. The total heat loss is 54.09 kWh.

According to Fig. 23, the January data for each of our 3 provinces gives a consistent result since it is below the maximum heat loss value for the building.

7.2 *Heat Loss Calculation with MMO Heat Scale*

The calculations made for three provinces are calculated using the formulas in the MMO (Chamber of Mechanical Engineers) book and according to the tables in the book and the heat loss is determined and included in the spreadsheet.

The outside temperature value for Istanbul is −3 °C, +3 °C for Antalya and −21 °C for Erzurum. Bedrooms have an indoor air temperature value of 20 °C in HVAC projects. Therefore indoor temperature were taken as 20 °C in the calculations. The heat transmission coefficient values U, the wall types and thicknesses were taken the same as in the Izoder program. The heat loss calculation were carried out for the provinces of Istanbul, Erzurum and Antalya.

In the calculations, the total heat requirement was determined with the formula $Q_i = A.U.\Delta t$. Its value in the formula is for the total area of all surfaces. For Δt, Istanbul outside temperature value was taken as −3 °C from the table and the heat loss was calculated for each surface. The total heat loss was 17.271 kWh and this value was multiplied with the correction factors. The total correction factor Z_d is 0.7 because it is residential, the height correction factor Z_w is 1 because it has 2 floors and the direction correction factor Z_h is 0 because all facades are considered together. Thus, the total heat requirement was calculated. Then, the formula $Q_s = a \times R \times H \times Z \times L_x\ D_t\ X_e$ was used to determine the air leakage heat loss. Here, the unit

Table 3 Heat loss calculation with TS-825 program for Istanbul province

Months	Heat loss			Heat gain			GUR	Gain usage factor	Heating energy need
	Specific heat loss	Temperature difference	Heat losses	Internal heat gain	Solar energy gain	Total			
	$H = H_T + H_v$ (W/K)	$\theta_i = \theta_e$ $(K, ^\circ C)$	$H(\theta_i - \theta_e)$ (W)	ϕ_i (W)	ϕ_s (W)	$\phi_T = \phi_i + \phi_s$ (W)	γ (−)	η_{ay} (−)	Q_{ay} (kJ)
January	1.038,10	16.1	16.713	2.755	4.464	7.219	0.43	0.90	26.480.157
February		14.6	15.156		5.421	8.176	0.54	0.84	21.483.170
March		11.7	12.146		6.086	8.841	0.73	0.75	14.294.543
April		6.2	6.436		6.667	9.422	1.46	0.50	4.471.511
May		1.0	1.038		7.274	10.029	9.66	0.00	0
June		0.0	0		7.581	10.336	0.00	0.00	0
July		0.0	0		7.403	10.158	0.00	0.00	0
August		0.0	0		7.114	9.869	0.00	0.00	0
September		0.0	0		6.333	9.088	0.00	0.00	0
October		4.9	5.087		5.411	8.166	1.61	0.46	3.447.852
November		10.5	10.900		4.227	6.982	0.64	0.79	13.955.717
December		15.2	15.779		3.932	6.687	0.42	0.91	25.126.122

(continued)

Table 3 (continued)

Months	Heat loss			Heat gain			GUR	Gain usage factor	Heating energy need
	Specific heat loss	Temperature difference	Heat losses	Internal heat gain	Solar energy gain	Total			
	$H = H_T + H_v$ (W/K)	$\theta_i = \theta_e$ $(K, ^\circ C)$	$H(\theta_i - \theta_e)$ (W)	ϕ_i (W)	ϕ_s (W)	$\phi_T = \phi_i + \phi_s$ (W)	γ (−)	η_{ay} (−)	Q_{ay} (kJ)
$Q_{ay} = [H(\theta_i - \theta_e) - \eta(\phi_{i,ay} + \phi_{s,ay})].t(J)$ 1 kJ =0.278 × 10 KWh^{-3}							$Q_y = \Sigma Q_{ay} = 109.259.563$		
Total heat loss $Q_y = 0.278 \times 10^{-3} \times 109.259.563$ (kJ) $= 30.37$ kWh									
Internal heat gain $\phi_{i,ay} =\leqq 5.A_n$ (W)									
Solar energy gain $\phi_{g,ay} = \Sigma_{ay} \times g_{i,ay} \times l_{i,ay} \times A_i$									
Gain usage factor $KKO_{ay} = (\phi_{i,ay} + \phi_{s,ay})/H(\theta_{i,ay} - \theta_{e,ay})$ $\eta_{ay} = 1 - e^{(-1/KKO_{ay})}$ $A_{total} = 999.1$ m^2 $V_{specific} = 1722$ m^2									
Heating requirement per unit area $Q = Q_y/A_n$ 55.12 kWh/m^2 $A_n = 0.32 \times V_{brüt} = 551.04$ m^2 $A_{too}N_{brüt} = 0.58$ $Q' = 70 \times A/V + 24.4$ $Q' = 65.01$ kWh/m^2									
The annual heating energy need calculated for this building is below the maximum required value. This project complies with the standards according to the calculation method given in these standards. $Q < Q'(55.12 < 65.01)$									

Table 4 Heat loss calculation with TS-825 program for Antalya province

Months	Heat loss			Heat gain			GUR	Gain usage factor	Heating energy need
	Specific heat loss	Temperature difference	Heat losses	Internal heat gain	Solar energy gain	Total			
	$H = H_T + H_v$ (W/K)	$\theta_i = \theta_e$ $(K, ^\circ C)$	$H(\theta_i - \theta_e)$ (W)	ϕ_i (W)	ϕ_s (W)	$\phi_T = \phi_i + \phi_s$ (W)	γ (−)	η_{ay} (−)	Q_{ay} (kJ)
January	133.02	10.61	12.010	2.755	4.464	7.219	0.60	0.81	15.972.972
February		10.0	11.330		5.421	8.176	0.72	0.75	13.473.216
March		7.4	8.384		6.086	8.841	1.05	0.61	7.753.315
April		3.2	3.626		6.667	9.422	2.60	0.00	0
May		0.0	0		7.274	10.029	0.00	0.00	0
June		0.0	0		7.581	10.336	0.00	0.00	0
July		0.0	0		7.403	10.158	0.00	0.00	0
August		0.0	0		7.114	9.869	0.00	0.00	0
September		0.0	0		6.333	9.088	0.00	0.00	0
October		0.5	567		5.411	8.166	14.41	0.00	0
November		6.0	6.798		4.227	6.982	1.03	0.62	6.399.959
December		9.7	10.990		3.932	6.687	0.61	0.81	14.447.015

(continued)

Table 4 (continued)

Months	Heat loss			Heat gain			GUR	Gain usage factor	Heating energy need
	Specific heat loss	Temperature difference	Heat losses	Internal heat gain	Solar energy gain	Total			
	$H = H_T + H_v$ (W/K)	$\theta_i = \theta_e$ $(K, ^\circ C)$	$H(\theta_i - \theta_e)$ (W)	ϕ_i (W)	ϕ_s (W)	$\phi_T = \phi_i + \phi_s$ (W)	γ (−)	η_{ay} (−)	Q_{ay} (kJ)
$Q_{ay} = [H(\theta_i - \theta_e) - \eta(\phi_{i,ay} + \phi_{s,ay})].t(J)$ 1 kJ =0.278 × 10 KWh^{-3} Total heat loss $Q_y = 0.278 \times 10^{-3}$ × 109.259.563 (kJ) = 16.137 kWh Internal heat gain $\phi_{i,ay} \leq 5.A_n$ (W) Solar energy gain $\phi_{g,ay} = \Sigma\, ri_{n,ay} \times g_{i,ay} \times l_{i,ay} \times A_i$ $KKO_{ay} = (\phi_{i,ay} + \phi_{s,ay})/H(\theta_{i,ay} - \theta_{e,ay})$ $\eta_{ay} = 1 - e^{(-1/KKO_{ay})}$ Gain usage factor $A_{total} = 999.1\ m^2$ $V_{specific} = 1722\ m^2$							$Q_y = \Sigma Q_{ay} = 109.259.563$		
Heating requirement per unit area	$Q = Q_y/An$ 29.28 kWh/m^2 $A_n = 0.32 \times V_{brüt} = 551.04\ m^2$ $A_{too} N_{brüt} = 0.58$ $Q' = 44.1 \times A/V + 10.4$ $Q' = 35.99\ kWh/m^2$								
The annual heating energy need calculated for this building is below the maximum required value. This project complies with the standards according to the calculation method given in these standards.$Q < Q'(29.28 < 35.99)$									

Table 5 Heat loss calculation with TS-825 program for Erzurum province

Months	Heat loss			Heat gain			GUR	Gain usage factor	Heating energy need
	Specific heat loss	Temperature difference	Heat losses	Internal heat gain	Solar energy gain	Total			
	$H = H_T + H_v$ (W/K)	$\theta_i = \theta_e$ $(K, ^\circ C)$	$H(\theta_i - \theta_e)$ (W)	ϕ_i (W)	ϕ_s (W)	$\phi_T = \phi_i + \phi_s$ (W)	γ (−)	η_{ay} (−)	Q_{ay} (kJ)
January	966,76	24.4	23.589	2.755	4.464	7.219	0.31	0.96	43.178.946
February		23.7	22.912		5.421	8.176	0.36	0.94	39.467.378
March		18.7	18.078		6.086	8.841	0.49	0.87	26.922.098
April		11.1	10.731		6.667	9.422	0.88	0.68	11.027.642
May		6.2	5.994		7.274	10.029	1.67	0.45	3.838.265
June		1.7	1.643		7.581	10.336	6.29	0.00	0
July		0.0	0		7.403	10.158	0.00	0.00	0
August		0.0	0		7.114	9.869	0.00	0.00	0
September		2.5	2.417		6.333	9.088	3.76	0.00	0
October		8.7	8.411		5.411	8.166	0.97	0.64	8.253.996
November		15.9	15.371		4.227	6.982	0.45	0.89	23.735.680
December		21.8	21.075		3.932	6.687	0.32	0.96	37.987.491

(continued)

Table 5 (continued)

Months	Heat loss			Heat gain			GUR	Gain usage factor	Heating energy need
	Specific heat loss	Temperature difference	Heat losses	Internal heat gain	Solar energy gain	Total			
	$H = H_T + H_v$ (W/K)	$\theta_i = \theta_e$ $(K, ^\circ C)$	$H(\theta_i - \theta_e)$ (W)	ϕ_i (W)	ϕ_s (W)	$\phi_T = \phi_i + \phi_s$ (W)	γ (−)	η_{ay} (−)	Q_{ay} (kJ)
$Q_{ay} = [H(\theta_i - \theta_e) - \eta(\phi_{i,ay} + \phi_{s,ay})].t(J)$ 1 kJ =0.278 KWh^{-3} Total heat loss $Q_y = 0.278 \times 10^{-3}$ $\times$ 194.591.889 (kJ) = 54.097 kWh Internal heat gain $\phi_{i,ay} \leq 5.A_n$ (W) Solar energy gain $\phi_{g,ay} = \Sigma\, r_{i_{n,ay} \times g_{i,ay}} \times l_{i,ay} \times A_i$ Gain usage factor $KKO_{ay} = (\phi_{i,ay} + \phi_{s,ay})/H(\theta_{i,ay} - \theta_{e,ay})$ $\eta_{ay} = 1 - e^{(-1/KKO_{ay})}$ $A_{total} = 999.1\ m^2$ $V_{specific} = 1722\ m^3$							$Q_y = \Sigma Q_{ay} = 194.591.889$		
Heating requirement per unit area	$Q = Q_y/An$ 98.17 kWh/m^2 $A_n = 0.32 \times V_{brüt} = 551.04\ m^2$ $A_{too}N_{brüt} = 0.58$ $Q' = 82.8 \times A/V + 50.7$ $Q' = 98.74$ kWh/m^2								
The annual heating energy need calculated for this building is below the maximum required value. This project complies with the standards according to the calculation method given in these standards. $Q < Q'(98.17 < 98.74)$									

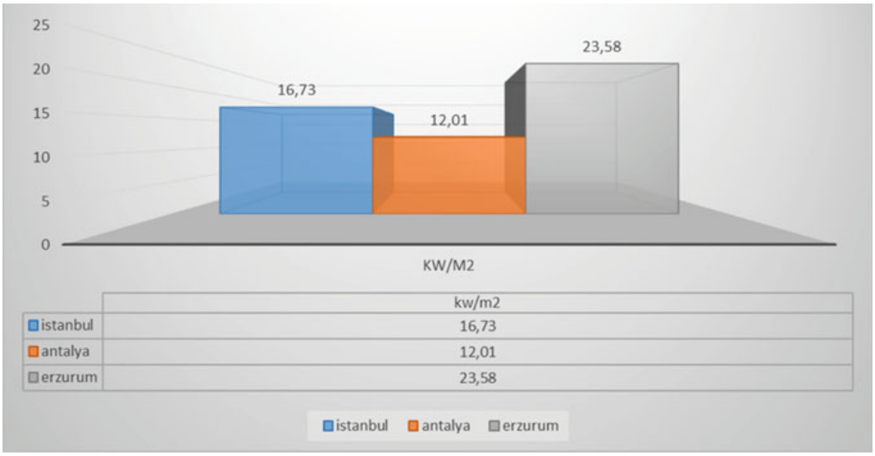


Fig. 23 Heat loss comparison of the provinces for January with the Izoder Program

gap sealing $a = 2\text{m}^3/\text{hm}$, the leakage gap perimeter (window frames) $L = 24$ m, the room property coefficient $R = 0.9$, the building coefficient of the windy free zone $H = 0.48$, the corner correction factor $Z = 1$, $T_{\text{in}} = 20$ °C were assumed. Air leak heat loss was found to be $Q_s = 761$ Wh. The total heat loss was found to be $Q_h = (Q_i + Q_s)$ 19,599 kWh for İstanbul. The same procedures were repeated for Antalya and Erzurum provinces. The total heat loss for Antalya province was found to be 15.91 kWh. The total heat loss for Erzurum province was found to be 30.32 kWh.

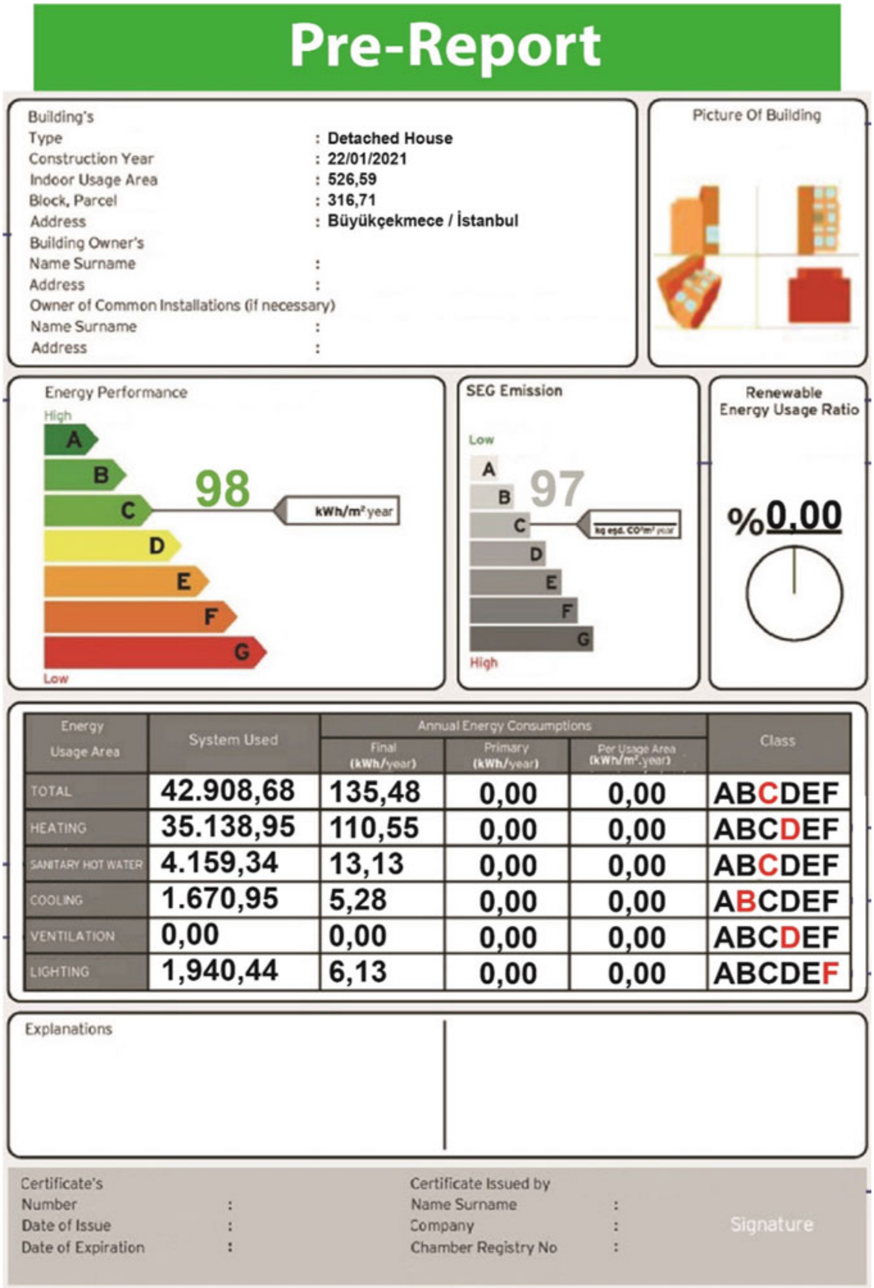
7.3 Heat Loss Calculation with BEP-TR

Finally, using BEP-TR, heat loss calculations were made for three provinces, and the energy consumption of the building for heating, cooling, ventilation, sanitary hot water and lighting and their energy class and building energy performance were determined. First, heat loss for Istanbul was calculated and presented in Table 6.

According to the result of the pre-calculation report of the heat loss calculation made for the province of Istanbul with BEP-TR, the annual total energy consumption is 42908.22 kWh/year. Total energy class is C, heating class D, sanitary hot water class C, cooling class B, ventilation class D, lighting class F. According to the report results, the greenhouse gas emission is 32.65 kg eq. CO_2/m^2 year. The building located in Istanbul has a high energy class and low greenhouse gas emission (Table 6).

According to the result of the preliminary calculation report of the heat loss calculation made for the province of Antalya with BEP-TR, the annual total energy consumption is 31183.22 kWh/year. Total energy class is C, heating class E, sanitary hot water class C, cooling class B, ventilation class D, lighting class E. According

Table 6 Heat loss calculation for the province of Istanbul with BEP-TR



Pre-Report

Building's
Type : Detached House
Construction Year : 22/01/2021
Indoor Usage Area : 526,59
Block, Parcel : 316,71
Address : Büyükçekmece / İstanbul
Building Owner's
Name Surname :
Address :
Owner of Common Installations (if necessary)
Name Surname :
Address :

Picture Of Building

Energy Usage Area	System Used	Annual Energy Consumptions			Class
		Final (kWh/year)	Primary (kWh/year)	Per Usage Area (kWh/m².year)	
TOTAL	42.908,68	135,48	0,00	0,00	ABCDEF
HEATING	35.138,95	110,55	0,00	0,00	ABCDEF
SANITARY HOT WATER	4.159,34	13,13	0,00	0,00	ABCDEF
COOLING	1.670,95	5,28	0,00	0,00	ABCDEF
VENTILATION	0,00	0,00	0,00	0,00	ABCDEF
LIGHTING	1,940,44	6,13	0,00	0,00	ABCDEF

Explanations

Certificate's
Number :
Date of Issue :
Date of Expiration :

Certificate Issued by
Name Surname :
Company :
Chamber Registry No :

Signature

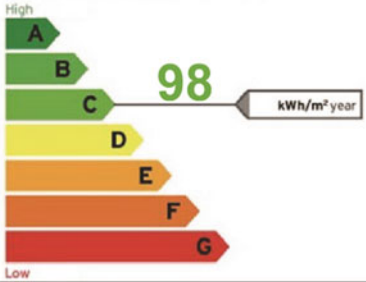
Table 7 Heat loss calculation for Antalya province with BEP-TR

Pre-Report

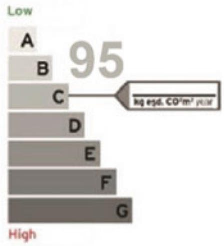
Building's
Type : Detached House
Construction Year : 22/01/2021
Indoor Usage Area : 526,59
Block, Parcel : 316,71
Address : Alanya / Antalya
Building Owner's
Name Surname :
Address :
Owner of Common Installations (if necessary)
Name Surname :
Address :

Picture Of Building

Energy Performance



SEG Emission



Renewable Energy Usage Ratio

%0,00

Energy Usage Area	System Used	Annual Energy Consumptions			Class
		Final (kWh/year)	Primary (kWh/year)	Per Usage Area (kWh/m².year)	
TOTAL	31.102,22	98,46	0,00	0,00	ABCDEF
HEATING	14.409,58	45,56	0,00	0,00	ABCDEF
SANITARY HOT WATER	4.150,34	13,13	0,00	0,00	ABCDEF
COOLING	10.749,35	33,94	0,00	0,00	ABCDEF
VENTILATION	0,00	0,00	0,00	0,00	ABCDEF
LIGHTING	1.865,94	5,89	0,00	0,00	ABCDEF

Explanations

Certificate's
Number :
Date of Issue :
Date of Expiration :

Certificate Issued by
Name Surname :
Company :
Chamber Registry No :

Signature

to the report results, the greenhouse gas emission is 25.90 kg eq. CO_2/m^2 year. The building located in Antalya has a high energy class and low greenhouse gas emission (Table 7).

According to the result of the preliminary calculation report of the heat loss calculation made for the province of Erzurum with BEP-TR, the annual total energy consumption is 93936.12 kWh/year. Total energy class is C, heating class C, sanitary hot water class C, cooling class D, ventilation class D, lighting class E. According to the report results, the greenhouse gas emission is 70.14 kg eq. CO_2/m^2 year. The building located in Erzurum has high energy class and low greenhouse gas emission.

7.4 Comparison of Heat Loss Analyses

The heat loss analysis from BEP-TR was compared with MMO Heat Table and Izoder for three provinces and the results are given in percentage in Table 8.

Istanbul has the least deviation in the calculation. The deviation percentage was higher in the analysis results for Antalya and Erzurum. However, the temperature values used in the calculation by the Izoder program are slightly different from the temperature values we use from the MMO book and the A * U values on the surface contacting the soil are multiplied by a factor of 0.5 and the ceiling by 0.8. For this reason, it is a natural situation to have a facial deviation (Fig. 24).

Three different analysis results for three provinces have been calculated and are included in Table 10.

As seen in Fig. 25, the most erroneous result was found in the heat loss for the Erzurum region in the BEP-TR software. The values of Antalya and Istanbul are closer when compared with the results of the other two methods.

In this study, heat losses occurring in the building with the same features in Istanbul, Antalya and Erzurum provinces were investigated by three different methods. It was calculated with the calculation method in TS 825 first, then with the calculation methods in the "Heating Installation" book of the Chamber of Mechanical Engineers and finally with the BEP-TR software, which includes the new energy technologies in buildings. Results obtained with the three methods were compared in terms of energy performance.

As a result of the heat loss calculations of the architectural plan using the Izoder TS 825 program, the annual heating energy requirement calculated for the building in Istanbul was 55.12 kWh/m^2 and the total heat loss 30.37 kWh, the annual heating energy requirement in Antalya was 29.28. kWh/m^2 and total heat loss 16.13 kWh, annual heating energy requirement in Erzurum was 98.17 kWh/m^2 and total heat loss 16.13 kWh. Since the annual heating energy calculated for the building is below the required maximum value, this project complies with the standards according to this calculation method. In the second method, MMO heat loss calculation method, the total heat loss was found to be 19.599 kWh for Istanbul, 15.91 kWh for Antalya and 30.32 kWh for Erzurum. Finally, using BEP-TR, heat loss calculations were carried out for the three provinces. The annual total energy consumption for Istanbul

Table 8 Heat loss calculation for Erzurum province with BEP-TR

Pre-Report

Building's

Type	: Detached House
Construction Year	: 22/01/2021
Indoor Usage Area	: 526,59
Block, Parcel	: 316,71
Address	: Yakutiye / Erzurum

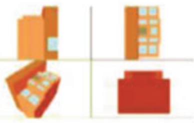
Building Owner's

Name Surname :
Address :

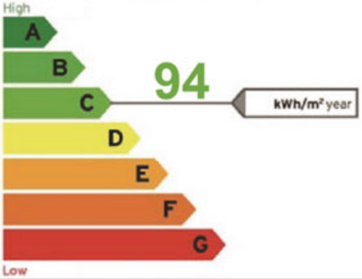
Owner of Common Installations (if necessary)

Name Surname :
Address :

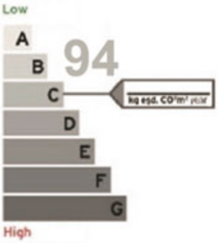
Picture Of Building



Energy Performance



SEG Emission



Renewable Energy Usage Ratio

%0,00

Energy Usage Area	System Used	Annual Energy Consumptions			Class
		Final (kWh/year)	Primary (kWh/year)	Per Usage Area (kWh/m².year)	
TOTAL	93.936,12	296,60	0,00	0,00	ABCDEF
HEATING	87.759,40	277,10	0,00	0,00	ABCDEF
SANITARY HOT WATER	4.158,34	13,13	0,00	0,00	ABCDEF
COOLING	0,00	0,00	0,00	0,00	ABCDEF
VENTILATION	0,00	6,37	0,00	0,00	ABCDEF
LIGHTING	2.018,39	0,00	0,00	0,00	ABCDEF

Explanations

Certificate's		Certificate Issued by		
Number	:	Name Surname	:	
Date of Issue	:	Company	:	Signature
Date of Expiration	:	Chamber Registry No	:	

Table 9 Comparison of heat loss analysis from BEP-TR with MMO Heat Table and Izoder for three provinces

City	MMO (kW/h)	İzoder (For the month of January) (kW/h)	Percent deviation rate
İstanbul	19.59	16,71	%14
Antalya	15.91	12,01	%24
Erzurum	30.32	23,58	%22

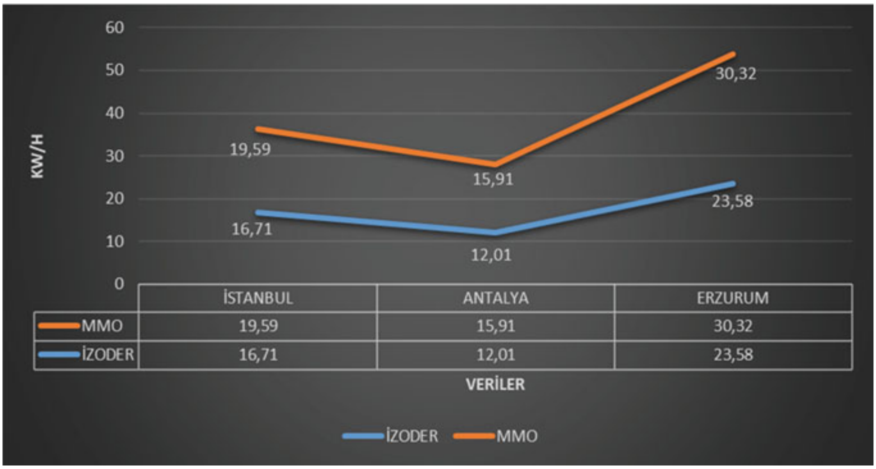


Fig. 24 MMO and Izoder heat loss comparison

Table 10 Comparison of three different analysis results for the three provinces

CITY	MMO (kW/h)	İZODER (kW/h)	BEP-TR (kW/h)
İstanbul	19.59	30,374	26,285
Antalya	15.91	16,137	14,409
Erzurum	30.32	54,097	87,759

was 42908.22 kWh/year, for Antalya 31,183.22 kWh/year and for Erzurum 93,936.12 kWh/year. The energy class of the buildings was C class. The buildings had a high energy class and low greenhouse gas emission.

When the heat loss results by the three methods were compared, the most erroneous result was found in the heat loss for the Erzurum region in the BEP-TR software. The values of Antalya and Istanbul were closer when compared with the results of the other two methods. In line with the data obtained, it has been determined that new energy technologies can be applied as an alternative to traditional methods in building heat loss reduction applications to bring positive results.

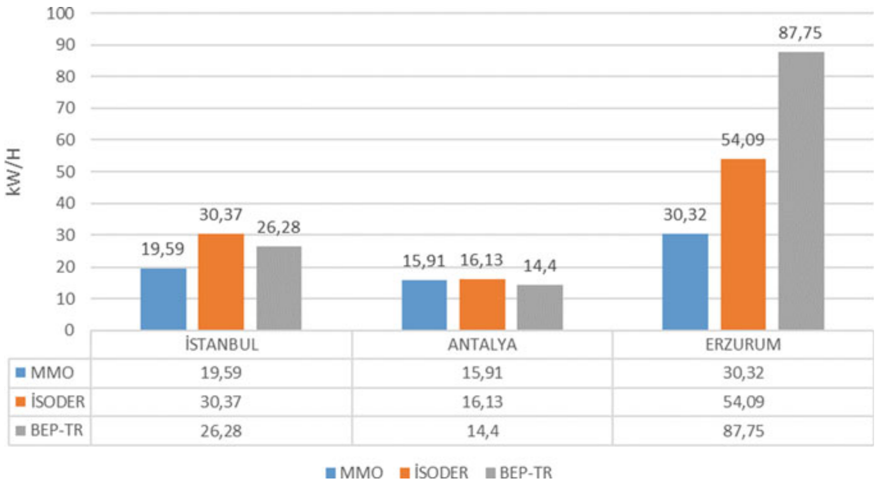


Fig. 25 Analyses results for three provinces

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Swarm Grids—Distributed Power Grid Control for Distributed Renewable Power Generation

Eberhard Waffenschmidt

1 Introduction: Swarm-Principle

Electrical power distribution is more than just building power lines.

Especially nowadays, the control of the electrical power flow from distributed power sources to the more and more controllable loads requires a smart control system. Converting to a fully renewable energy system means converting to a nearly complete electrical energy system, because the majority of renewable energy sources like photovoltaics and wind turbines are electrical. This includes the increase of the electrical power demand by a factor of three to four. Fortunately, these huge upcoming electrical applications like electric vehicle charging or heating with heat pumps are controllable loads, which means, they can be switched off for a certain amount of tine and can such contribute to a load management. This offers the possibility to smartly manage the necessary matching of loads with fluctuating decentralized generation. Furthermore, the loads of the line can be managed this way.

However, a large amount of devices is difficult to manage centrally. Thus, a distributed power generation with renewable energies benefits from a distributed control of the power distribution. The concept of cellular grids proposes a distributed structure of the power grid for such a purpose. Here, a proposal for the control of such a cellular power grid structure is made, which is named "Swarm Grid" by the author. The name refers to the swarm-like control structure, which implies no master control for the coordination of the grid components.

In a swarm (e.g. a swarm of fish), members are able to measure (e.g. fish can see), know about the others or communicate (e.g. keeping an eye on each other), decide and react (e.g. change the direction of swimming). Likewise, components in

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T. S. Uyar and N. Javani (eds.), *Renewable Energy Based Solutions*,
Lecture Notes in Energy 87, https://doi.org/10.1007/978-3-031-05125-8_6

a Swarm Grid should be able to measure, communicate to each other, process the information and react. Precisely, the presented concept includes the following:

The components are able to measure the voltage at the connection point and the power or current of the device connected to this point. In a more advanced environment, the devices are able to detect the voltage phasor or even the grid impedance.

The components communicate to each other by exchanging the measured information. This way, each component can get an overview of a much large portion of the grid than only the point of connection. Preferably, the communication is based on powerline communication, such that only components on the same branch of the grid communicate to each other.

By considering the measured values, each grid component is able to calculate a detailed view of the actual grid state. From these calculations, the components can make decisions on their performance, e.g. power management to avoid overload.

Inherently, this applies only to controllable loads, which power may be modulated without deterioration of its function. It may apply to components like charging boxes for electric vehicles, electrical heat pumps, climate controls, batteries or combined heat and power (CHP) systems. Such components will dominate future distribution grids in a 100% renewable energy society.

As exemplary grid components, charging stations of electric vehicles and the background of this use case are discussed here more in detail. First results from a related research project will also be presented which include methods to estimate the grid's topology from the measurements and then the calculation of voltage and current states in the determined power grid.

2 Example for a Swarm Control: Distributed Control of Electric Vehicle Charging

The problem becomes obvious looking at the charging management of electric vehicles. The maximum amount of vehicles, which can be charged in one power grid branch, is rather limited. If no charging management is applied, the grid provider typically allows only a low charging power per vehicle like e.g. 3.3 kW in order to avoid overloading of the power grid.

If the charging power per vehicle is increased to a higher value to 11 kW or 22 kW, as preferred by the customers, the grid can soon be overloaded, if all vehicles charge simultaneously. However, this is only seldom the case. It is more likely that the vehicles arrive arbitrary distributed. For such a case, the cumulated power of 80 vehicles is exemplarily shown as a function of time for one day in Fig. 1. Comparing the yellow curve with 3.3 kW charging power per vehicle with the grey curve of 22.2 kW charging power per vehicle, it can be observed that the cumulated power does not increase proportionally with the charging power per vehicle. The reason for this behaviour is that a higher charging power leads to shorter charging times

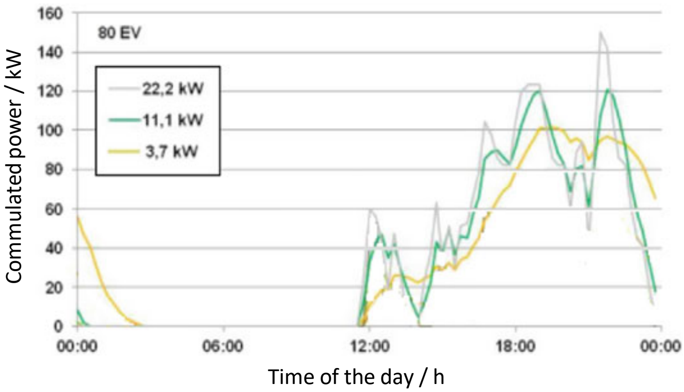

Fig. 1 Cumulated power of 80 electric vehicles (EV) arriving arbitrarily, charging with 3.7 kW, 11.1 kW or 22.2 kW (Doum 2015)

and therefore the simultaneous factor of the loads decreases. As a conclusion, in most typical cases a higher charging power can be allowed to the customers without overloading the power grid.

However, this larger charging power can only be allowed, if technical measured prohibit the simultaneous charging of all vehicles. Therefore, a load management needs to be applied in such a case.

Usually, such a load management is done by a central controller. However, as a disadvantage such a central controller can soon be overloaded, its software could be hacked and furthermore, it needs investment and maintenance by the power grid operator. Contrary, a decentralized load management can easily be extended, hacking of the system is more difficult and locally limited, and it doesn't need central investments by the power grid operator.

3 Single Device Control

There exist approaches for a decentralized load control. All of them use only single devices on one node of the power grid.

3.1 Grid Control with Voltage Measurements

Typically, they use the grid voltage as a control parameter. A widely spread method is a real power or reactive power reduction as a function of the grid voltage. Such a type of control must be available in modern inverters of decentralized power generators like photovoltaic (PV) systems in Germany, as demanded by the actual grid code for low voltage grids.

The company GridSense offers products that at least estimate the state of the grid. In a patent specification (Giusti et al.), GridSense claims a system in which the charging start and end times for the charging process are estimated from previously measured charging starts and end times. In addition, the expected electricity price is estimated from recorded data and included in the planning of the charging process. Likewise, the grid load is included in this manner. However, there is no description there of how the grid condition is determined. The description describes the measurement of the grid voltage at the connection point, but in no way addresses how the grid state is determined from the grid voltage.

3.2 Determination of the Grid State with Grid Impedance Measurements

A further possibility is to measure the grid impedance. A simple method, which does not need any additional hardware effort, is shown here with own results.

Figure 2 shows schematically the typical initial situation in a power system. At the top there is the representation as a grid diagram and below the same structure as an electrical circuit diagram, which is summarized below. On the left is the grid connection, which is regarded as the ideal voltage source U_N in the electrical circuit diagram. The different loads in the grid branch are shown as complex impedances. They are connected by power lines, which also have complex impedance. The transformer can also be represented as a complex impedance. The loads can vary. This is represented here by a variable load ("Variable Load", shown in purple). Other loads

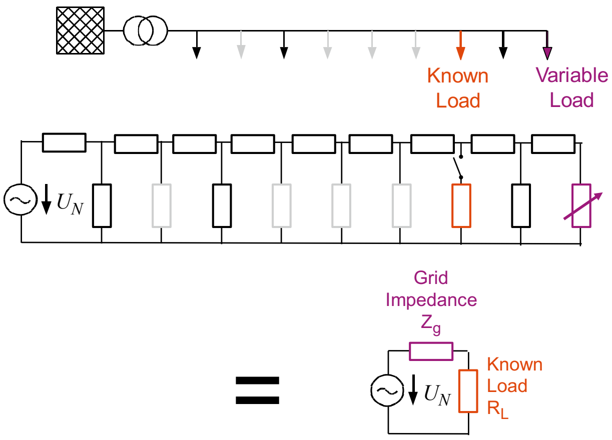

Fig. 2 Typical configuration to determine the power grid state with a single device

in gray are currently not switched on. In red the controllable known load ("Known Load") is shown, for example the charging box.

The task now is to determine whether the grid is overloaded using only parameters that can be measured at the connection point of the known load.

A first possibility is to track the grid voltage. If the unknown load requires more power and thus more current, the voltage in the grid branch collapses somewhat. This voltage collapse could be tracked at the connection point of the known load to get a first idea of the state of the grid. However, it may also be that the grid voltage U_N of the upstream grid varies. Unfortunately, it is not possible to distinguish the causes of the voltage dip with a simple voltage measurement. Therefore, a method which does not contain this uncertainty is described below.

From the point of view of the known load, the entire grid branch can be summarized (as illustrated). In this case, all impedances are combined into one grid impedance ("Grid Impedance"). A change in the variable load is then reflected in a change of the grid impedance. Therefore, if the grid impedance can be measured accurately, it can be used to determine the variable load and, in turn, the load on the grid.

For the following illustrations, the impedances are assumed to be real resistances. Particularly in the low-voltage grid, resistance predominates over inductive apparent resistance in the lines, and the loads are largely active powers, so this assumption is justified as a first approximation. The parameters used to create this (and the following graphs) are significantly exaggerated compared to real parameters to make the illustration of the principle clearer.

The grid impedance can be determined if the power or current of the known load is varied. Then a characteristic curve field is obtained, which is shown in Fig. 3. The horizontal axis shows the current through the known load, and the vertical axis shows the voltage at the connection point of the known load. The impedance of the unknown load is varied as a parameter for the various curves. It can be seen that

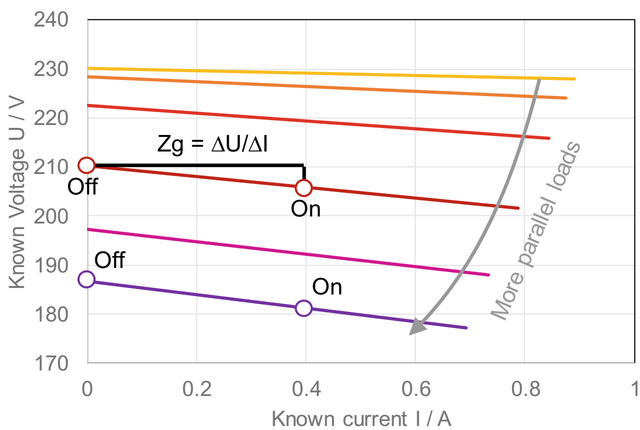

Fig. 3 Principle of the grid impedance measurement

the voltage generally decreases as the power of the unknown load increases ("More parallel loads"). However, it can also be seen that the slope of the curves increases as the unknown load increases.

This slope is proportional to the line impedance and is independent of the line voltage U_N. Thus, a variation in the voltage of the superimposed grid has no effect on the determination.

To determine the slope, at least two measuring points are needed. These can result from the variation of the power and thus the current of the known load. In the simplest case, one measures the voltage when the load is switched off ($I = 0$, "Off") and when the load is switched on (here, for example, $I = 0.4$ A, "On"). However, two other arbitrary points (I_1, U_1) and (I_2, U_2) can also be used. The mains impedance is then given by $Z_g = \Delta U/\Delta I$, where $\Delta U = U_2 - U_1$ and $\Delta I = I_1 - I_2$.

The two measurements should be made in quick succession so that no significant change in line impedance occurs in the meantime. Figures 4 and 5 show an

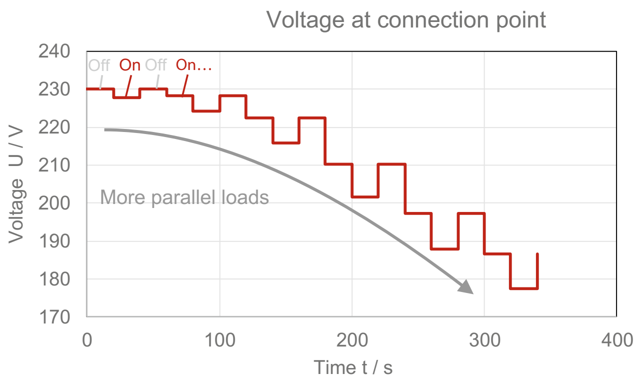

Fig. 4 Concrete procedure for measuring the grid impedance

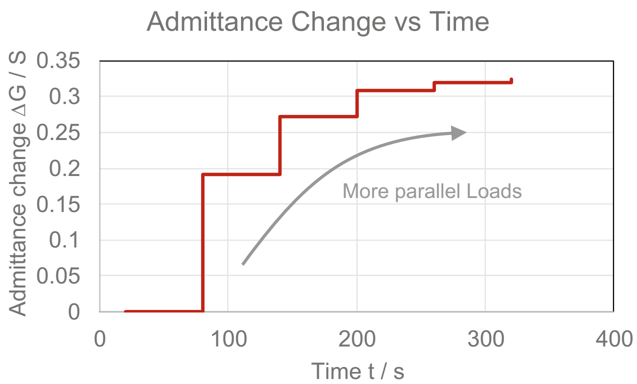

Fig. 5 Example of the determined grid admittance as the inverse of the grid impedance

exemplary curve: Alternately, the known load is switched off and on ("off", "on"). After switching off and on once, the mains impedance can be determined. This is shown in Fig. 5: Here the inverse value to the grid impedance, the grid admittance (complex conductance), is plotted against time. Since the loads on the grid are always connected in parallel, the admittances of the loads add up.

In summary, the grid impedance can be determined by measuring the grid voltage at the known load at different load states of the known load in short succession and offsetting it with the respective known currents of the known load.

Unfortunately, this method requires very precise voltage measurements. The voltage steps are only in the order of less than a percent of the grid voltage amplitude and if one wants to distinguish load changes, the preciseness must be fractions of this percentage.

An exemplary measurement is shown in Fig. 6, which was presented already in Waffenschmidt (2018). Here, two loads were switched in a household grid. The figure shows the time dependence of the current of the "known load" according to the previous paragraphs and the current of a "variable load". In parallel, the measured grid voltage at the "known load" is shown in red. The measured amplitude has been smoothed by a running average algorithm (gray) to improve the impedance calculations.

From these measurements the grid impedance has been calculated according to the previously explained procedure. It is shown in the lower diagram. An at least visible change of the grid impedance would be expected, when the "variable load" is switched on and off. However, such a correspondence cannot be determined in this particular measurement. This shows that even more precise measurements are needed and the further measures must be taken to exclude external influence from the upstream grid.

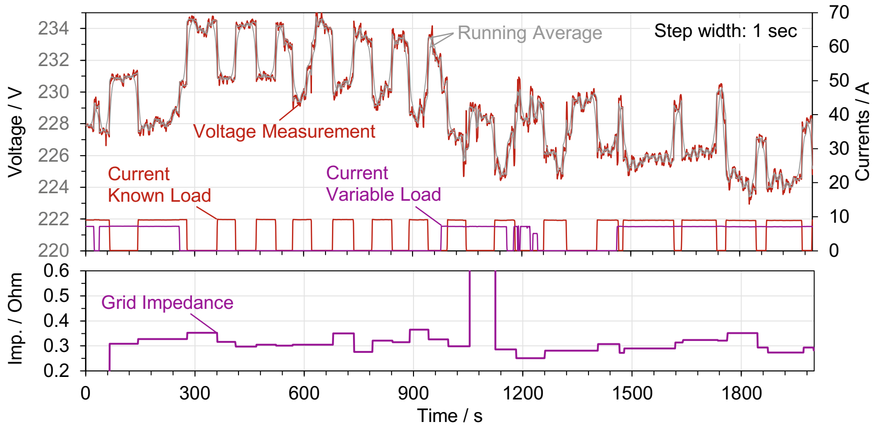

Fig. 6 Real grid impedance measurements (Waffenschmidt 2018)

3.3 Voltage Angle Measurement

The voltage angle (or phasor) of the voltage at the connection point of the known load or its change can be used as a further measurement variable. Here the inductive part of the supply lines becomes effective. To understand this, one first considers the phase angle of the voltage at the connection point compared to the phase angle of the line voltage U_N at the beginning of the line branch. Due to the line inductance, a phase angle difference of the voltage at the two points is observed when active power is transmitted. To a first approximation, this phase angle difference is proportional to the transmitted active power. However, since measurements can only be made at the point of known load, this phase angle difference is not known. Also, the absolute phase angle of the voltage at the connection point cannot be measured, since the line frequency also varies.

However, especially when there are abrupt changes in the load (known or unknown), there is also an abrupt change in the phase angle of the voltage. If this happens within one or two periods of the line frequency, these periods will lengthen (or shorten) by the value of the phase angle change (converted to time shift). So, with a precise measurement of the period, such load jumps can be detected.

Figure 7 shows such a measurement: In the picture, the time is shown on the horizontal axis. It runs from 0 to 4 s. On the vertical axis, the voltage at the connection point of the known load is shown. The instantaneous voltage is shown in light blue. One recognizes the individual periods of the sinusoidal course. In orange the respective amplitude, which was determined with a fit algorithm, is shown. Above this, the period duration is plotted with another vertical axis. This was determined with the same fit algorithm from the instantaneous voltage curve.

Two jumps can be seen in the course of the voltage amplitude. Here, a further "unknown" load was added in each case. In the course of the measured period

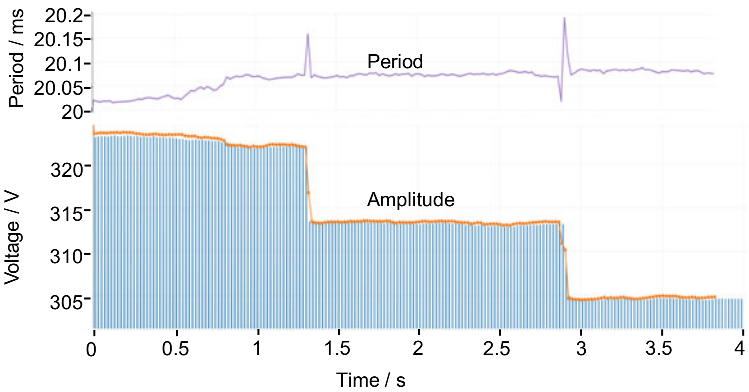

Fig. 7 Measurement of the period of the mains voltage (top) and the amplitude of the mains voltage (bottom) for two load jumps

duration, an extension of the period duration for one or two periods can be clearly recognized during the load jumps.

As a finding, the additional measurement of the period duration (or the phase angle change of the voltage) makes it possible to distinguish whether a voltage jump has occurred due to a load change in the investigated grid branch or due to a voltage change in the superordinate grid. A change in the voltage angle only occurs when the load current changes in the grid branch under consideration. A change in the line voltage in the superordinate grid will not cause a change in the phase angle of the voltage. It is therefore possible to assign a voltage jump to a load change if a brief lengthening or shortening of the period of the AC voltage occurs simultaneously with the jump.

4 Grid Control with Multiple Devices

As has been shown in the previous chapter, it is very difficult for single device to get information about the grid state.

Therefore, it is proposed that several devices communicate to each other and exchange information about their needed power and measured data, especially the measured grid voltage on the grid node, to which the device is connected. The principle is illustrated in Fig. 8. The general idea applies to all kinds of controllable loads like charging boxes of electric vehicles, heating (or cooling) systems, battery storages or PV systems (which power can only be reduced). In the further text, charging boxes are used as exemplary devices.

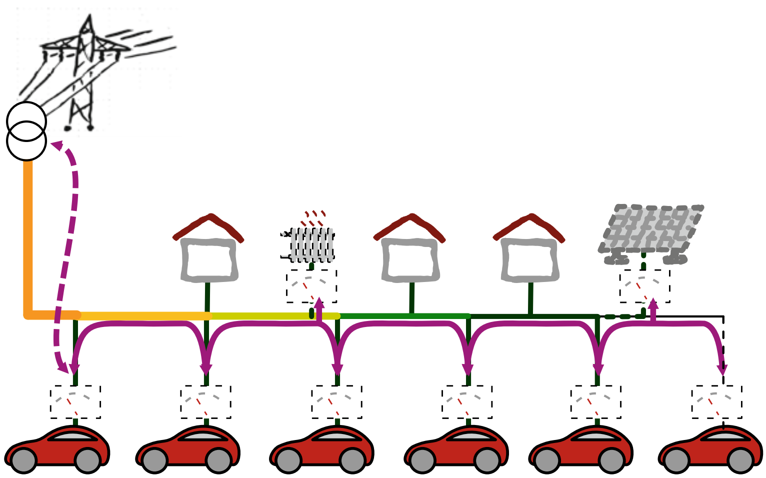

Fig. 8 Illustration of the decentralized grid management system

4.1 Communication

The devices should be able to coordinate with each other. However, in contrast to currently existing systems, the devices should omit a central instance. Instead, the charging stations should be able to coordinate decentrally with other charging stations to form a self-organizing network. Via this network, the decentrally collected information on the network status can then be summarized and evaluated in the charging boxes. In particular, for example, the charging powers set by the charging boxes can be summed. Likewise, limited available power can be negotiated among the charging boxes via the network.

However, the necessary data connection between the charging boxes cannot be provided via general private internet connections. These cannot be provided reliably and necessary short latency times cannot be guaranteed to control a power grid operation over it. Instead, communication via powerline communication or a proprietary radio link is the target. These two options do not require any additional connections and connecting lines.

4.2 Control Aspects

4.2.1 Three Levels of the Grid Control

The type of control can be distinguished into three levels. They are illustrated in Fig. 9. The horizontal axes corresponds to the time and the vertical axis to the power. The grey area on the bottom illustrates the unknown power in the grid by the uncontrollable loads, e.g. households. The red and orange area illustrate the power demand of the controllable loads.

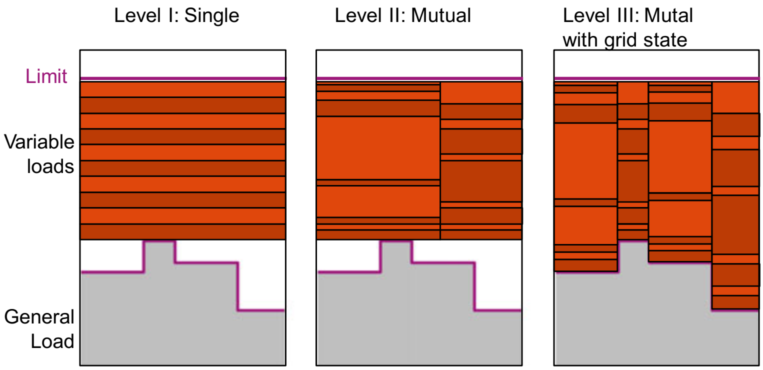

Fig. 9 Three levels of grid control

Level I is the simplest kind of avoiding grid overload and corresponds to the standard method used by grid operators: Each device is assigned to a "save", but rather low power level, where all devices can operate simultaneously. This level will be used, if the devices fail to establish a data connection between each other.

Level II means that the devices can communicate and are able to negotiate a mutual power budget. The mutual power limit is fixed and once set by the grid operator as a safe limit for all cases. Some of the device may not need any power or only a low power. Then other devices can increase their power. If some devices finish charging, the available power budget can be negotiated again and it is then distributed differently.

Level III requires the knowledge of the grid state. Then the mutual power budget can be set according to the actual grid state. For example, in the night, when only few other loads are active, the charging stations may share a large power budged than in the evening, when the households have a high power demand. This way, the grid capabilities can be used to its greatest extend. The grid state can be determined in collaboration by exchanging and processing the available measured data of all devices. (see further chapter).

The tree level method is a very secure mode of operation: If the requirements of a higher level cannot be met, the devices can degrade into a lower, but secure mode. E.g. if grid state measurements cannot be performed, the devices degrade from Level III into Level II and can still operate securely.

4.2.2 The Grid Traffic Light

If the devices operate in Level II or Level III and share a mutual power budget, an optimization process can take into account the forecast of the demands of the devices. This is helpful to plan load shifting, if necessary. For this optimization a state description like "grid traffic light" can be defined, as illustrated in Fig. 10.

The green state means that there are no restrictions and every device can operate as planned by the user, e.g. an electric vehicle can be charged immediately.

The yellow state means that there are restrictions by the power grid expected. However, the all demands by the users can still be met by load shifting. E.g. an electric vehicle cannot be charged immediately, but it can be charged fully until the desired time given by the user.

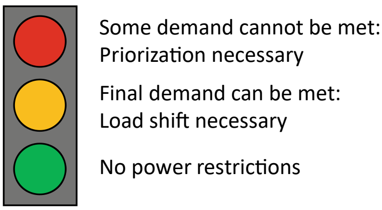

Fig. 10 Grid traffic light for the optimization process

The red state means that grid restrictions prevent that all demands by the users can be met, even with load shift. In this case a priorization for the distribution of the limited energy has to be done. Several algorithms cold be applied, where some examples are listed briefly here:

- First come first serve
- Equal power reduction
- Pay more for higher priority
- Higher priority by social aspects

4.3 Determination of the Grid Topology and the Grid State

In the following, it is assumed that at least two similar components are present in the same network branch and that these components can communicate with each other. It is assumed that communication between the controllable components takes place in real time, i.e. the time offset during communication is significantly less than one network period. Details on communication are explained in Sect. 2.4. This provides further and more precise possibilities for determining the network state.

Figure 11 shows an exemplary configuration with two switchable components 1 and 2 ("Known Load 1" and "Known Load 2"). The circuit can be extended analogously for any number of additional switchable loads.

The measurement with at least two components at different points in the grid branch offers the possibility to determine the current, and thus the grid load, between the two connection points in absolute terms. However, the line impedance Z_L between the two points must be known. In addition, it must be known at which point in the network branch the respective components are located. The process therefore includes a topology estimation phase during which the relevant parameters can be determined. During the subsequent operating phase, the grid load can then be determined continuously.

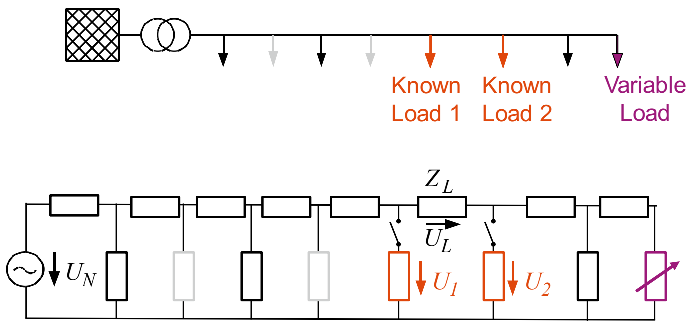

Fig. 11 Typical configuration to determine the power grid state with two devices

4.3.1 Grid Topology Estimation

During the topology estimation phase, the components involved agree among themselves on a switching sequence of the known loads, by which the parameters can be determined by suitable measurements.

Two Components

An exemplary switching sequence for two components looks as follows:

1. First both components are switched off. Both components measure the respective voltage at their connection and store it as a reference.
2. Both components agree that one of the two components (which one can be left to chance) switches on, i.e. becomes "active".
3. Both components measure again the respective voltage at their connection and calculate the voltage difference to the respective reference voltage.
4. the components exchange this difference voltage and compare them. This can produce various results from which the positions of the two components relative to each other in the network can be determined:
   a. The voltage difference is greater for the active component. This means that an additional voltage difference U_L occurs across the line Z_L between the components and thus an additional current flow between node 1 and node 2. From this it can be concluded that the active component is further away from the grid connection than the inactive component. Thus, in the example shown, component 2 would be active.
   b. The voltage differences are the same, but the two voltages are different. This means that there is no additional voltage difference across the line between the components and therefore no additional current flow between node 1 and node 2. It can be concluded that the active component is closer to the grid connection than the inactive component. Thus, in the example shown, component 1 would be active.
   c. The voltage differences are equal, but both voltages are also equal. Then either no additional load is connected beyond the last component. A swap of the two components (see point 5) should then result in case a. Or both components are connected to the same grid node. Swapping the components (see point 5) will then also not result in a voltage difference. In this case, both components must be considered together as one, and a network state determination is only possible as in the case of a single component.
   d. In the case of the inactive component, there is no additional voltage drop at all. In this case, the component has a contact via the communication link, but it is located in a different network branch or on a different three-phase phase. In this case, both components must be considered as individual devices in their respective network branch or phase.

5. If case *d* occurs, the further procedure is terminated. In the other cases, the configuration is noted and points 2 to 4 are repeated, this time with the other component becoming active. In one of the two attempts, result a should then have occurred.
6. If case *a* occurs, the active device additionally measures its own current draw and reports it. From the additional voltage difference U_L and the current of the device 2 I_2, the magnitude of the line impedance Z_L can now be calculated directly. The superposition principle is observed and according to Ohm's law the following then applies

$$Z_L = \Delta U_L / I_2$$

This quantity is stored and used to determine the line load in the operating phase.

Grid Topology Estimation with More Than Two Components

For the grid topology estimation with more than two components, the following procedure is proposed. Analogous to the previous chapter, each of the involved devices alternately becomes an active device once and connects its load. All devices communicate their measured line voltages and can thus determine the differential voltage to each other device. Devices which detect the same differential voltage as the respective active device are located on the side of the active device facing away from the mains connection. For the other devices, the higher the respective measured mains voltage, the closer the device is to the mains connection. In this way, the order of the devices in the mains branch can be determined from the order of the mains voltages. This sequence can be checked for each additional active device. At any of these measurements, the last device in the network branch will also become active. Then the order can be finally and completely clarified.

Each active device also communicates its current consumption. This, and the measured voltages are stored. At the end of the initialization, when the sequence of the devices is clear, the line impedances between the devices can be calculated from the respective current draw and the voltage differences of the neighboring devices according to the description in the previous chapter.

Grid Connection from Several Sides and Feeding into the Grid String

In case of a (rare) supply of the mains string with two mains connections from two sides, the mains status detection does not work without any problems. This can be detected by the fact that even when active devices are swapped, the voltage difference remains unequal. In this case, the network state detection cannot be used.

In open ring networks it can happen that in case of a fault the whole configuration changes and a part or the whole network string is supplied "from behind". This case can be detected by the fact that all voltage differences under load are suddenly negative. When this is detected, a complete re-initialization is triggered and the new network state is determined and stored.

Nowadays, decentralized feeders are often connected to the grid and it is not unlikely that there are such in the grid string. However, inverter-fed feeders such as photovoltaic systems or batteries are current-controlled and therefore behave as current sources to a first approximation. Therefore, they have no influence when determining the line impedances according to the superposition principle. During operation, however, the injected current is determined normally.

In the case of feeders are synchronous or asynchronous generators, however, the network behaves more like a network fed from two sides. In this case, the decentralized feeders would have to be switched off briefly for initialization.

Grid State Estimation

During operation, the devices involved regularly measure the mains voltage at their connection point at the same time and exchange these measured values with each other. From the voltage difference ΔU_L between adjacent components and the line impedances Z_L between the components, the magnitude of the current I on the line between the components can be calculated approximately according to Ohm's law:

$$I = \Delta U_L / Z_L$$

The calculation is only approximate because U_L is calculated from the difference in the magnitudes of the respective voltages. For a precise calculation, however, one would have to determine the difference of the complex voltages and then use their magnitude. Nevertheless, the current determined in this way can be used as a very good approximation in practice.

With this method, the network load "behind" the "first" component can be reliably determined. Since the current of the "first" component is also known, the current in the supply line to the "first" component is also known. Only further loads, which are placed between the first component and the mains connection, cannot be considered in this way.

If necessary, these could be determined with a mains impedance measurement.

Determination of Active and Reactive Power

In order to determine the load without approximation, the phase angle of the voltage at the respective device relative to each other is necessary. If this is known, the real and imaginary parts of the line impedances can also be determined and the complex currents and thus also active and reactive power can be calculated.

For this purpose, regular synchronization with a switching edge can be used. The phase angle can then be determined from the time difference to the next zero crossing of the voltage.

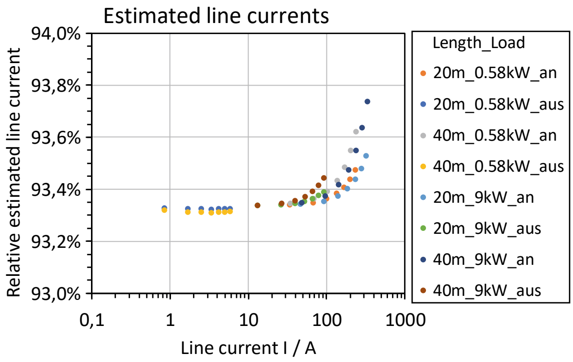

Fig. 12 Estimated line currents in relation to the real line current

Alternatively, measuring equipment of the individual components can be synchronized by a precise external timer. The GPS (Global Positioning System) time signal is particularly suitable for this purpose, since it is accurate to within a few nanoseconds and can be received anywhere in the world.

Results for a Grid State Estimation

To test the grid state estimation algorithm an exemplary grid string with several household loads is simulated using the grid simulation tool PandaPower, which runs with Python programming language. The distance between the nodes is 20 m and 40 m. The line type is a NAYY 4 × 150 SE, which has a line resistance of $R' = 208$ mΩ/km, a reactive line impedance of $X' = 80$ mΩ/km and a line capacitance of $C' = 261$ nF/km. Loads of 0.58 kW and 9 kW are switched on and off. From the voltage simulation results the line current is estimated according to the previously described algorithm. The estimated current is related to the actual current in the line resulting from the simulation. The results are shown in Fig. 12. The resulting estimated currents are about 7% smaller than the actual current. The reason for this is that only the voltage differences of the amplitudes are measured and the phase shift is not considered. However, this deviation can still be tolerated, if a safety margin in the grid state estimation is applied.

5 Conclusion

As a conclusion, future grids with many controllable loads should be managed decentrally. It is preferred to have communication between the devices. This way they can manage and negotiate a mutual power budget. In an even more advanced step, such devices can share voltage measurements and estimate the grid topology and the gird state by processing this information. Due to the exchange of information, the grid state can be much easier determined than with information from one single device only.

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Impact of Global Warming on Renewable Energy Potentials and Electricity Production in Turkey

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1 Introduction

1.1 Literature Review

World electrical energy production is on a radical change for the last ten years on the supply side. According to International Energy Agency (IEA), conventional fuel resources are rapidly disappearing from being primary resources for electricity production process and they are being replaced by renewable resources. In 2017, the total global electricity production was about 22,500 TWh. In the same year total electricity produced from the renewable technologies accounted for 6270 TWh representing 27% of the total global electricity production. We should note that the order of installed capacities in terms of percentages produced, started with coal, followed by natural gas, then hydropower, wind and solar PV and finally nuclear power.

As of the beginning of 2021, global use of solar energy exceeded 760 GW, wind energy 700 GW and hydroelectric power 1324 GW (International Energy Agency 2020). The total installed capacity from the nuclear power, on the other hand, remained below 400 GW (International Energy Agency 2020). In the same year, at the end of 2020, installed capacity of hydroelectric power was 31,336 MW, wind

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energy was 9294 MW and solar energy exceeded 7065 MW in Turkey (Enerji Atlası 2021).

We can see that for the period in question, both globally and in Turkey, hydropower was the main renewable energy for producing electrical energy until today. In 2010, 82% of all the energy produced from the renewable energy resources was hydropower.

The major reason for this change is the impact of global warming and accompanying climate change. Whereas on one side, heating and cooling demand patterns is changing as a result of rising temperatures, the biggest change is on the supply of energy side (Honsberg and Bowden 2019). In addition to disappearing of conventional resources, those renewable resources such as solar energy, wind power and hydropower are going through significant changes globally and locally due to global warming as well (Ebinger and Vergara 2011).

To ensure proper mitigation and adaptation options to the energy system all affects should properly be accounted for and carefully examined to calculate correctly their feasibility, costs, and technology options. Further research into climate impacts on the energy system as a whole is highlighted in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2014).

This study focuses on the supply side of the energy system especially on solar radiation hydropower and wind energy, known as the top three renewable energy sources for Turkey. The demand side and the impact of the climate change will be taken up in another study.

A number of previous reviews examine elements of this topic (Ebinger and Vergara 2011; Mideksa and Kallbekken 2010; Schaeffer et al. 2012; Arent et al. 2015; Cronin et al. 2018). These focus largely on the climate change impacts on technologies currently in use with little or no discussion of the impacts on future technologies.

1.2 Short Overview of the Existing Studies

Impacts studies on hydropower and wind resources dominate the literature. With global warming, everybody has turned their attention to CO_2 increase in the atmosphere and there is no doubt that CO_2 is the major player in global warming. However, the increase of CO_2 levels may also play an important part in the reduction (however small to start with) of solar radiation, thus negatively affecting the use of solar radiation as a renewable source of energy. The reader is referred Cronin et al. (2018) for detailed information on these studies.

For hydropower generation there are two schools of thought. Hamududu and Killingtveit (2017) and Turner et al. (2017) believe that climate change will have little effect on total global hydropower and local resources and van Vliet et al. (2016) and others argue that there will be sizeable decrease on global hydropower capacity. Turner et al. (2017) and van Vliet et al. (2016), and other studies (Cronin et al. 2018) project an increase of 5–20% areas located at high latitudes and decrease by same amount in regions such as southern Europe including Turkey, southern USA and other areas located in the mid latitudes.

On wind power, Pryor and Barthelmie (2010) found average wind speeds would remain within ±15% of current values in Europe and North America. Later, this limit was revised upwards to ±30% by several researchers including Carvalho et al. (2017).

On solar energy, the impact studies are much more limited. Because of an expected decrease in cloud cover at mid-latitude regions an increase in solar resources is expected. However, a decrease in energy efficiencies should be more or less the same. Regional studies tend to predict a change in solar generation of less than ±10% by the end of the century (Crook et al. 2011; Gaetan et al. 2014; Panagea et al. 2017).

There are also a limited number of studies indicating a reduction in the transmission effectiveness of the overhead lines (Bartos et al. 2016; Tyusov et al. 2017). Cronin et al. (2018) contains more studies on the transmission lines especially for UK.

Electrical Energy Production from Renewable Resources

As of the beginning of 2021, global use of solar energy exceeded 760 GW, wind energy 700 GW and hydroelectric power 1324 GW (International Energy Agency 2020). The total installed capacity from the nuclear power, on the other hand, remained below 400 GW (International Energy Agency 2020).

A closer look at the renewables/electrical energy production can also be seen from Table 1. We can see that for the period in question, hydropower was the main renewable energy for producing electrical energy until today. In 2010, 82% of all the energy produced from the renewable energy resources was hydropower. Then, we experience the drive through the developed world to invest in especially wind energy

Table 1 Global electricity production from renewable resources (International Energy Agency 2020) (The table is in TWh)

Years	Hydropower	Wind	Solar PV	W + PV	Other Renewables	Non-hydro renewables	Total
2010	3448	342	32	376	381	755	4204
2015	3894	834	250	1084	545	1629	5523
2016	4043	963	330	1292	591	1884	5926
2017	4072	1133	444	1577	622	2199	6270
2018	4210	1273	554	1828	660	2488	6698
2019	4246	1428	680	2108	670	2779	7024
2020	4330	1606	838	2444	712	3156	7486
2022	4398	1790	982	2772	782	3553	7952
2023	4504	1973	1136	3108	814	3923	8427
2024	4606	2340	1464	3803	883	4687	9293
2025	4649	2542	1635	4177	918	5095	9743

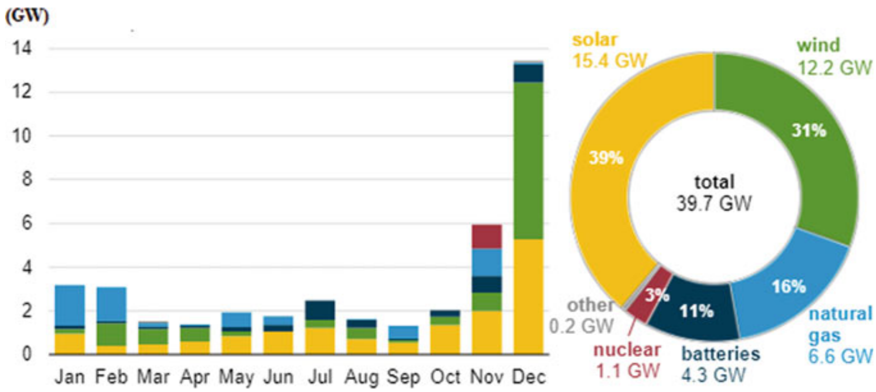


Fig. 1 Planned US. Electricity generating capacity investments in 2021 (U.S. Energy Information Administration 2020)

and solar energy, dominantly in the form of photovoltaics. In 2010, they accounted for less than 9% of the global electricity production with a total of 376,000 GWh.

In 2017, the total global electricity production was about 22,500 TWh. In the same year total electricity produced from the renewable technologies accounted for 6270 TWh representing 27% of the total global electricity production. We should note that the order of installed capacities in terms of percentages produced, started with coal, followed by natural gas, then hydropower, wind and solar PV and finally nuclear power.

For the coming five years period, almost all the electricity demand increase are expected to be met by renewable resources.

It is expected that by 2024, hydro will lose its dominance among the renewables and its share will drop below 50% and in 2025 wind and solar PV together will overtake the hydropower production. Figure 1 gives the latest on new electricity production distribution by resources in the USA (U.S. Energy Information Administration 2020).

Of the total 39.7 GW, solar will be 15.4 GW, making up the largest share at 39%, followed by wind with 12.2 GW at 31% (U.S. Energy Information Administration 2020). In addition, EIA expects the battery power of 4.3 GW at the end of battery power capacity additions are slated to come online by the end of 2021.

In 2019, U.S. annual energy consumption from renewable sources exceeded coal consumption for the first time since before 1885, according to the EIA (U.S. Energy Information Administration 2021).

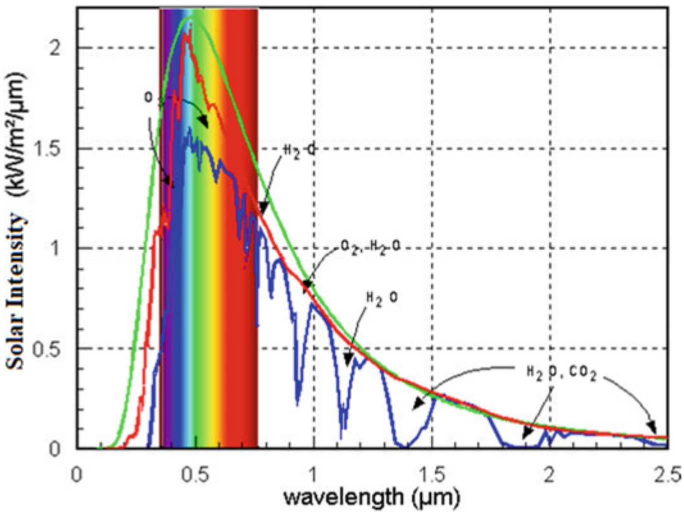


Fig. 2 Terrestrial solar radiation and absorption in the atmosphere (Honsberg and Bowden 2019)

2 A Look Solar Radiation and Carbon Dioxide Emissions

2.1 Solar Radiation

The major heat source for the Earth is solar radiation. Solar radiation travels to the Earth without the loss of any of its energy. Once it enters the Earth's atmosphere, the solar radiation is attenuated due to various atmospheric effects or mechanisms. The distribution of solar radiation in terms of wavelength is shown in Fig. 2.

The graph given in Fig. 3 compares global surface temperature changes (red line) and the Sun's energy received by the Earth (yellow line) in watts per square meter since 1880. Starting from 1950s we observe a drop in solar radiation reaching the Earth, amounting to at least 0.8 W/m^2. It may look like it is merely 0.6% in a 70-year span, but the evidence is indicating an alarmingly increasing drop especially from the beginning of the twenty-first century.

2.2 Carbon Dioxide Emissions

Gases that trap heat in the atmosphere are called greenhouse gases. CO_2 is the principal greenhouse gas. When it is emitted, it will stay in the atmosphere for a long time up to 300–1000 years. The global carbon cycle involves billions of tons of carbon in the form of CO_2. Carbon dioxide is absorbed by oceans and living biomass and is

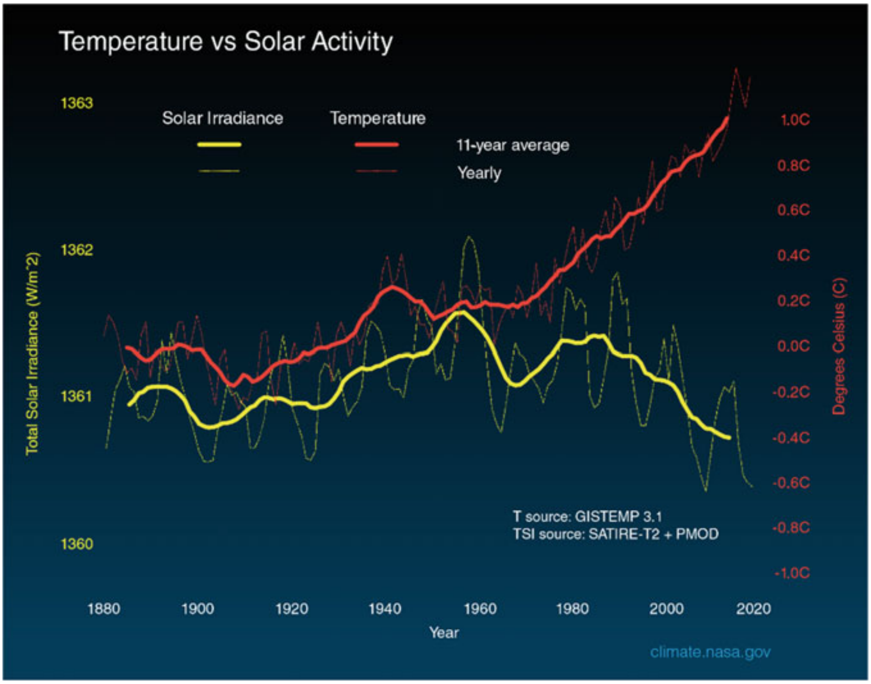


Fig. 3 Global surface temperature changes (°C) and the sun's energy received by the earth (W/m^2) Since 1880 (NASA 2020)

emitted to the atmosphere annually through natural processes. When in equilibrium, carbon movement among these various reservoirs is roughly balanced.

On April 3 of this year, the concentration of atmospheric carbon dioxide was measured at more than 420 parts per million at the Mauna Loa Observatory on the Big Island of Hawaii (Halverson et al. 2021). This is a clear sign that doubling of carbon dioxide will be reached at a much earlier date than previously envisaged.

The Mauna Loa Observatory has been measuring carbon dioxide since 1958. Figure 4 shows the recent measurements of CO_2 in the Mauna Loa Observatory. The dashed red line in the figure represents the monthly mean values; the black line shows the same data after the seasonal effects have been averaged out (Global Monitoring Laboratory 2021).

Carbon dioxide levels today are higher than at any point in at least the past 800,000 years (Voiland 2019; Woods Hole Oceanographic Institution 2015; Lindsey 2020). Figure 5 gives the CO_2 levels going back almost 800,000 years. As indicated on the figure, CO_2 was never higher than 300 ppm before 1950. The increase (orange dashed line) from 1950 onwards looks virtually instantaneous considering the time span (Global Monitoring Laboratory 2021).

Carbon dioxide enters to the atmosphere by several processes. Two of the most significant processes are given below:

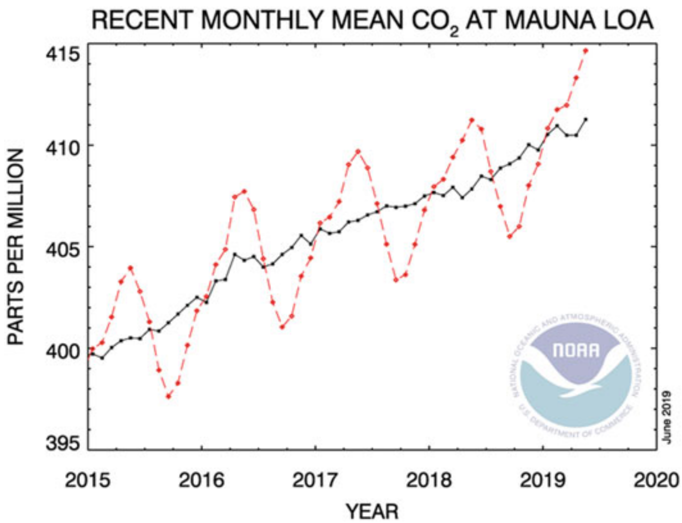


Fig. 4 Recent CO_2 measurements at Mauno Loa Observatory in Hawaii (Global Monitoring Laboratory 2021)

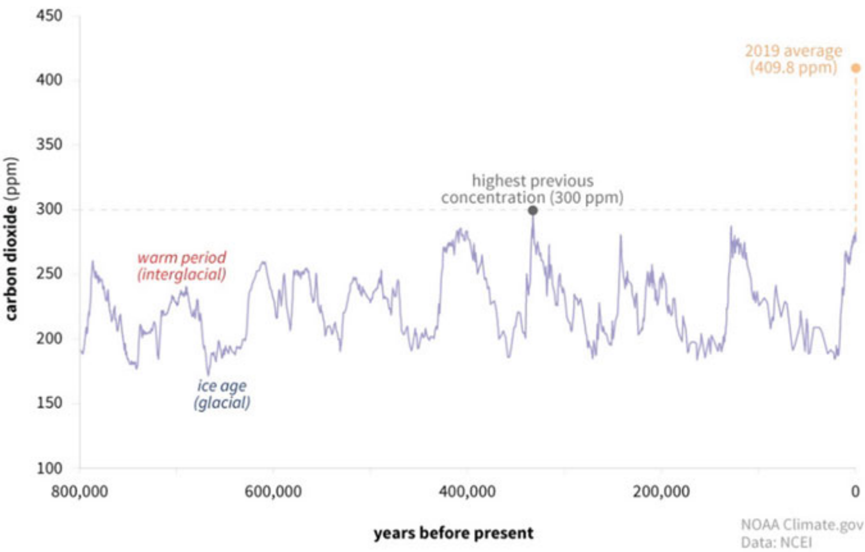


Fig. 5 Atmospheric CO_2 concentration for the last 800,000 Years (Global Monitoring Laboratory 2021; Lindsey 2020)

1. The most prolific CO_2 emissions are due to burning of fossil fuels in residences, power sector and transportation sectors.
2. Land-use change CO_2 emissions. Deforestation causes most of the CO_2 emissions.

About half of the CO_2 emitted since 1850 remains in the atmosphere. The rest of it has partially dissolved in the world's oceans. While the terrestrial biosphere is currently also a sink for fossil fuel CO_2, the cumulative emissions of CO_2 from land use changes such as deforestation cancel terrestrial uptake over the 1850–2018 period (Friedlingstein et al. 2019; Voiland 2021).

Figure 6 shows the heating influence of the greenhouse gases. Accordingly, annual greenhouse gas index has increased approximately 45% from 1990 to 2019 and increases in atmospheric carbon dioxide is responsible for about two-thirds of the total energy imbalance that is causing Earth's temperature to rise.

With the human related carbon dioxide emissions starting to increase with industrial revolution in 1750, it gradually arose to 2 billion tons in the beginning of twentieth century. As it can be seen from Fig. 7 to about 5 billion tons a year in the mid-twentieth century and to more than 35 billion tons per year by the end of the century (Global Monitoring Laboratory 2021) .

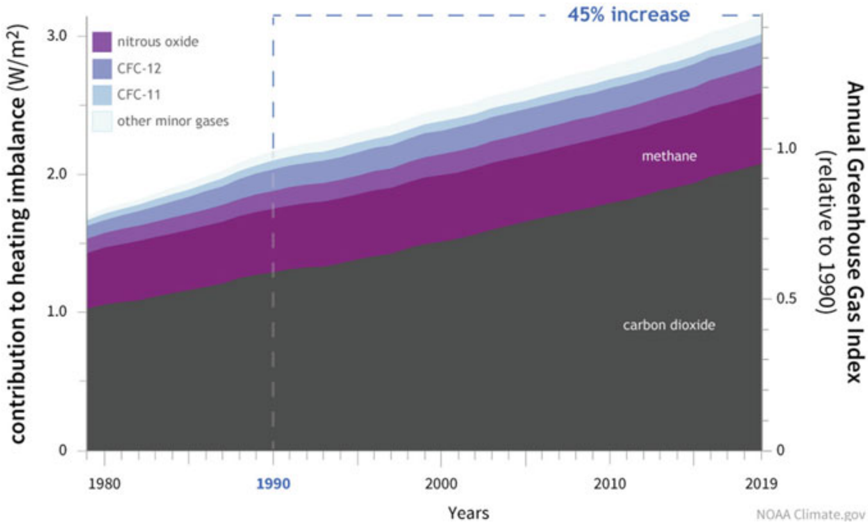


Fig. 6 Combined Heating Influence of Greenhouse Gases (Global Monitoring Laboratory 2021; Voiland 2019; Lindsey 2020)

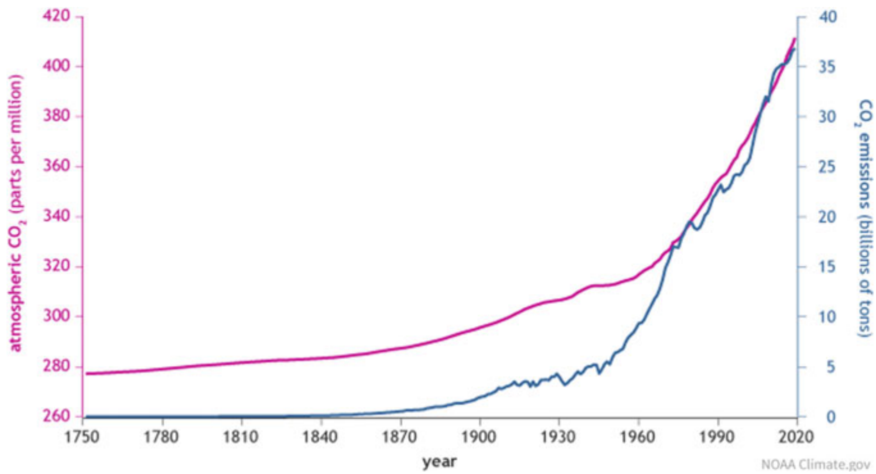


Fig. 7 CO_2 in the atmosphere 1750–2020 (Global Monitoring Laboratory 2021; Lindsey 2020)

3 Global Warming and Turkey

3.1 Introduction

Turkey is strategically located at the southeast corner of Europe, a continent which has seen the industrial revolution, two world wars and massive movement of people throughout the centuries and it is only natural that it is experiencing the global warming and climate change effects at high levels. Turkey is also blessed with ample renewable sources including solar radiation, hydropower, wind energy and geothermal energy.

Parallel to the CO_2 increase, the world is also getting warmer. Thermometer readings around the world have been rising since the Industrial Revolution, and the causes are mostly of human activities. According to an ongoing temperature analysis conducted by scientists at NASA's Goddard Institute for Space Studies (GISS), the average global temperature on Earth has increased by a little more than 1° Celsius since 1880. Two-thirds of the warming has occurred since 1975, at a rate of roughly 0.15–0.20 °C per decade (NASA 2020).

The global temperature record represents an average over the entire surface of the planet. The temperatures we experience locally and in short periods can fluctuate significantly due to predictable cyclical events (night and day, summer, and winter), hard-to-predict wind and precipitation patterns. However, the global temperature mainly depends on how much energy the planet receives from the Sun and how much it radiates back into space—quantities that should change little.

The line plot in Fig. 8. shows yearly temperature anomalies from 1880 to 2019 as recorded by NASA, NOAA, the Berkeley Earth research group, the Met Office Hadley Centre (United Kingdom), and the Cowtan and Way analysis [Kevin Cowtan

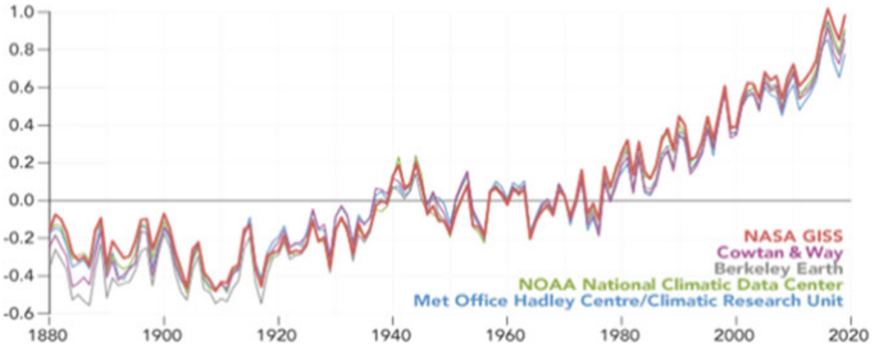


Fig. 8 Yearly temperature anomalies recorded and predicted by five different organizations and groups with the global baseline temperature level taken as from 1951 to 1980 (NASA 2020)

and Robert Way, Department of Chemistry, University of York, 2014]. Though there are minor variations from year to year, all five records show peaks and valleys in sync with each other. All show rapid warming in the past few decades, and all show the last decade as the warmest (NASA 2020).

Table 2 shows the monthly average and the annual average of temperatures in Turkey (Stat World 2020).

From 1951 to 1980, which were taken as Global Baseline temperature levels.

We have plotted global temperature anomalies for the Earth starting from 1923 (Fig. 9), the foundation year of Turkish Republic and 2020 (Fig. 10). We have also given the corresponding monthly average mean temperature values and the yearly averages.

Figure 11, on the other hand gives the anomalies over the years. As it is evident from the figure, the anomalies are on the rise for many years.

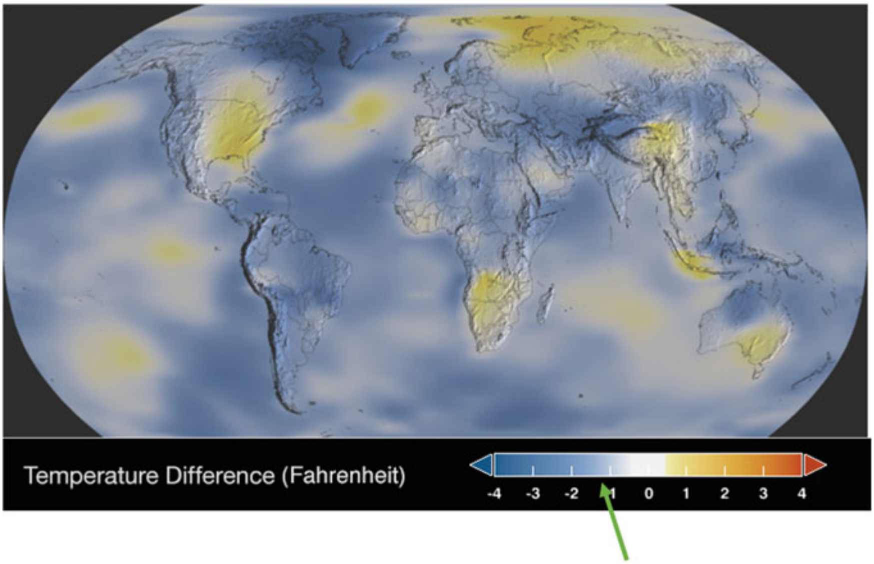
In terms of anomalies, there seems to be some difference between the General Directorate of Turkish State Meteorological Service measurements and NASA graphs. We should note that while NASA uses as the basis of anomalies the years starting from 1950 to 1981; the General Directorate of Turkish State Meteorological Services uses 1981 to 2010. Regardless of what is taken as base anomaly, they both indicate steady warming in the last twenty years.

3.2 Mean Average Temperatures in Turkey

Mean average surface temperatures for Turkey from 1971 to 2020 is shown in Fig. 12 and the mean temperature anomalies are shown in Fig. 13 (General Directorate of Turkish State Meteorological Service 2021). From 1971 to 2019 the average mean areal surface temperature of Turkey is calculated to be 13.5 °C (from here on words areal and surface will be omitted). The figure starts with the warmest year and shows the yearly average values in descending order. For example, 1992 was the coldest

Table 2 Monthly and annual average temperature levels of Turkey from 1951 to 1980 (Stat World 2020)

Year	January (°C)	March (°C)	May (°C)	July (°C)	September (°C)	November (°C)	Yearly average (°C)
1951	+1.91	+8.13	+15.66	+22.71	+19.26	+8.31	+12.06
1952	+1.17	+4.80	+14.31	+22.57	+21.35	+8.70	+12.53
1953	+2.96	+1.66	+14.63	+22.96	+18.37	+4.81	+11.09
1954	−1.73	+5.80	+15.26	+24.06	+19.62	+9.08	+12.04
1955	+3.61	+6.77	+15.71	+22.94	+19.34	+8.36	+12.97
1956	+2.07	+2.65	+13.79	+22.54	+17.45	+6.57	+11.14
1957	−1.52	+5.87	+14.15	+23.04	+20.65	+8.02	+12.16
1958	+2.33	+6.68	+16.39	+22.08	+17.96	+7.92	+12.27
1959	+2.67	+4.35	+14.99	+22.77	+16.43	+7.50	+11.18
1960	+2.84	+5.30	+16.31	+22.53	+19.01	+9.98	+12.58
1961	+1.03	+4.59	+16.29	+22.76	+16.83	+8.82	+12.08
1962	+1.87	+8.30	+16.31	+23.70	+19.55	+11.45	+13.12
1963	+3.32	+4.00	+14.04	+22.77	+19.45	+8.93	+12.28
1964	−3.37	+6.23	+14.09	+22.44	+18.12	+8.06	+11.27
1965	+1.21	+6.32	+14.74	+22.59	+19.36	+7.84	+11.67
1966	+4.16	+6.81	+14.79	+23.52	+18.56	+11.69	+13.41
1967	+0.31	+3.94	+15.04	+21.73	+18.32	+7.13	+11.02
1968	−0.67	+4.88	+17.21	+22.76	+18.65	+9.13	+11.93
1969	+0.63	+6.29	+16.22	+21.13	+19.25	+8.20	+11.97
1970	+3.47	+7.72	+14.97	+23.28	+18.40	+9.26	+12.55
1971	+3.84	+6.77	+16.01	+22.70	+19.74	+8.04	+11.95
1972	−3.27	+5.12	+14.72	+22.99	+19.28	+7.08	+11.20
1973	−0.85	+4.69	+15.65	+22.67	+19.52	+5.03	+11.52
1974	−2.33	+6.91	+15.41	+22.34	+17.79	+8.15	+11.62
1975	−0.00	+6.62	+15.03	+23.47	+19.03	+7.13	+11.70
1976	−0.34	+4.19	+14.66	+21.43	+17.69	+9.20	+11.06
1977	−0.49	+5.84	+15.46	+22.66	+18.98	+9.55	+11.95
1978	+1.59	+7.06	+15.62	+23.24	+18.48	+5.71	+12.14
1979	+2.99	+7.86	+15.86	+21.93	+20.01	+9.33	+12.87
1980	−0.31	+5.16	+15.09	+24.23	+17.88	+9.11	+11.98



1923 Temperature Distribution - Turkey

Yr	January	February	March	April	May	June	July	August	Septem	October	Novemb	Decemb	Total
1923	+0.93 °C	+2.60 °C	+5.72 °C	+8.82 °C	+16.07 °C	+20.17 °C	+22.24 °C	+21.21 °C	+19.73 °C	+14.03 °C	+10.27 °C	+5.37 °C	+12.26 °C

Fig. 9 Global temperatures of the earth, 1923 (Global Monitoring Laboratory 2021; Stat World 2020) (We have kept graphs in degrees Fahrenheit because the originals are in degrees Fahrenheit)

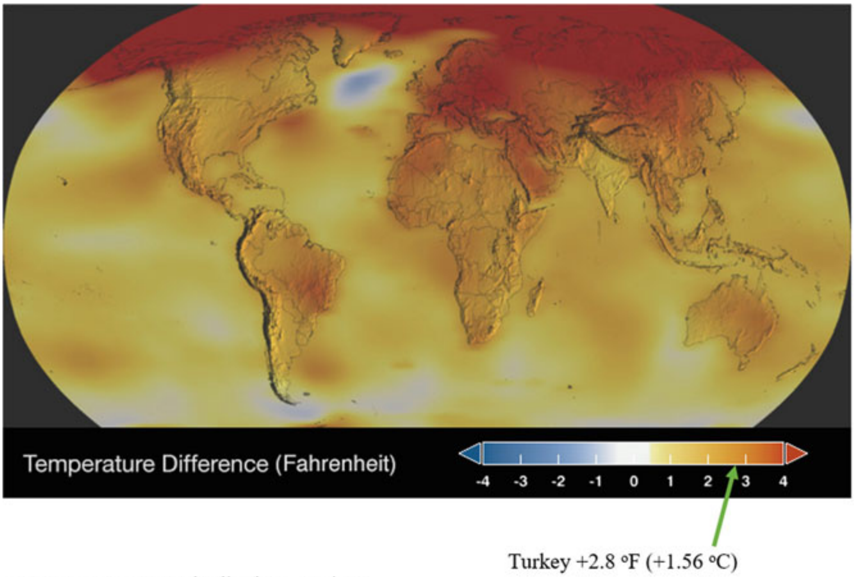
year with annual average 11.8 °C. The four warmest years recorded are 2010 with 15.6 °C, 2018 with 15.4 °C, 2020 with 14.9 °C (not shown in the graph), 2014 with 14.8 °C and 2019 with 14.7 °C.

According to the 2020 Assessment Report of the Climate of Turkey, published in January 2021, fourteen of the warmest years have occurred since 2000, with the exception of 2011. The warmest years were 2010 and 2018 (Figs. 12 and 13). The anomalies indicate upward trend in temperature scale. We can say, starting with 1998 with the exception of 2011, positive temperature anomalies exist in Turkey. The hottest year on the record is 2010 with a positive anomaly of +2.0 °C.

Distribution of the mean temperature anomalies geographically in Turkey, which is given in Fig. 14. Eastern Turkey has lower anomalies even with few sub-regions indicating negative anomalies, whereas Western Turkey indicate higher temperature anomalies.

Figure 15 on the other gives the monthly distribution of the mean temperatures and anomalies for 2020 together with the baseline values of 1981–2010. Accordingly, the highest mean temperatures are observed in July and August. However, the anomalies are highest for the months of September and October followed by March and December (General Directorate of Turkish State Meteorological Service 2021).

Global warming is also happening over the seas surrounding Turkey. Based on the General Directorate of Turkish State Meteorological Service's annual reports,



2020 Temperature Distribution - Turkey

Jan	Feb.	March	Apr	May.	June	July	Aug.	Sep	Oct	Nov	Dec	Total
3.3	4.9	9.5.	12.1	17.6	21.7	25.9	25.2	23.9	18.4	9.6	7.2	14.9

Fig. 10 Global temperatures of the earth, 2020 (Global Monitoring Laboratory 2021; Stat World 2020)

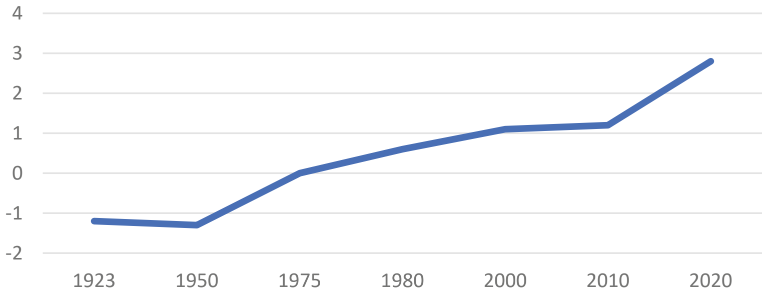


Fig. 11 Distribution of temperature anomalies for Turkey 1923–2020 (Estimated) (Stat World 2020)

the latest sea temperatures available are from the year 2017 and they are shown in Table 3 (General Directorate of Turkish State Meteorological Service 2016, 2018, 2021).

Accordingly, the sea temperatures are steadily rising together with the land temperatures. We see from Fig. 12 that the mean temperature for the land was measured to be 14.1 °C for the year 2017. Corresponding mean sea temperatures for the four seas surrounding Turkey, the arithmetic mean seawater temperature is 18.0 °C. The

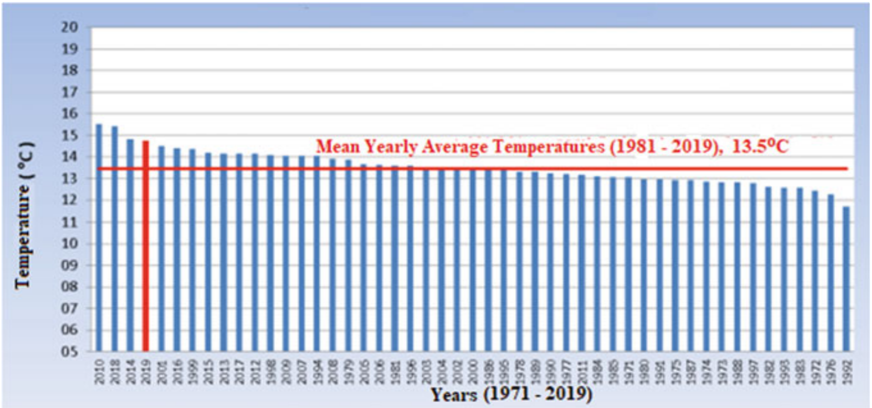


Fig. 12 Mean yearly average temperatures recorded in Turkey (1971–2019) (General Directorate of Turkish State Meteorological Service 2021)

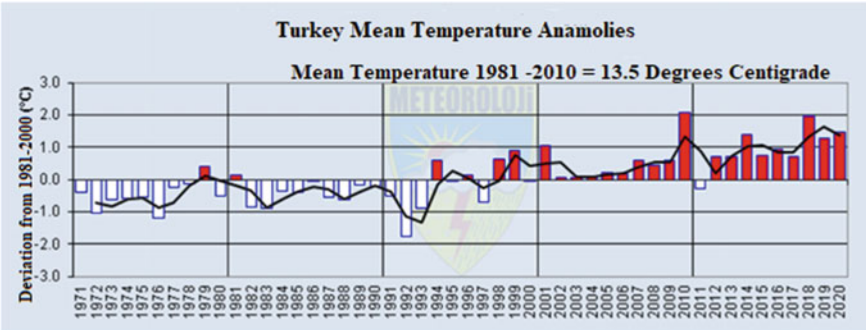


Fig. 13 Distribution of temperature anomalies for Turkey 1971–2020, based on local measurements and base temperatures of 1981–2020 (General Directorate of Turkish State Meteorological Service 2021)

temperature of the Sea of Marmara increased more than 0.6 °C in 2017, followed by the Black Sea and Mediterranean Sea 0.3 °C each and the Aegean Sea 0.2 °C. The anomaly on the seawater temperature for 2017 was 0.35 °C.

It is quite difficult to give the areal mean temperatures of the seawater temperatures because the surface areas of those seas with the exception of Sea of Marmara is difficult to assess. However, we think the anomaly value is correct for the Aegean and Eastern Mediterranean.

It is also interesting to note that there is more than 11.5 °C difference for the coldest and the warmest seawater temperatures in the Mediterranean and the Aegean seas. This difference goes up to 15 °C in the Sea of Marmara and Black Sea.

In order to see the effect of global warming on the seawater temperatures, let us look at Table 4. Table 4 shows the sea temperatures for the Aegean Sea in 2017 and

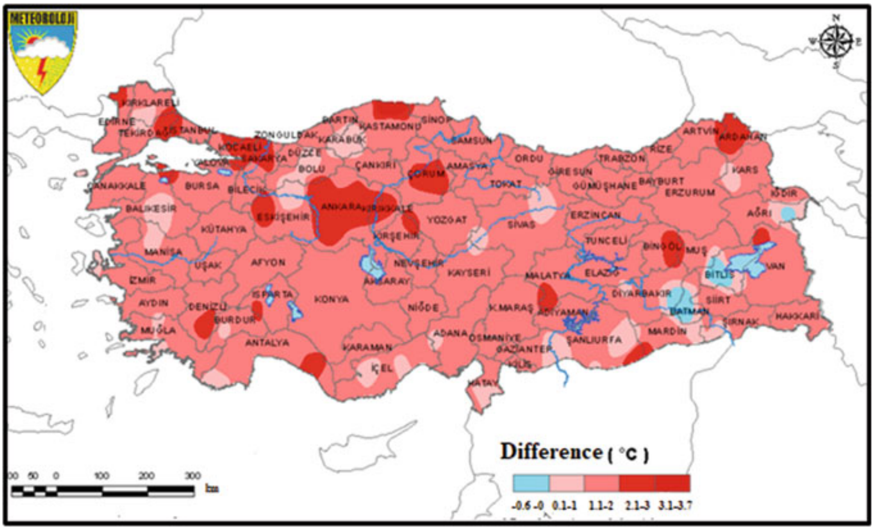


Fig. 14 Geographical distribution of mean temperatures in Turkey (General Directorate of Turkish State Meteorological Service 2020, 2021)

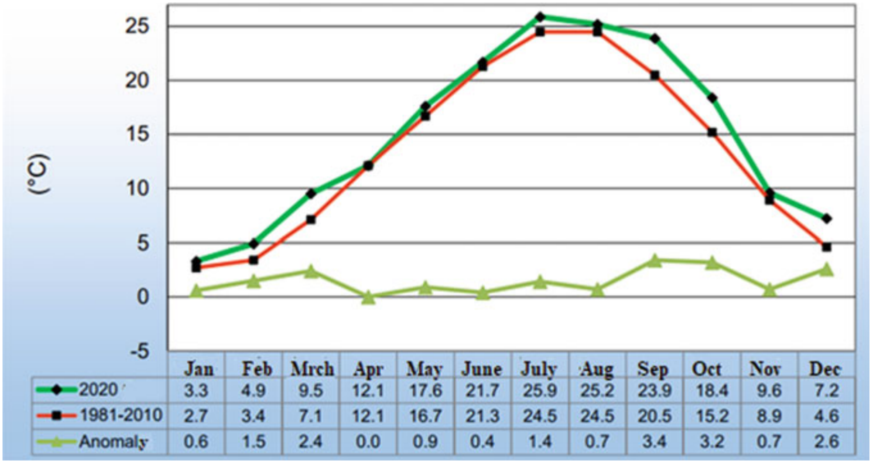


Fig. 15 Monthly distribution of the mean temperatures and anomalies for 2020 together with the baseline values of 1981–2010 (General Directorate of Turkish State Meteorological Service 2021)

2019 and gives the areal surface temperatures for Turkey. The reason Aegean Sea values were selected is because this region has the highest wind potential in Turkey. It is quite apparent that both the surface and seawater temperatures are in the rise. Seawater temperatures have gone up from 18.5 to 18.7 °C for the year 2017 and to

Table 3 Long term and 2017 sea water temperatures of Turkey (General Directorate of Turkish State Meteorological Service 2018, 2021)

Mediterranean	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ave
1970–2017 Ave	16.4	15.7	16.4	18	20.6	23.8	27	27.9	26.9	24.3	21.1	18.3	21.3
2017	16.3	15.9	16.5	18	20.5	23.8	27	27.9	28.1	24.5	21.9	19.4	21.6
Aegean Sea	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ave
1970–2017 Ave	13.7	13.2	13.9	15.8	18.7	22	24	24.4	24.4	21.2	18.4	16.6	18.5
2017	13.7	13.2	13.9	15.8	18.7	22	24	24.4	23.1	20.6	17.8	15.4	18.7
Marmara Sea	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ave
1970–2017 Ave	9	7.9	8.4	11	15	19.8	23	24	22	18.6	14.9	11.7	15.5
2017	8.5	8	9.6	12.6	16.3	20.7	23	24	22.6	19.5	15.5	13.5	16.1
Black Sea	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ave
1970–2017 Ave	9	7.8	8	9.9	13.7	18.9	23	24.1	22.3	18.9	15.1	11.6	15.2
2017	8.8	7.2	8.3	10.2	13.7	19.5	23	24.1	24.4	19.5	15.5	11.8	15.5

19.2 °C for 2019. Similarly, areal mean surface temperatures have risen to 14.3 and 14.7 °C in 2019.

The figure also shows the difference between the seawater and land temperatures which drives the wind energy potential on the coastline. We see that monthly differences vary together with diurnal variation (not shown here). In 2017, there were four months during which mean areal surface temperatures were higher than seawater temperatures; in 2019 only in June, mean areal surface temperature exceeded the seawater temperature. A clear indication that wind energy potentials have changed together with the direction of the wind.

3.3 *Extreme Meteorological Events Occurring in Turkey*

The International Federation of Red Cross and Red Crescent Societies (IFRC) defines natural hazards as naturally occurring physical phenomena caused either by rapid or slow onset events. Such events can be geophysical (earthquakes, landslides, tsunamis and volcanic activity), hydrological (avalanches and floods), climatological (extreme temperatures, drought and wildfires), meteorological (cyclones and storms/wave surges) or biological (disease epidemics and insect/animal plagues).

Most of the natural disasters are either climatological or meteorological in nature that may likely result in injuries or deaths and extremely high economic losses. Here, we will concentrate on the extreme meteorological events in order to rule out the disasters of all events. Of course, certain extreme meteorological events may also cause destruction, loss of life and high economic losses immediately. However, some extreme meteorological events may affect our lives in later times. General

Table 4 Long term, 2017–2019 sea water temperatures of Aegean Sea and 2017–2019 mean yearly average surface temperatures of Turkey (General Directorate of Turkish State Meteorological Service 2018, 2021)

Aegean sea	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ave
1970–2017 Ave	13.7	13.2	13.9	15.8	18.7	22	24	24.4	24.4	21.2	18.4	16.6	18.5
2017	13.7	13.2	13.9	15.8	18.7	22	24	24.4	23.1	20.6	17.8	15.4	18.7
2019	14.3	13.8	14.4	16.2	18.9	21.7	24.2	25.4	24.3	21.4	18.8	16.4	19.2
1981–2010 Ave	2.7	3.4	7.1	12.1	16.7	21.3	24.5	24.5	20.5	15.2	8.9	4.3	13.5
2017 Land	1.8	3.6	7.9	12.0	17.5	22.7	26.3	26.0	23.2	15.0	9.0	7.0	14.3
2019 Land	4.2	5.2	8.0	12.2	18.0	23.5	24.2	25.0	21.6	17.0	11.8	6.8	14.7
2017 ($T_{mast} - T_{swt}$)	−12.9	−9.6	−6.0	−3.8	−1.2	0.7	2.3	1.6	0.1	−5.6	−8.8	−8.4	−4.4
2019 (T_{mast} -T_{swt})	−10.1	−8.6	−6.4	−4.0	−0.9	1.8	0	−0.4	−2.7	−4.4	−7.0	−9.6	−4.5

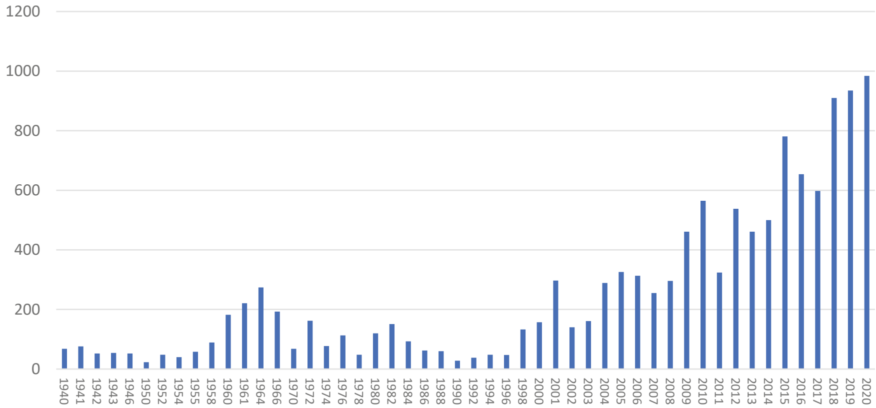


Fig. 16 Meteorological events that have occurred from 1940 to 2020 (General Directorate of Turkish State Meteorological Service 2021)

Directorate of Turkish State Meteorological Service also uses this approach in their annual reports.

According to the IPCC, an increase in the average global temperature is likely to lead to changes in precipitation and atmospheric moisture. Increased temperatures cause changes in atmospheric circulation and increase evaporation and water vapor, resulting in precipitation increases, more intense precipitation, more storms and sea level rise (Collins et al. 2013).

Starting from 1940, extreme meteorological events are being recorded in Turkey (General Directorate of Turkish State Meteorological Service 2016, 2021; Ministry of Environment and Urbanization 2016). Figure 16 gives the meteorological events that have occurred in Turkey from 1940 to 2020.

We see that the lowest number of extreme meteorological events witnessed in Turkey corresponds to 23 in 1950, in the era when meteorological event counting began in 1940. The extreme meteorological events exceeded 100 for the first time in 1957, 300 extreme events were first recorded in 1963, 500 extreme events in 2010 and 900 extreme meteorological events in 2018. The highest extreme meteorological number of events to this date have occurred in 2020.

The distribution of the meteorological events for 2015 and 2020 are given in Figs. 17 and 18, respectively. A comparison of these two figures show that heavy rainfall, flooding, and storms are the two leading extreme meteorological events followed by hail. Those three together make up 63% of the events in 2015 and 80% of the events in 2020.

We should emphasize once more that, these are the extreme meteorological events that will affect the renewable energy efficiencies and production the most.

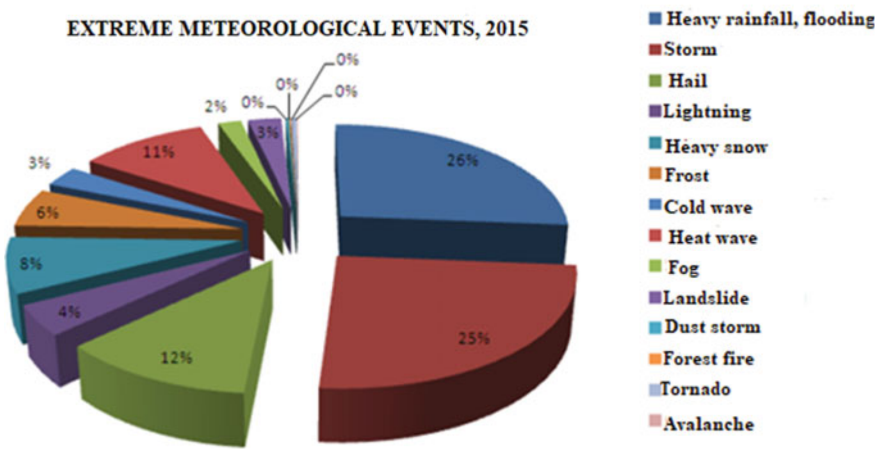


Fig. 17 Distribution of extreme meteorological events in 2015 in Turkey (General Directorate of Turkish State Meteorological Service 2016)

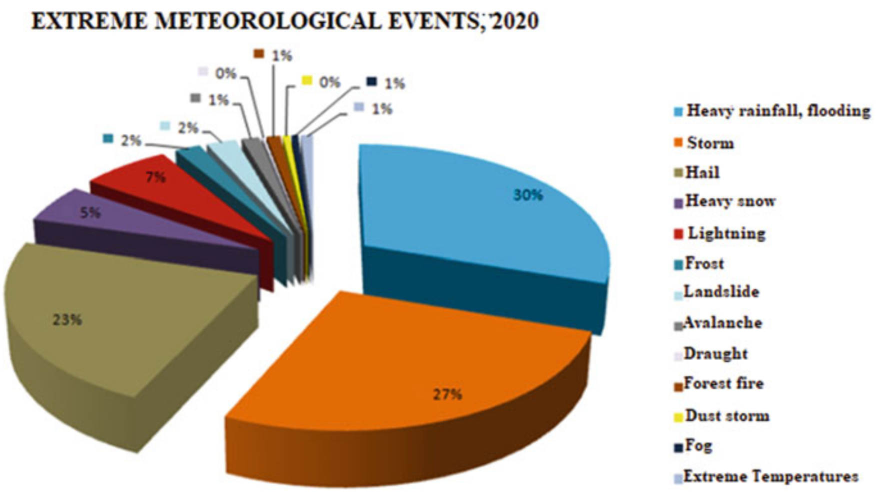


Fig. 18 Distribution of extreme meteorological events in 2020 in Turkey (General Directorate of Turkish State Meteorological Service 2021)

4 Global Warming and Renewable Energy Resources of Turkey

4.1 Introduction

As was previously stressed, Turkey is blessed with ample renewable resources including solar energy, wind energy, hydraulic energy, and geothermal energy. With global warming, everyone is concerned with CO_2 emissions and the accumulation of CO_2 in the lower layers of atmosphere. It looks as if; the negative effect of CO_2 on the supply side is being ignored or taken lightly. This work, from the beginning is trying to point out the significance of the climate on the renewable energy resources.

When we speak of whether or not Turkey is ready for 100% renewable energy system, we are asking whether all the electrical power requirement can be met by renewable energy resources. In order to understand and explore the possibility, we will look at electrical power production process and the available options first.

Then we will explore how the climate change we are experiencing now affects the electricity production from the renewable resources. We should expect the impact of the climate change at all stages including the potential, production, distribution, and transmission.

4.2 A Short Look at Electrical Energy Production

Global electricity consumption continues to increase faster than world population, leading to an increase in the average amount of electricity consumed per person (per capita electricity consumption), according to the U.S. Energy Information Administration's (EIA) (2021). Electricity is used most commonly in buildings for lighting and appliances, for heating and cooling purposes, in industrial processes for producing goods, and in transportation for powering rail and light-duty vehicles.

As of 2017, the global average for per capita electricity consumption was about 3000 kWh. Growth in global electricity consumption is related to economic growth, but the relationship differs, depending on the country (Fig. 19).

Electricity production is a well-known process (Özil et al. 2012a, b, c, d; BBC 2021). It can be produced from

- Conventional energy resources such as natural gas, coal all of which we identify as combustible fuels,
- Renewable resources,
- Nuclear energy.

Simple electricity production process can be seen from Fig. 20. Conventional energy resources are fossil fuels (coal, oil, and natural gas). Simply the chemical energy is burned to release heat energy, which goes through several steps to generate electricity to generate electricity. Figure 21 gives us the classical flow diagram.

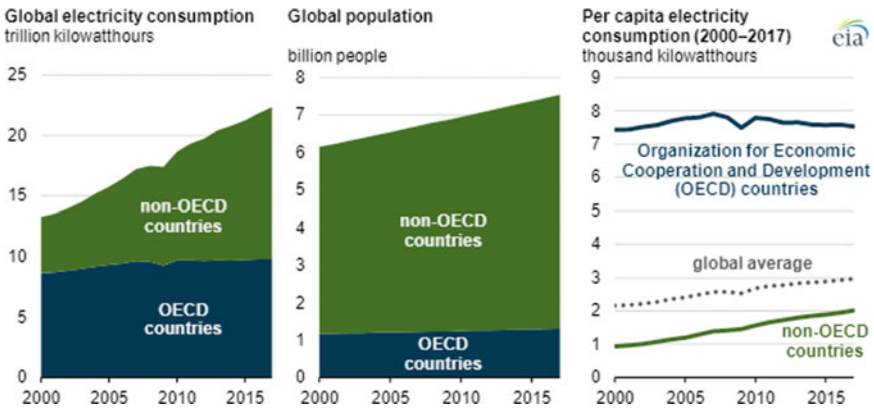


Fig. 19 Global electricity consumption, global population and per capita electricity consumption (U.S. Energy Information Administration 2021)

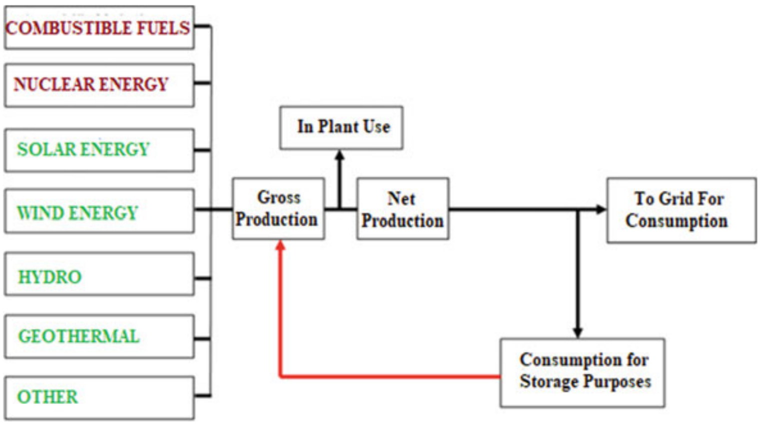


Fig. 20 Simple electricity production process (Özil et al. 2012a, b)

Most renewable energy resources are clean because they do not produce any pollution. They are also inexpensive and they are not in the hands of few nations thereby making them non-political and virtually free.

Among renewable energy options solar energy has a unique characteristic. It can produce electricity in two ways. First method is so called "solar thermal" application in which heat is collected and transferred to a working fluid, usually a special oil, in line or point concentrating solar parabolic or parabolic trough type solar collectors and the heat collected follows the steps given in Fig. 21. The other method is the photovoltaics application, in which solar energy is converted to electricity within the panel.

Figure 22 gives us most of the options for electricity production. Because conven-

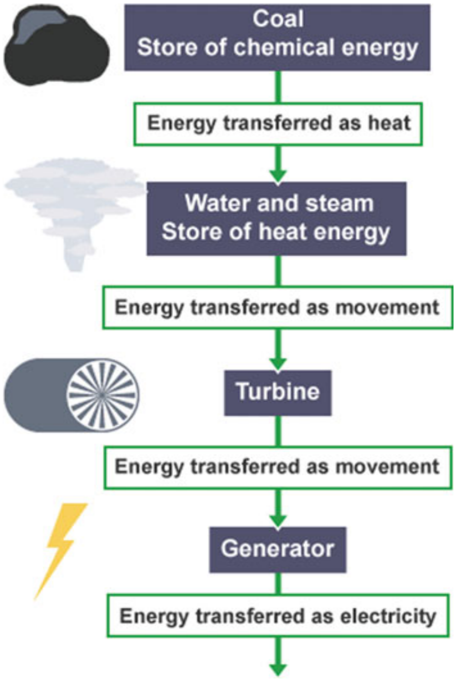


Fig. 21 Electricity production diagram from fossil fuels (BBC 2021)

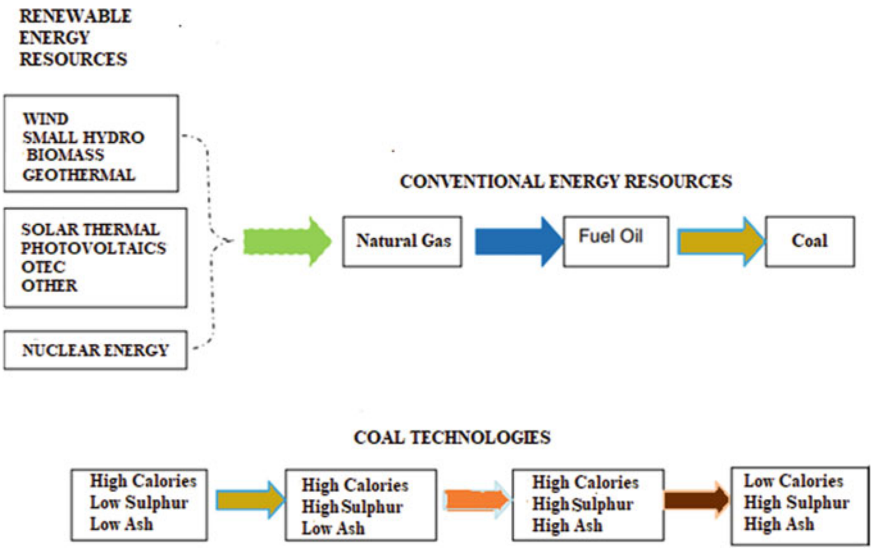


Fig. 22 Electricity production preference chart (Özil et al. 2012b)

Table 5 Electrical power plant emissions according to fuel type (Özil et al. 2012a, b, c, d)

Power plant fuel type	Efficiency	kcal/kg	kg CO_2/kWh
Coal, imported coal, asphaltite	0.36	6000	1.06
Lignite, high quality	0.34	4000	1.39
Lignite, medium quality	0.32	2500	1.77
Lignite, low quality	0.30	1250	2.52
Natural gas	0.45	8250	0.64
Fuel oil	0.3	9600	0.88
Diesel	0.3	10,200	0.78

tional fuels add to CO_2 emissions, they are no longer preferred by developed countries such as USA, European Union, and OECD member countries. However, if we must use the conventional fuels the figure gives the best option (natural gas) and the worst option (low calorie, high ash, and high sulfur content—low quality lignite) and others in between.

Table 5 shows us how bad the electricity produced from conventional energy resources in terms of CO_2 emitted per kWh produced (Özil et al. 2012a, b; Yurtsever 2019). Low quality lignite used in some of the power plants in Turkey, emits approximately 2.52 kg of CO_2 per kWh, whereas electricity produced from natural gas only emits 0.64 kg of CO_2.

Although we know that renewable energies do nor emit any CO_2 emissions, we must consider how much CO_2 was emitted during their production. Especially, photovoltaic cells production may be unexpectedly high and pay back periods in terms of energy should be calculated.

4.3 Global Electrical Energy Production from Renewable Resources

As of the beginning of 2021, global use of solar energy exceeded 760 GW, wind energy 700 GW and hydroelectric power 1324 GW (International Energy Agency 2020). The total installed capacity from the nuclear power, on the other hand, remained below 400 GW (International Energy Agency 2020). At the end of 2020, installed capacity of hydroelectric power was 31,336 MW, wind energy was 9294 MW and solar energy exceeded 7065 MW in Turkey (Enerji Atlası 2021). Although it is not taken up in this work, installed geothermal energy was 1624 MW and bio-energy was 1124 MW.

Figure 23 gives the total electricity production in Turkey over the years by all resources. The distribution among the resources can be seen from Table 6. Coal is the leading electricity producer with a share of about 35.2%. Hydropower follows

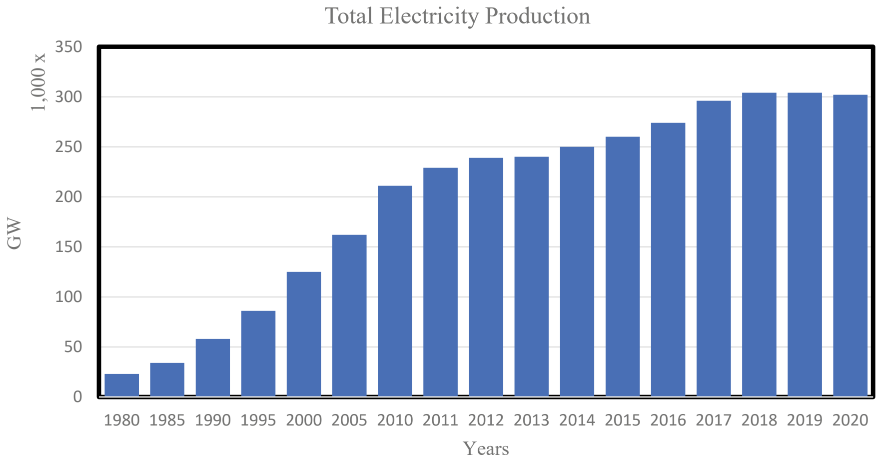


Fig. 23 Electricity production from all resources (1980–2020) in Turkey (Enerji Atlası 2021b)

Table 6 Electricity production from all the sources in 2019 and 2020 in Turkey (Enerji Atlası 2021)

Resource	Electricity produced (TWh)		2020 Percentage (%)
	2019	2020	
Hydropower	88.9	77.9	25.8
Natural gas	56.5	68.0	22.5
Imported coal	60.4	62.5	20.7
Asphaltite. coal and lignite	52.7	43.8	14.5
Wind	21.7	24.6	8.1
Solar	9.6	11.2	3.7
Geothermal	8.9	9.3	3.1
Biogas	4.5	4.3	1.4
Fuel oil and diesel	0.7	0.3	0.1
Total	303.9	301.9	100

the coal with 25.8% and then natural gas with 22.5%. The total electricity produced from the renewables is approximately 41%, totaling to 123,000 MWh.

Electricity production from renewable sources in Turkey over the years is shown in Figs. 24, 25, 26 and 27. We should note that reliable data could not be obtained for the year 2018 for hydropower and it was left out. Similarly, we have retrofitted the data for wind and solar production in 2018. In addition, some of the biogas statistics included consumption of conventional fuels for all the years in question and no distinction was made between the conventional fuels and renewable resources. Thus,

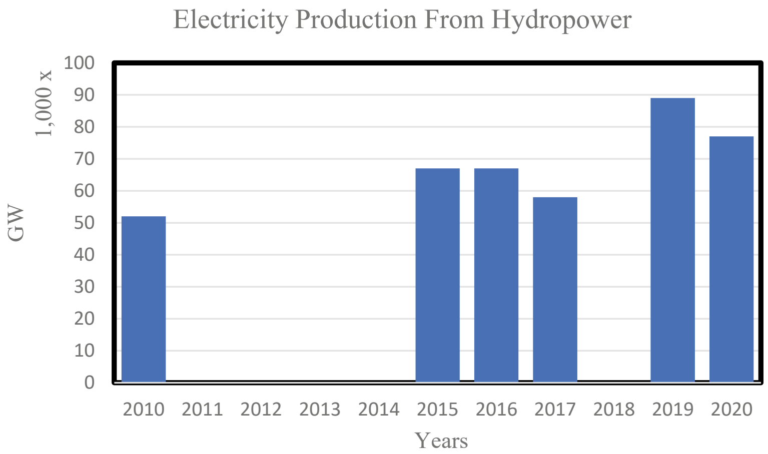


Fig. 24 Electricity production from hydropower (1980–2020) in Turkey (Enerji Atlası 2021c)

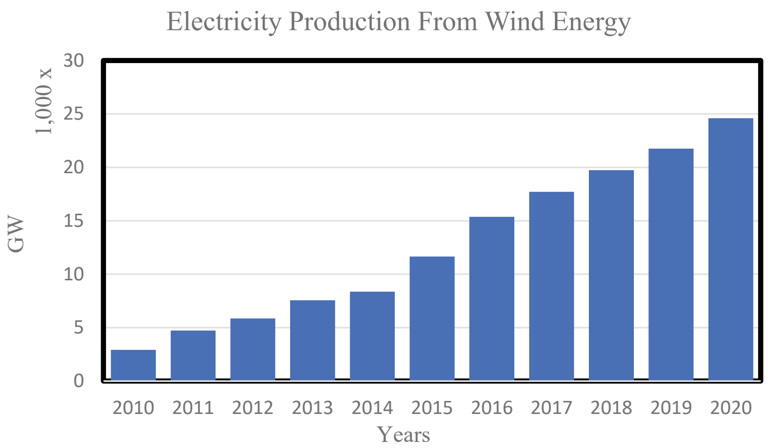


Fig. 25 Electricity production from wind energy (1980–2020) in Turkey (Enerji Atlası 2021d)

biogas was also left out. There is definitely an additional electricity generation from the bio-gas renewable portion, which we estimate it to be around 1–2%.

Table 7 was prepared in the IEA format and is used for comparing the hydropower with wind, solar and other renewable energies. In the year 2010, total electricity produced from the renewables was 55,587 GWh which corresponded to 26.3% of 211,000 GWh of the total production. Among the renewables, hydropower accounted for 93% of the renewable electricity production. In 2015, the share of hydropower dropped to 81.6% followed by wind energy at 14.4%, other renewables (mainly geothermal) approximately 4% and finally solar with a share of 0.2%. In 2020, we see the impact of solar and wind investments on the renewable electrical energy

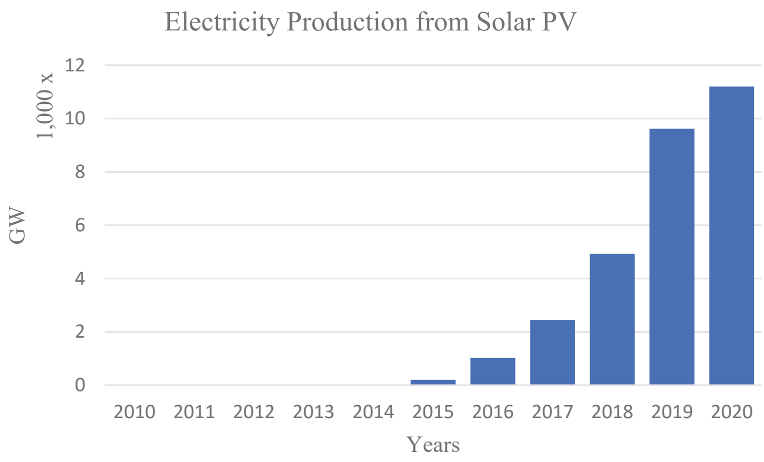


Fig. 26 Electricity production from solar energy (1980–2020) in Turkey (Enerji Atlası 2021e)

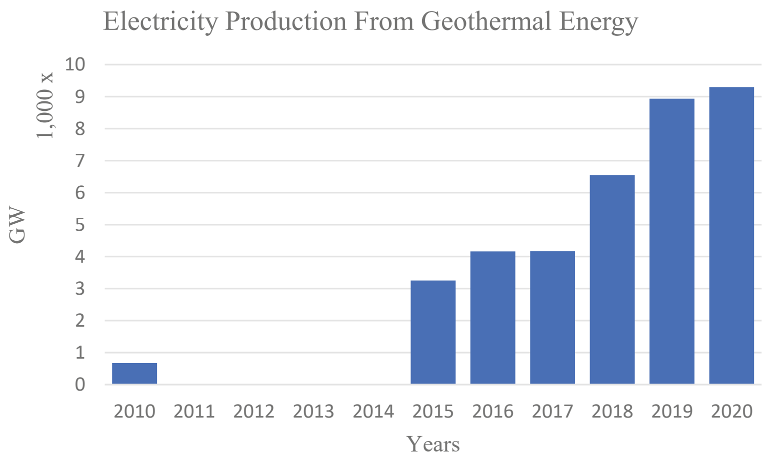


Fig. 27 Electricity production from geothermal energy (1980–2020) in Turkey (Enerji Atlası 2021f)

production. Hydropower is still the leading renewable resource with a share of 63.3%, followed again by wind energy with a share of 20%. For the first time in history, solar energy takes the third spot with 9.1% and geothermal energy completes the list with 7.6%.

Based on the granted energy investment licenses by Energy Market Regulatory Authority of Turkey (EMRA, in Turkish EPDK) and on-going investments, hydropower is expected to go below 50% within the coming three years.

Table 7 Electricity production from renewable resources (2010–2020) in Turkey (Enerji Atlası 2021) (All the figures are in GWh)

Years	Hydropower	Wind	Solar PV	W + PV	Other renewables	Non-hydro renewables	Total
2010	52,000	2916	0	2916	671	3587	55,587
2015	67,000	11,652	194	11,846	3250	15,096	82,096
2016	67,000	15,370	1020	16,394	4160	20,554	87,554
2017	58,000	17,716	2439	20,455	4164	24,619	82,619
2019	89,000	21,750	9620	31,370	8937	40,307	129,307
2020	77,900	24,600	11,200	35,800	9300	45,100	123,000

4.4 Theoretical Energy Potentials of Renewable Energies in Turkey

There are a number of studies made by several researchers in Turkey on the theoretical potentials of Turkey. Naturally, measurements made by General Directorate of Turkish State Meteorological Service weather stations and their calculations dictate a more precise potential data for hydropower, wind energy and solar energy. We shall here mainly use the Turkish State Meteorological Service and those given or calculated by the authors.

4.4.1 Solar Energy

Turkey is blessed with plenty of sunshine in the summers and throughout the year. Figure 28 gives the long-term averages from 1994 to 2018. The direct irradiance received on a plane normal to the sun over the total solar spectrum is defined as direct normal irradiance (DNI) and the figure essentially shows the DNI over Turkey. The map is also utilized for PV application in Turkey and has been published by the Energy Sector Assistance Program of the World Bank (ESMAP). We see that daily totals vary from 2.8 to 6.4 kWh/m^2 and the range for yearly totals is from 1022 to 2337 kWh/m^2-year. Figure 29, on the other hand, hourly values vary between 1145 to 1875 kWh/m^2 in all of Turkey. With the exception Eastern Black Sea coastline, all of Turkey daily receives over 3 kWh/m^2. This can also be observed from Fig. 30, which shows the availability of solar radiation in the Eastern Mediterranean and Turkey. As expected, the potentials are similar in both regions with the exception of Northern Turkey. In terms of solar PV applications, all regions of Turkey can be utilized. However, realistically speaking economics of investment would be quite favorable in Regions I and II of Turkey as shown in Fig. 31.

Remembering from the previous section that, the installed of solar energy exceeded 7065 MW. In 2020, there is an ample solar energy potential available for electrical energy production.

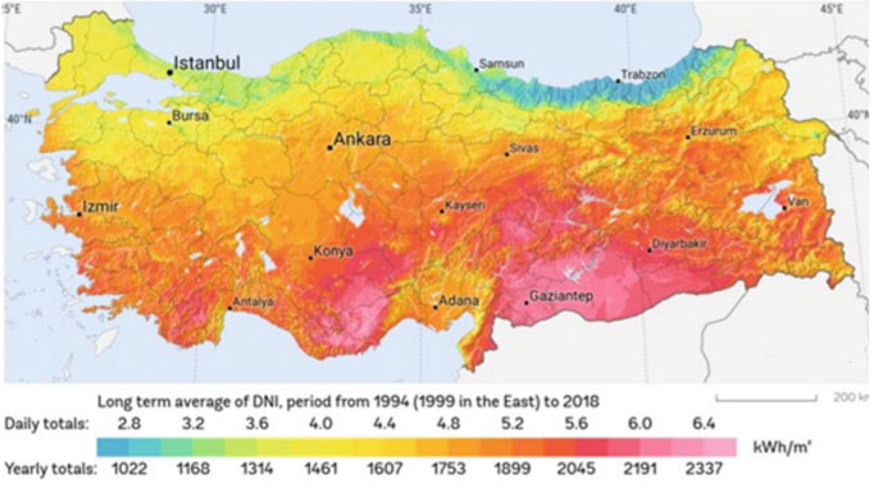


Fig. 28 Long term average direct normal irradiance over Turkey (1994–2018) (General Directorate of Turkish State Meteorological Service 2020, 2021; ESMAP 2019)

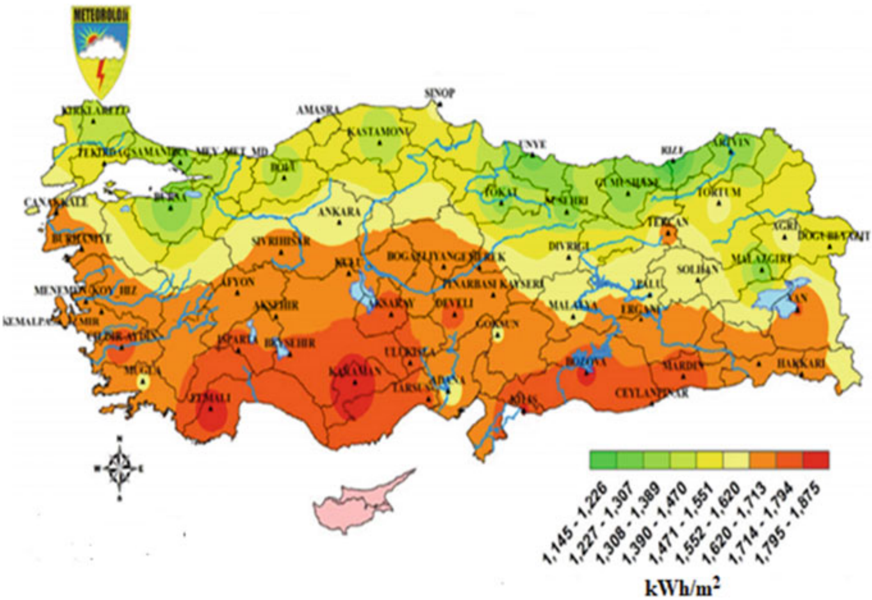


Fig. 29 Long term averages of hourly direct normal irradiance over Turkey (General Directorate of Turkish State Meteorological Service 2021)

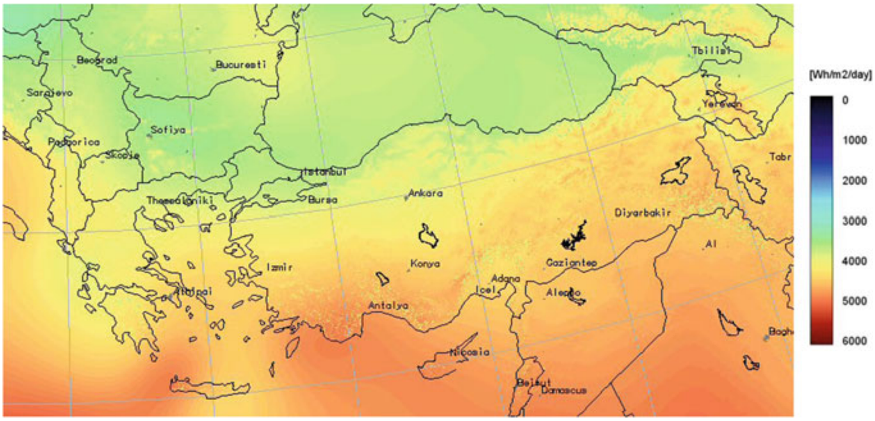


Fig. 30 Availability of solar radiation for the eastern mediterranean and Turkey (Hoyer-Klick et al. 2011)

4.4.2 Wind Energy

According to the Republic of Turkey Ministry of Energy and Natural Resources data, the wind potential of Turkey is given in Fig. 32 (Özil et al. 2012d; Turkish State Ministry of Energy and Natural Resources 2021). As it can be seen from the graph, Turkey is surrounded by Mediterranean Sea, Aegean Sea, the Sea of Marmara, and Black Sea. Since wind energy scales have the cube of wind speed, slight changes in wind profiles can significantly affect the extractable energy output. To summarize wind power in Turkey's current climate especially Turkey's location in mid-latitudinal areas on the Earth produces a strong seasonal cycle in wind resources and their variability (Ohba 2019). Wind energy increases in winter and decreases in summer due to higher mean wind speeds associated with the winter months. In addition, wind speeds tend to be higher during the day than at night due to temperature gradients and this effect is intensified in summer.

Table 8 gives the wind potentials of the country both on land and on the sea (offshore). We can safely say that only a small portion of the available wind potential has been utilized to this date.

4.4.3 Hydropower Potential

The average height of the areal surface area of Turkey is approximately 1200 m. With the total rainfall of 643×10^9 m^3 annually, it has been estimated that the approximately 1/3 of the rainfall eventually makes up the rivers of the country which is estimated to be 186×10^9 m^3 annually [DSI—General Directorate of State Hydraulic Works). The hydropower potential figures can be seen from Table 9.

The yearly precipitation for Turkey can be seen from Fig. 33. This figure shows

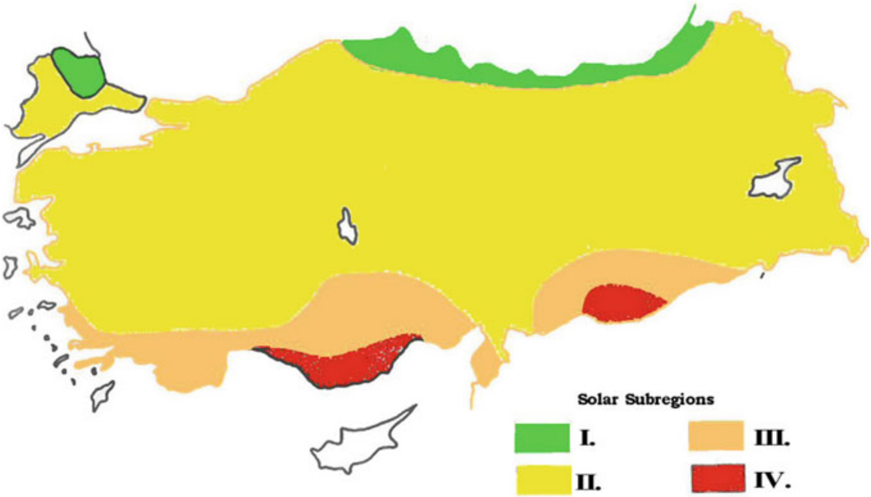


Fig. 31 Solar sub-regions in Turkey (Özil et al. 2012c, 2012d)

U (m/s)	> 7.5	6.5 – 7.5	5.5 –6.5	4.5 – 5.5	< 4.5
P (W/ m^2)	> 500	300 - 500	200 - 300	100 - 200	< 100

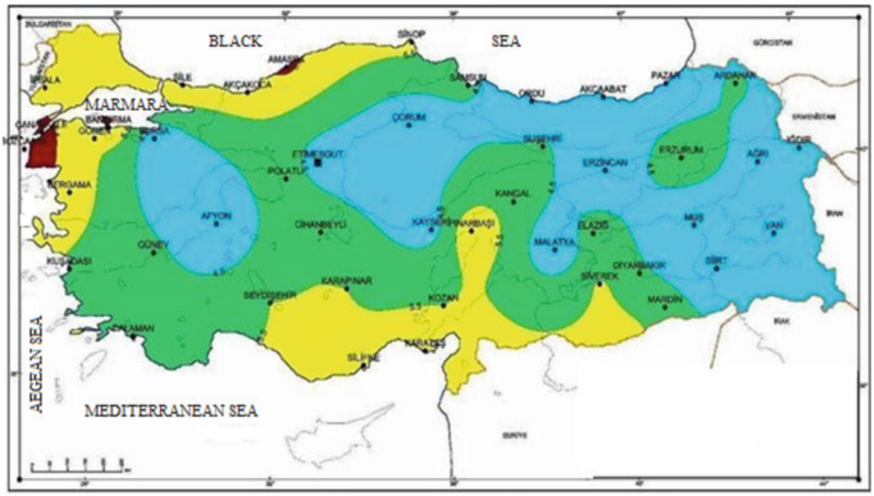


Fig. 32 Wind energy potential in Turkey (Turkish State Ministry of Energy and Natural Resources 2021)

Table 8 Theoretical technical and economic potentials of wind energy in Turkey (Özil et al. 2012d; Turkish State Ministry of Energy and Natural Resources 2021)

Wind energy potential	
Theoretical potential	800 (400) TWh
Technical potential	260 (120) TWh
Economic potential	100 (50) TWh
2020 Potential use	9.26 GW
2020 Electricity produced	24.6 TWh
2020 Total electricity produced	301.9 TWh

Table 9 Theoretical technical and economic potentials of hydropower in Turkey (Özil et al. 2012a, b, c, d; DSI 2018)

Hydropower potential	
Theoretical potential	435 TWh
Technical potential	250 TWh
Economic potential	130 TWh
2020 Potential use	31.3 GW
2020 Electricity produced	77.9 TWh
2020 Total electricity produced	301.9 TWh

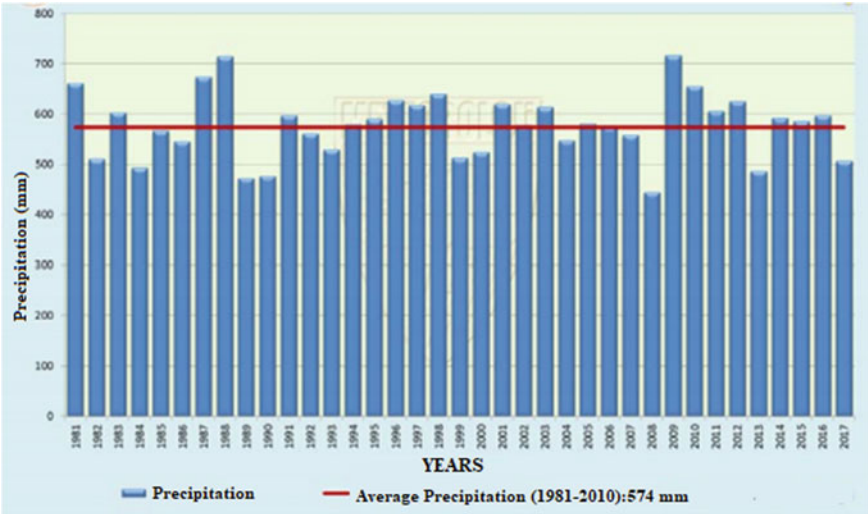


Fig. 33 Yearly precipitation in Turkey (1981–2018) (General Directorate of Turkish State Meteorological Service 2016)

that the average rainfall from 1981 to 2010 was 574.0 mm. When this figure is multiplied with the surface area of the country, the result is 446.6 × 10^9 m^3 which is smaller than the figure given by General Directorate of State Hydraulic Works. Figure 34, on the other hand, shows the comparison of the yearly rainfall with the

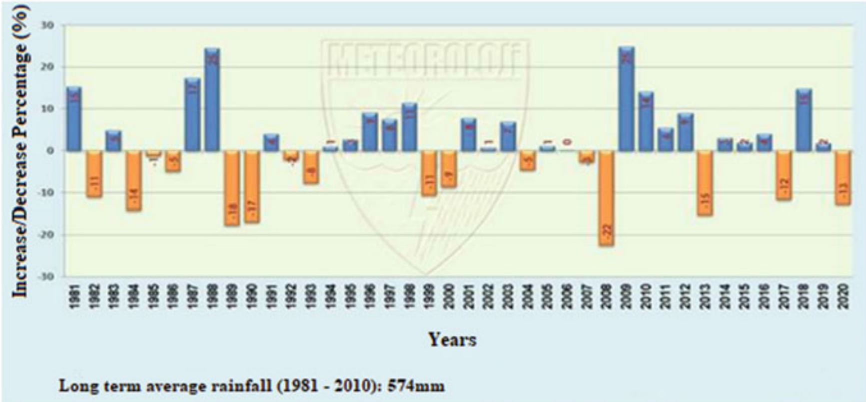


Fig. 34 Comparison of yearly precipitation with long term average precipitation in Turkey (1981–2020) (General Directorate of Turkish State Meteorological Service 2021)

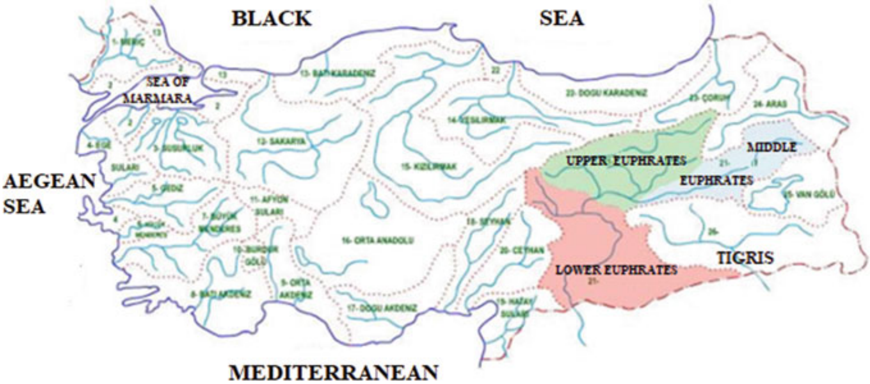


Fig. 35 Major river basins in Turkey (DSI 2018)

long-term average rainfall. It is evident that yearly rainfall is decreasing over the last five years. Figure 35 shows the major river basins on which the potentials are based.

4.5 *The Impact of Global Warming and Climate Change on the Renewable Energy Potentials in Turkey*

As was stressed at the introduction section impacts studies on wind and hydropower resources dominate the literature. Recently we are seeing similar studies on the solar power appearing in the literature. With global warming everybody has turned their attention to CO_2 increase in the atmosphere and there is no doubt that CO_2 is the major player in global warming. However, the increase of CO_2 levels may also play an important part in the reduction (however small to start with) of solar radiation, thus negatively impacting the use of solar radiation as a renewable source of energy.

4.5.1 The Impact of Global Warming and Climate Change on Solar Energy Potential

Section 2 of this work tells us the amount of solar energy received by the Earth has followed the Sun's natural 11-year cycle of small ups and downs with no net increase since the 1950s. However, starting about the same time we begin to observe a drop in solar radiation reaching the Earth, amounting to at least 0.8 W/m^2 by 2020. It may look like it is merely 0.6% in a 70-year span, but the evidence is indicating an alarmingly increasing drop especially from the beginning of the twenty-first century.

We can see the evidence from the solar radiation measurements from 55 major weather stations in Turkey. The results are given in Fig. 36. The red line in the figure represents the linear fit to the solar radiation data and in a 10 year span the value of the average of total global solar radiation has dropped from 1600 to 1550 kWh/m^2 representing a drop of 3% in a period of ten years (NASA 2020). We should note that this figure represents a higher percentage, because the measurements on these weather stations also include the meteorological events that hinders the arrival of the solar radiation to the weather station such as cloudiness, dust storm and other extreme meteorological events.

The climate change projections tend to agree that cloud cover will decrease low to mid altitude regions including Turkey (Patt et al. 2013). However, increases in solar energy will often be counterbalanced not only by increase in the amount of carbon dioxide present in the lower atmosphere, but by decreasing efficiency due to rising temperatures. As such, regional studies tend to project changes in solar generation of less than ± 10% by the end of the century (Crook et al. 2011; Gaetan et al. 2014; Panagea et al. 2017).

On photovoltaics, more research has to be carried on the effect of temperature on the efficiencies. However, on solar thermal applications, the expected drops on the overall efficiencies are more or less well established. These efficiency drops can be seen from Figs. 37 and 38.

Figure 37 shows a typical ideal Rankine cycle, which operates between two temperatures. It is the ideal cycle for vapor power plants. It includes four reversible processes: isentropic compression, constant P heat addition, isentropic expansion, and constant P heat rejection.

The thermal efficiency of the Rankine cycle is given by,

$$\eta = \frac{w_{net}}{q_{in}}. \tag{1}$$

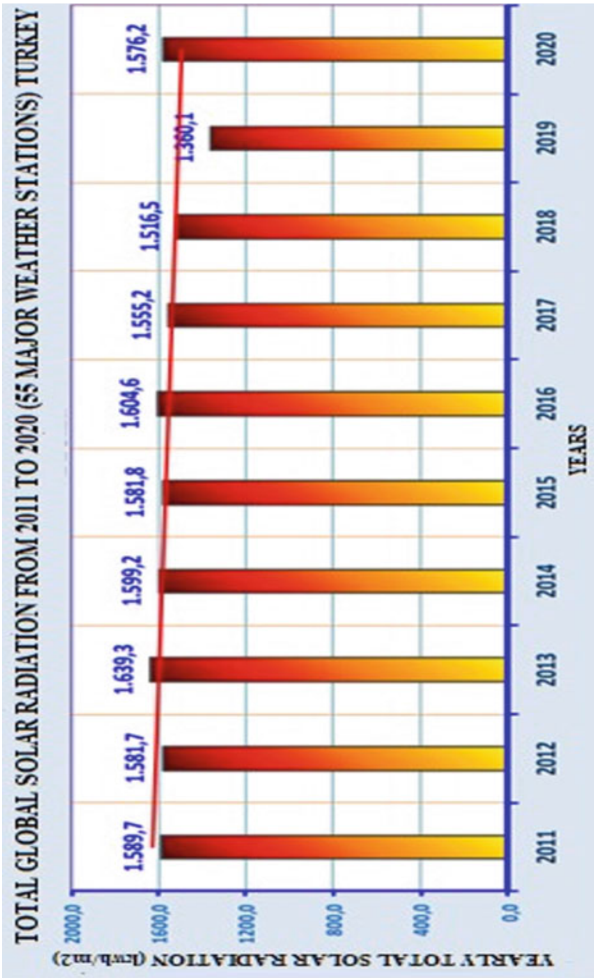


Fig. 36 Total global solar radiation from 2011 to 2020 (55 Major Stations) in Turkey (General Directorate of Turkish State Meteorological Service 2021)

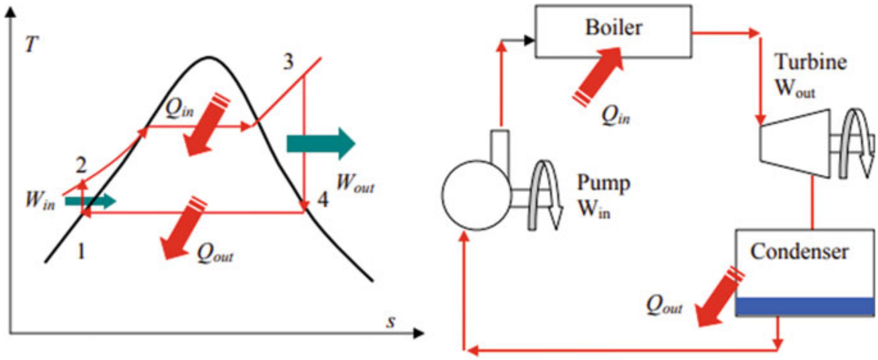
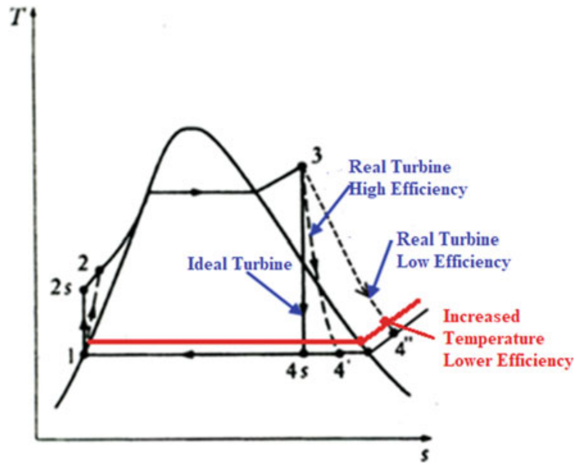


Fig. 37 The ideal rankine cycle (Özil et al. 2012a, b; Bahrami 2021)

Fig. 38 The effect of temperature rise on efficiency in a real rankine cycle (Özil et al. 2012a, b, c; Bahrami 2021)



This efficiency is proportional to the following expression of,

$$\eta_{th} = 1 - \frac{T_{low}}{T_{high}} \tag{2}$$

Based on the application, especially the degree of superheating, the thermal efficiency will drop between 1.5 and 5% due to warming of the environment.

We shall experience a similar drop in the cooling water temperatures for Rankine cycle, combined cycle and turbine topping process as shown in Fig. 39. Based on the application, the thermal efficiency will drop. Thus, we may in total, drop in the overall efficiency of a cycle in the vicinity of 3.0–7.5%.

Finally we can observe the impact of global warming in solar energy potential and both solar thermal and PV applications from Fig. 40. One may notice that, this impact

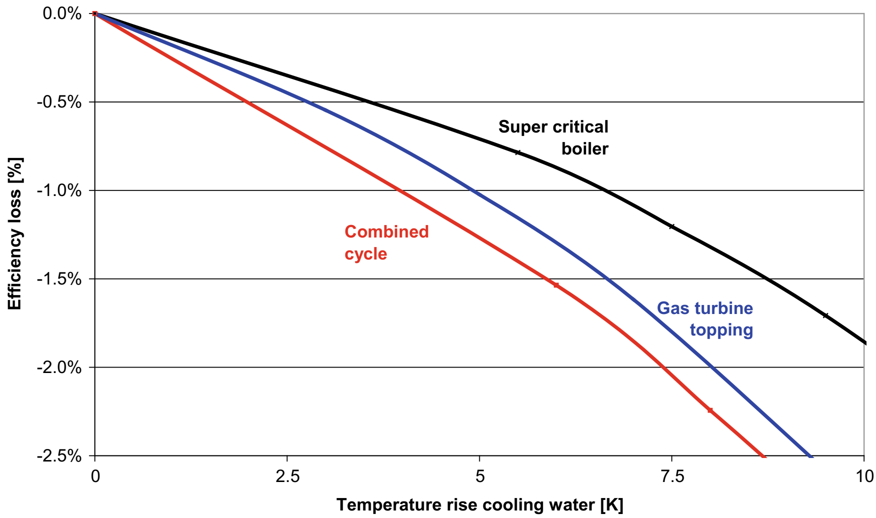


Fig. 39 The effect of temperature rise of the cooling water on efficiency (Özil et al. 2012a, b; Bahrami 2021)

is not only on the annual resource capacity but also on all stages of applications until the consumption at the end use point.

Turkey already has high distribution losses in the main grid. Also from Sect. 1 we know that the expected additional grid loss for the transmission lines is around 6% (Cronin et al. 2018; Bartos et al. 2016; Tyusov et al. 2017).

It is expected that if no steps are taken to mitigate global warming, the total drop may exceed 10% for the coming four years and may increase to 15–25% for the end of the century.

4.5.2 The Impact of Global Warming and Climate Change on Wind Energy Potential

Reviewing wind impacts literature, Pryor and Barthelmie (2010) found average wind speeds around Europe and North America would remain within ±15% of current values by the end of the century. This limit has since been revised up to 30% (Carvalho et al. 2017). The most studied impacts are for wind power is for Europe.

With the enormous increase in the number of extreme meteorological events, the impact should be on the negative side for the wind energy potential over Turkey. As it was mentioned before, the lowest number of extreme meteorological events in Turkey corresponds to 23 in 1950, over 100 for the first time in 1957, over 500 in 2010 and 900 in 2018. Last year the number of extreme meteorological events exceeded 980 for the first time in history (General Directorate of Turkish State Meteorological Service 2021).

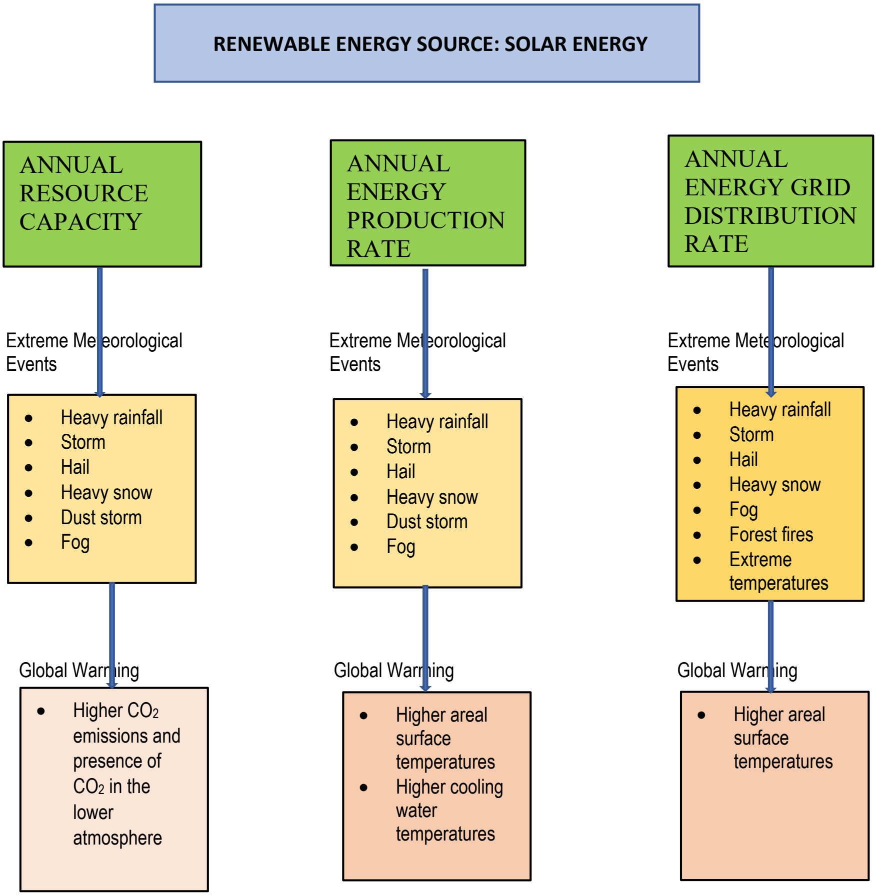


Fig. 40 Effect of global warming on solar potential and solar electricity production

According to the Republic of Turkey Ministry of Energy and Natural Resources data, the wind potential of Turkey is given in Fig. 32 (Özil et al. 2012d; Turkish State Ministry of Energy and Natural Resources 2021). As it can be seen from the graph, Turkey is surrounded by Mediterranean Sea, Aegean Sea, the Sea of Marmara, and Black Sea. Since wind energy scales have the cube of wind speed, slight changes in wind profiles can significantly affect the extractable energy output. To summarize, Turkey's current climate and Turkey's location in mid-latitudinal areas on the Earth produces a strong seasonal cycle in wind resources and shows seasonal variability (Ohba 2019). Wind energy increases in winter and decreases in summer due to higher mean wind speeds associated with the winter months. In addition, wind speeds tend to be higher during the day than at night due to temperature gradients and this effect is intensified in summer. Global warming may also produce changes in the temperature gradients as shown in Table 4. The temperature gradients shown for 2017 and 2019 for

Aegean Sea precisely indicates the change in the temperature gradients. In addition, we have to stress the fact that the change in temperature gradient will also change the direction of the wind. The change in the direction will also affect the farm design and the distances between the individual turbines meaning a drop in the wind farm's overall efficiency.

Sudden large increases and decreases in wind energy output over a short period, caused by wind speed fluctuations, are known as wind ramping and is one of the major problems wind energy (Ohba 2019). Although there is no data available on a national level, we know wind ramping negatively affects load generation balance and the stability of the power grid, they must be balanced by other power sources of electrical energy. Wind energy increases in winter and decreases in summer due to higher mean wind speeds associated with the winter months. It is estimated that wind ramping will be more important in fall and winter.

With the meteorological events, increasing the frequency of wind ramping happening is of great concern. As it was pointed out early wind energy and wind speeds are a strong function of seasons.

Another important factor affecting the loss of energy is the number of failures of the wind turbines. Figures 41 and 42 give us the average number of failures of the wind turbines. Of course, the number may change from one manufacturer to another. We also know the number of average failures annually, which currently stands at 6 (Nabipour et al. 2020). Looking at Fig. 42 we see that, electrical system, plant control system and sensors make up half the failures corresponding to 9 days. The other 50%

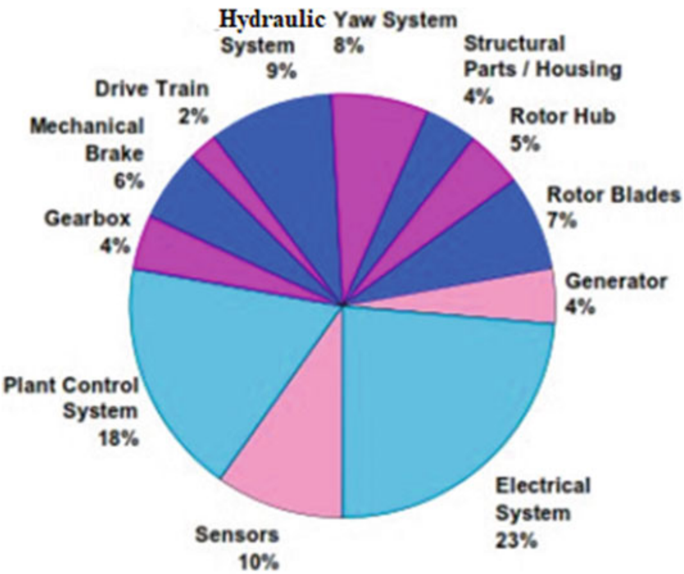


Fig. 41 Share of the main components of the system (total number of failures) (Nabipour et al. 2020)

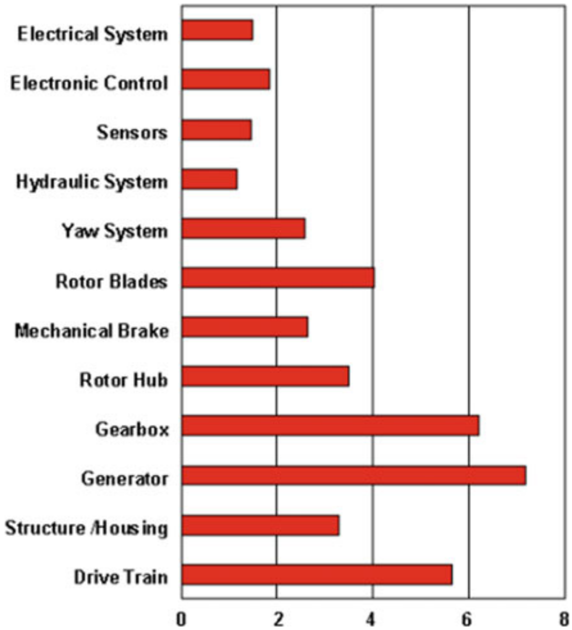


Fig. 42 Downtime of the main components per failure (days) (Sarkar A and Behera DK 2012)

averaging 4 days per failure. The number of days, a wind turbine is not operating is approximately totals to twenty-one (21) days annually and this is expected to increase over the years and with larger turbines (Nabipour et al. 2020).

The impact of global warming on wind energy potential can be seen from Fig. 43. We see that, this impact is minimal on the annual resource capacity among the three renewable resources in consideration. However, at energy production and distribution stages there will be a considerable drop in amount of electrical energy produced and made available to end users. As it was mentioned above, Turkey already has high distribution losses in the main grid. Also from Sect. 1 we know that the expected additional grid loss for the transmission lines is around 6% (Cronin et al. 2018; Bartos et al. 2016; Tyusov et al. 2017).

It is expected that if no steps are taken to mitigate global warming, the total drop in wind energy may exceed be increasing close 10% for the coming four years and may increase to 10–20% for the end of the century.

4.5.3 The Impact of Global Warming and Climate Change on Hydropower Potential

As it was discussed in Sect. 1, there are two distinctly different approaches. Hamududu and Killingtveit (2017) and Turner et al. (2017) believe that climate change will have little effect on total global hydropower and local resources. van Vliet et al. (2016) and others, on the other hand, argue that there will be sizeable

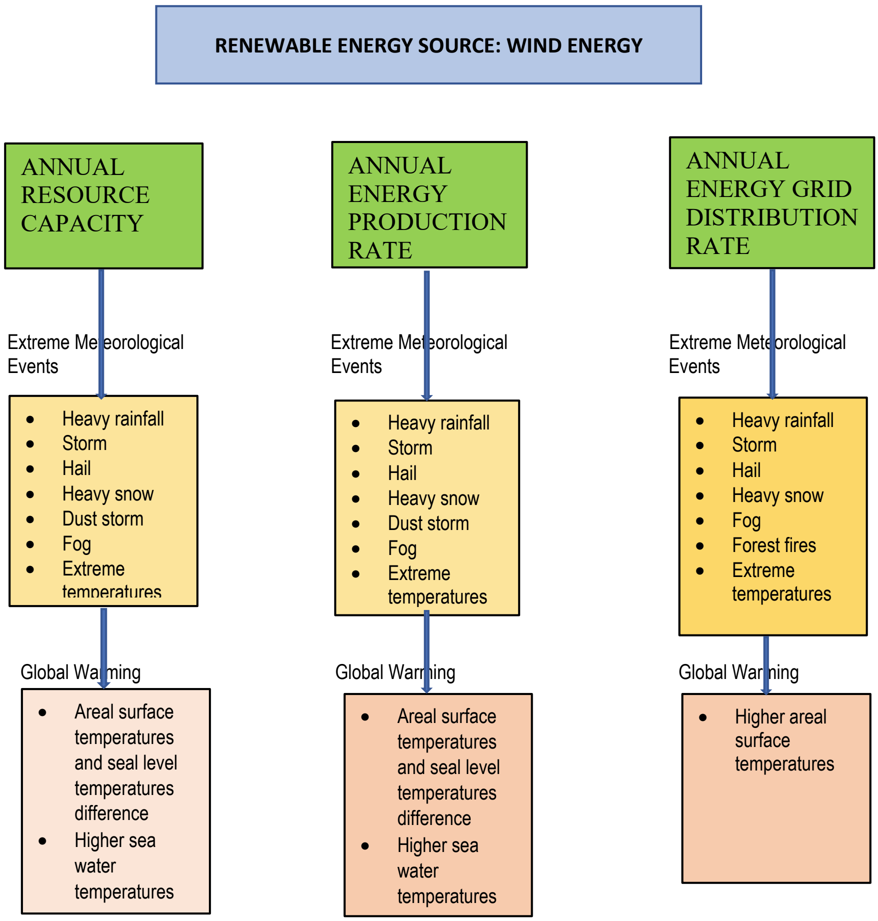


Fig. 43 Effect of global warming on wind energy potential

decrease on global hydropower capacity. Turner et al. (2017) and van Vliet et al. (2016), and other studies (Cronin et al. 2018) project an increase of 5–20% areas located at high latitudes and decrease by same amount in regions such as southern Europe including Turkey, southern USA and other areas located in the mid latitudes.

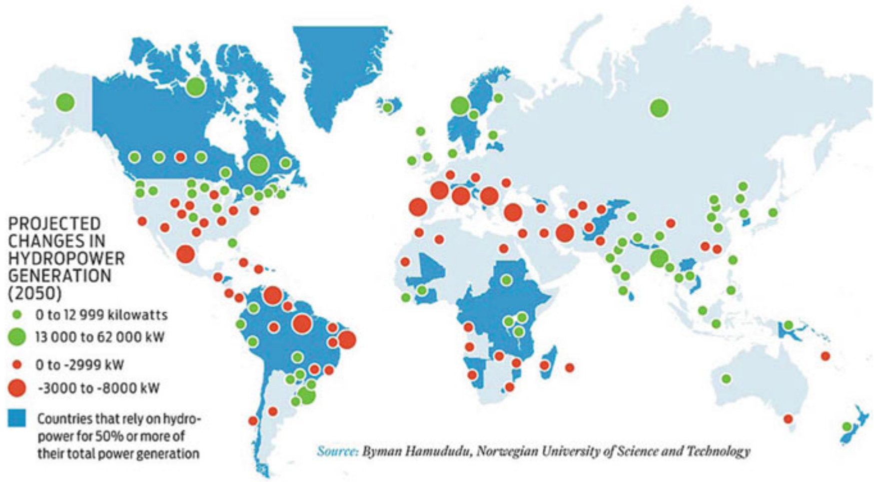


Fig. 44 Projected global changes in hydropower generation in 2050 Hamududu and Killingtveit (2017)

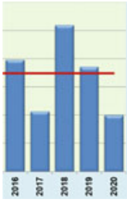
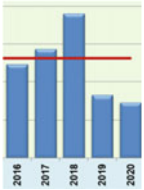
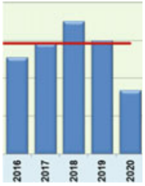
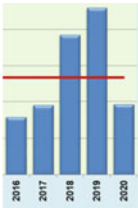
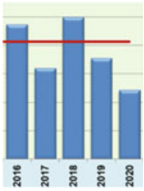
Figure 44 provides these projections. According to Hamududu and Killingtveit (2017), Turkey is to experience from −3000 to 8000 kW. With Table 6 showing the installed hydropower at about 31.3 GW, this effect seems to be small. However, we know this is not the case. On the other hand, van Vliet et al. (2016) predicts a drop in the hydropower anywhere from –5 to 20%.

The previous section gives the yearly average long-term precipitation for Turkey as 574.0 mm (General Directorate of Turkish State Meteorological Service 2021). Figure 34, on the other hand, shows the comparison of the yearly rainfall with the long-term average rainfall over the years. It is evident that yearly rainfall is on the decline for the last five years. This decrease is being experienced at all sub-regions of the country (Table 10). The third column, which gives the precipitation for the last years and the long-term average for that sub-region (red line), perhaps clearly indicates that the only exception is the Southeastern Anatolia region. We should remember that the river basins for Euphrates and Tigris rivers are located in this region and Eastern Anatolia.

Another indicator of the decrease in the level of precipitation is the intense drought experienced in 2020. As it can be seen from Fig. 45, majority of the country witnessed intense drought with wetness percentiles at or below 5%. Together with the drought, the depth of the average underground waters has almost doubled over the last two decades. As it is known, underground waters also feed rivers (NASA 2021; Anadolu Agency 2019, 2021; Cumhuriyet 2020).

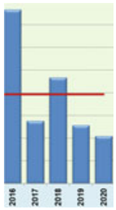
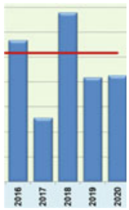
According to Table 7 hydropower contribution to electrical energy production was ~89 TWh in 2019 and it went down to ~77 TWh in 2020. Although no official

Table 10 Comparison of precipitation (2016–2020) in the sub-regions of Turkey with long term average precipitation in the same sub-regions (General Directorate of Turkish State Meteorological Service 2016, 2020, 2021; Çelik 2014)

The sub-regions of turkey	Average precipitation (1981–2010) (mm)	Precipitation (2016–2020)
Turkey as a whole	574	
Marmara	662	
Aegean	592	
Mediterranean	566	
Central Anatolia	406	

(continued)

Table 10 (continued)

The sub-regions of turkey	Average precipitation (1981–2010) (mm)	Precipitation (2016–2020)
Black Sea	696	
Eastern Anatolia	558	
Southeastern Anatolia	532	

explanation is given, Table 10 and Fig. 45 provides sufficient explanation. Finally, we can take a look at for the impact of global warming on hydropower potential from Fig. 46. We see that, this impact will perhaps be maximum on the annual resource capacity among the three renewable resources in consideration. Especially at energy production and distribution stages there will be a considerable drop in amount of electrical energy produced and made available to end users. As it was mentioned twice above, Turkey already has high distribution losses in the main grid. It is expected that if no steps are taken to mitigate global warming, the total drop in hydropower will exceed 15% for the coming four years and may increase to at least 20 to 30% for the end of the century.

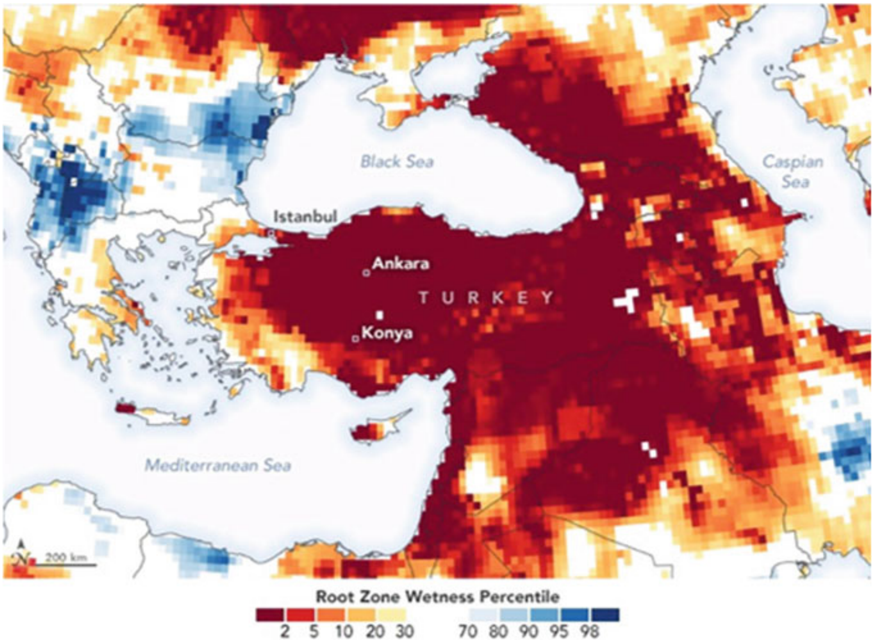


Fig. 45 Intense drought experienced in 2020 in Turkey (NASA 2021)

5 Conclusions

As was previously stressed, Turkey is blessed with ample renewable resources including solar energy, wind energy, hydropower energy and geothermal energy. With global warming, everyone is concerned with CO_2 emissions and the accumulation of CO_2 in the lower layers of atmosphere. It looks as if; the negative effect of CO_2 on the supply side is being ignored or taken lightly.

We have seen in the previous section that global warming and the climate change is telling us to make use of renewable energies for energy, especially electrical energy, production. We need renewables to minimize the negative effects of global warming, yet we know that global warming and the climate change is adversely affecting the electricity production from the renewable resources. We should expect the impact of the climate change in renewable energy potential, production of electricity and distribution and transmission systems. These changes will have implications for the reliability, cost, and local environmental impacts of energy supply.

When we speak of whether or not Turkey is ready for 100% renewable energy system, we are asking whether all the electrical power requirements of the country now or at the near future can be met by renewable energy resources. The answer to this question is partially given by Table 11. We see that total renewable electricity production goes from 55,587 GWh in 2010 to 123,000 in 2020; approximately %125.

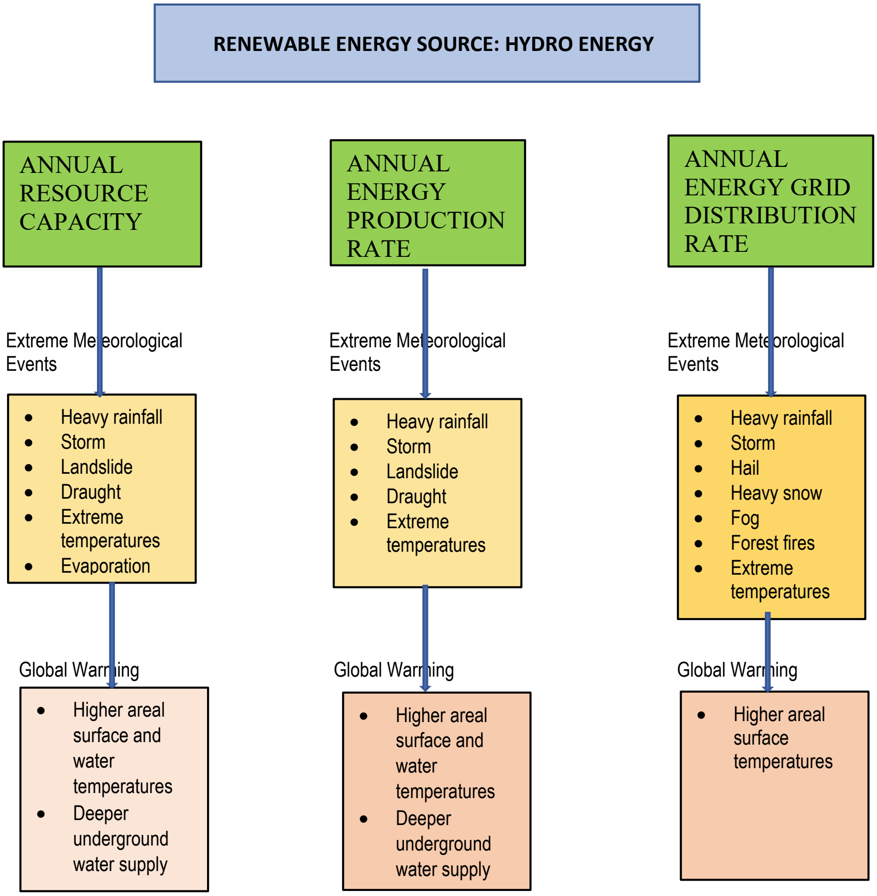


Fig. 46 Effect of global warming on hydropower potential

Table 11 Electricity production from renewable resources (2010–2020) in Turkey (All the figures are in GWh) (Enerji Atlası 2021)

Years	Hydropower	Wind	Solar PV	W + PV	Other Renewables	Non-hydro renewables	Total
2010	52,000	2,916	0	2,916	671	3,587	55,587
2015	67,000	11,652	194	11,846	3,250	15,096	82,096
2020	77,900	24,600	11,200	35,800	9,300	45,100	123,000

Figure 47 gives us the percentage of total electricity produced from renewable resources in Turkey. As it can be seen the largest value of 42.0% was achieved in 2019. Although the energy produced from wind and solar has increased, a large drop from hydropower has given us slightly lower percentage for 2020.

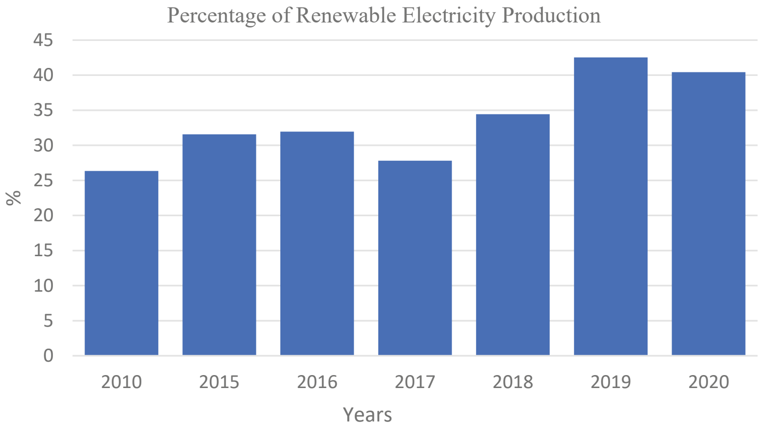


Fig. 47 Percentage of renewable electrical energy production over the years

In the year 2010, total electricity produced from the renewables was 55, 587 GWh which corresponded to 26.3% of 211,000 GWh of the total production. Among the renewables, hydropower accounted for 93% of the renewable electricity production. In 2015, the share of hydropower dropped to 81.6% followed by wind energy at 14.4%, other renewables (mainly geothermal) approximately 4% and finally solar with a share of 0.2%. In 2020, we see the impact of solar and wind investments on the renewable electrical energy production. Hydropower is still the leading renewable resource with a share of 63.3%, followed again by wind energy with a share of 20%. For the first time in history, solar energy takes the third spot with 9.1% and geothermal energy completes the list with 7.6%. Not included to this total is the contribution of the electricity produced from the biomass, which we estimate it to be around 1–2% bio-mass.

Based on the granted energy investment licenses by Energy Market Regulatory Authority of Turkey (EMRA, in Turkish EPDK) and on-going investments, hydropower is expected to go below 50% within the coming three years.

As was stressed at the introduction section, impact studies on wind and hydropower resources dominate the literature. Recently we are seeing similar studies on the solar power appearing in the literature. With global warming, everybody has turned their attention to CO_2 increase in the atmosphere and there is no doubt that CO_2 is the major player in global warming. However, the increase of CO_2 levels may also play an important part in the reduction (however small to start with) of solar radiation, thus negatively affecting the use of solar radiation as a renewable source of energy. In addition, impacts of gradual changes to climatic parameters such as temperature and precipitation have been studied more than changes to extreme weather events, as existing tools have limited ability to capture extreme events.

In solar energy potential for Turkey, existing work in the literature tells us the amount of solar energy received by the Earth has followed the Sun's natural 11-year cycle of small ups and downs with no net increase since the 1950s. However, starting about the same time we begin to observe a drop in solar radiation reaching the Earth, amounting to at least 0.8 W/m^2 by 2020. It may look like it is merely 0.6% in a 70-year span, but the evidence is indicating an alarmingly increasing drop especially from the beginning of the twenty-first century. The same phenomenon is also experienced in Turkey. The results of solar radiation measurements from 55 major weather stations in Turkey are shown in Fig. 36. Accordingly, in a 10 year span the value of the average of total global solar radiation has dropped from 1600 to 1550 kWh/m^2 representing a drop of 3% in a period of ten years. We should note that this figure represents a higher percentage, because the measurements on these weather stations also include the meteorological events that hinders the arrival of the solar radiation to the weather station such as cloudiness, dust storm and other extreme meteorological events.

Reviewing wind impacts literature, Pryor and Barthelmie (2010) found average wind speeds around Europe and North America would remain within ± 15% of current values by the end of the century. This limit has since been revised up to 30% (Carvalho et al. 2017). The most studied impacts are for wind power is for Europe.

With the enormous increase in the number of extreme meteorological events, the impact should be on the negative side for the wind energy potential over Turkey. As it was mentioned before, the lowest number of extreme meteorological events in Turkey corresponds to 23 in 1950, over 100 for the first time in 1957, over 500 in 2010 and 900 in 2018. Last year the number of extreme meteorological events exceeded 980 for the first time in history.

Sudden large increases and decreases in wind energy output over a short period, caused by wind speed fluctuations, are known as wind ramping and is one of the major problems wind energy (Ohba 2019). Although there is no data available on a national level, we know wind ramping negatively affects load generation balance and the stability of the power grid and they must be balanced by other power sources of electrical energy. Wind energy increases in winter and decreases in summer due to higher mean wind speeds associated with the winter months. It is estimated that wind ramping will be more important in fall and winter in Turkey.

On the hydropower electrical energy generation, there are two distinctly different approaches. Hamududu and Killingtveit (2017) and Turner et al. (2017) believe that climate change will have little effect on total global hydropower and local resources. van Vliet et al. (2016) and others, on the other hand, argue that there will be sizeable decrease on global hydropower capacity. Turner et al. (2017) and van Vliet et al. (2016), and other studies (Cronin et al. 2018) project an increase of 5–20% areas located at high latitudes and decrease by same amount in regions such as southern Europe including Turkey, southern USA and other areas located in the mid latitudes. According to Table 10, yearly rainfall is on the decline for the last five years in Turkey. This decrease is being experienced at all sub-regions of the country. Another indicator of the decrease in the level of precipitation is the intense drought experienced in 2020. As it can be seen from Fig. 45, majority of the country witnessed intense drought with wetness percentiles at or below 5%. Together with the drought the depth of the average underground waters has almost doubled over the last two decades. As it is known, underground waters also feed rivers.

Finally, we can take a look at for the impact of global warming in solar energy potential and solar thermal applications from Fig. 40, on wind energy potential from Fig. 44 and on hydropower from Fig. 46. We see that, this impact is not only on the annual resource capacities but also on all stages of applications until the consumption at end use point.

It is expected that if no steps are taken to mitigate global warming, all renewable potentials will drop considerably in the near future. Table 12 summarizes the results. The table is organized such that the resource on which global warming and climate change will have the maximum effect is placed on top and the least is at the bottom.

The potential drop figures given for the renewable resources are calculated from the available works in the literature and through estimates made by analyzing the statistics of the last twenty years. There needs to be experimental and theoretical studies made to find more reliable figures.

Table 12 The effect of global warming on renewable energy resources in Turkey in the 21st Century

Ranking	Renewable resource	Annual resource capacity	Annual energy production rate	Annual energy grid distribution rate capacity	Total expected drop (%)
1	Hydropower	• Heavy • rainfall • Storm • Hail • Heavy snow • Dust storm • Fog • Extreme temperatures • Evaporation	• Heavy rainfall • Storm • Hail • Extreme temperatures • Evaporation	• Heavy rainfall • Storm • Hail • Heavy snow • Extreme temperatures	20–30
2	Solar energy	• Heavy rainfall • Storm • Hail • Heavy snow • Dust storm • Fog	• Heavy rainfall • Storm • Hail • Heavy snow • Dust storm • Fog	• Heavy rainfall • Storm • Hail • Heavy snow • Extreme temperatures	15–25
3	Wind energy			• Heavy rainfall • Storm • Hail • Heavy snow • Extreme temperatures	10–20

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The Need for Dispatchable RES: A Closer Look at the Future Role of CSP in Europe

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1 Introduction

As part of the European Green Deal, the European Union (EU) aims at full climate-neutrality of the whole economy by 2050 and a 55% reduction of greenhouse gas emissions (GHG) by 2030 compared to 1990 levels (EC 2019, 2020a). The achievement of the EU's energy and climate targets will require high shares of wind and photovoltaics (PV) in the power system as well as dispatchable carbon-free generation technologies to balance the fluctuating generation patterns of wind and PV.

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Concentrating Solar Power (CSP) is a dispatchable, renewable power technology that facilitates the transition towards a decarbonised electricity system. It provides flexible, carbon-free electricity to the grid and supports the integration of other renewable electricity technologies.

Since solar resources for CSP are the richest in southern European countries, cooperation between the EU Member States may help make this potential also available to northern countries within the EU and facilitate the overall energy transition in accordance with climate targets. Cooperation is usually characterised by joint efforts and risks, cost-optimised investments across all countries instead of separate, national strategies (e.g. cross-border renewable projects), and high shares of energy trading (physical or statistical), cf. Boie and Franke (2020). There has been limited progress in EU renewable energy cooperation in recent years. To facilitate cooperation on renewable energies, various cooperation mechanisms have been defined in previous EU regulations. As stated in EC (2020b), four binational agreements are currently (as of October 2020) in order to cooperate in the achievement of the RES 2020 target. Further agreements are expected in the context of 2020 and beyond. In this context, the European Commission strongly encourages the EU member states to use these cooperation mechanisms to achieve the RES targets for 2020, 2030, and beyond in a cost-effective manner, cf. EC (2020b).

This chapter provides a model-based assessment of the possible future role of CSP in a European low-carbon electricity system in 2050 and the associated investments and public support needed for the development of CSP. The work builds on outcomes of the MUSTEC project—a European research project funded by the Horizon 2020 program that aims to explore the role of Renewable Energy Cooperation (RES) for the improved market uptake of CSP in Europe—, specifically the model-based analysis of drivers and policy trade-offs for a (possible) market uptake of CSP in Europe (Resch et al. 2020) and was first presented by Resch et al. (2022).

1.1 Structure of This Chapter

This chapter follows a classic structure. We begin with an overview of the methods used (Sect. 2), present the assessed policy paths and scenarios as well as the modelling system used, and provide information about the assumptions made in the modelling.

Since our modelling involves two complementary energy system models, which are closely linked in the modelling of future scenarios, we also differentiate between two elements in our presentation of results:

Section 3 is devoted to discussing the results of the power system analysis, in which we identify the need for CSP in a future decarbonised European power system. The first results presented in this section come from the Enertile model, a specialised energy system model which analyses the interplay of supply, demand, and storage in the European electricity sector in high temporal resolution. Our results provide information on how CSP can provide a part of the required system flexibility for the future EU electricity system, which will be sufficient with high shares of variable renewable energies.

In addition to the above, the second part of Sect. 3 is devoted to discussing the results of the prospective energy policy analysis on CSP and other RES technologies, as well as the role of RES cooperation in facilitating the introduction of RES in the coming years. This analysis was done by using the Green-X model, a specialised energy system model that provides a sound coverage of funding instruments for renewable energies as well as the available resources and the corresponding costs of individual RES technologies in Europe. This chapter provides information on the dynamics of renewable energy use, the investments required, and the related policy costs in terms of direct financial support. The analysis includes shedding light on the interaction between special renewable energy funding instruments and the EU emissions trading system, as well as the role and necessity of RES cooperation.

This chapter concludes with a summary of the most important findings and lessons learned (Sect. 4).

2 Methodology and Assumptions

This assessment of the European-wide needs for dispatchable CSP builds on modelling. Consequently, an overview of the underlying methodology is undertaken within this section, introducing the modelling system applied and the assumptions made in modelling, including information on the policy pathways and sensitivity scenarios assessed.

2.1 The Applied Modelling System

The modelling works have been conducted using two distinct energy system models in an integrated manner, complementing each other in the analysed aspects of the energy system:

- **Green-X**: the (renewable) energy policy assessment model; used for analysing policy-driven renewable investments, renewable developments, and related impacts on costs, expenditures and benefits.
- **Enertile**: the energy system model, which sheds light on the interplay between electricity supply, storage, and demand in the EU electricity market.

As shown in Fig. 1, Green-X analyses the renewable energy (RES) investments, RES diffusion rates, and related impacts on costs, expenditures and benefits for the energy system. Enertile simulates the hourly dispatch of all components of the electricity system: supply, storage, and demand in the electricity market. The covered

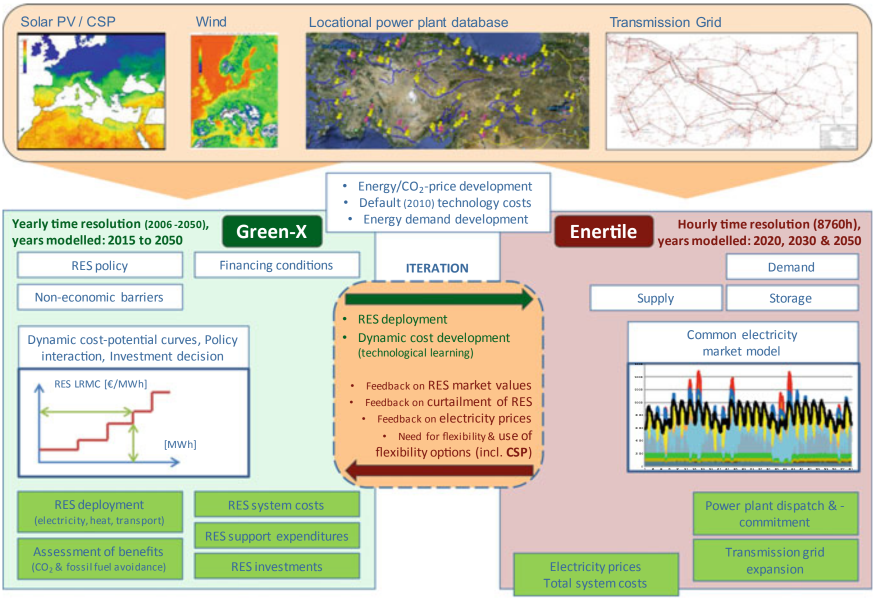

Fig. 1 Interplay of Green-X and Enertile

geographic area is EU28[1] for the years 2030, 2040, and 2050. Moreover, Enertile is also used within this integrated assessment to identify the gap in power system flexibility that can economically best be filled by CSP (in conjunction with internal thermal storage) under the given system boundaries like heading towards carbon neutrality by 2050 (Fig. 2).

The combination of both models allows to make use of each model's particular strength:

- On the one hand, Green-X is suitable for analysing the economic feasibility and prospects of future RES deployment in a dynamic context. Here, policy impacts are well incorporated, and diffusion limits of individual RES technologies serve to derive a realistic picture of the feasible RES uptake over time.
- On the other hand, Enertile allows for a detailed analysis of the power system for specific points in time (i.e., 2030, 2040, 2050), shedding light on the interplay between demand, supply and storage at a high temporal and geographical granularity that also reflects infrastructural constraints concerning the cross-border transmission of electricity.

The overall modelling of future RES developments in the EU and its neighbours is done for all energy sectors (i.e., electricity, heating & cooling, and biofuels in

[1] Enertile additionally covered Norway and Switzerland within the power system analysis to account for cross-border flows and interactions with the local electricity markets within these two countries that are well interconnected with the EU electricity market.

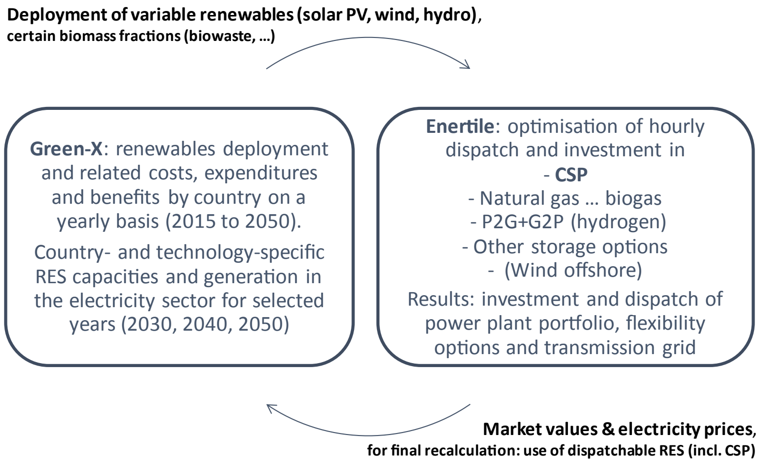

Fig. 2 Iteration process between Green-X and Enertile

transport) by Green-X, whereas our detailed assessment of enhanced cross-border RES cooperation through the use of CSP is limited to the electricity sector.

Complementary to this and specifically for the electricity sector, grid and transmission needs or constraints, respectively, together with the physical integration possibilities, are evaluated from a technical perspective in a power system analysis using Fraunhofer ISI's Enertile model. The output of Enertile is then fed back into the RES investment model Green-X. In particular, the feedback comprises the amount of RES that can be integrated into the grids, the electricity prices, and corresponding market revenues (i.e., market values of the produced electricity of variable and dispatchable RES) of all assessed RES technologies for each assessed country.

2.2 Scenarios and Assumptions

The EU-wide RES policy framework: Cooperation versus National Preferences

One of the most important questions for CSP deployment is the market environment where electricity generation occurs. These market conditions are determined by a broad range of factors like pricing mechanisms, the development of different power technologies, and energy and climate policies. Within the MUSTEC project, information on a wide range of policy pathways for renewables deployment and climate policy in the energy sector at the EU level and at the national level for Spain, Italy, France, and Germany has been collected and processed (cf. Lilliestam et al. 2020). The identified policy pathways are classified into dominant pathways, describing the currently valid policy aims and measures, and minority pathways, which are the positions of parties currently not in government and may be picked up in case of future government changes. Further, they are characterised by the different ideologies driving them: market-centred, state-centred, grassroots developments, and a fourth class outside of these classifications. These policy pathways form the basis of the modelling activities presented in this analysis by defining central input parameters like electricity demand, renewable targets, decarbonisation levels, and technology mix in future years (2030, 2050) in the different countries.

Two ideological worlds are represented by the scenarios.

- On the one hand, there is the setting of enhanced *"(RES) Cooperation"* across the EU. Here, we assume that all EU countries will intensify cooperation in the field of renewables in the forthcoming years. Specifically, we presume that a least-cost approach is followed, reflecting full competition across technologies and corresponding sites across the whole EU. Deployment of RES technologies will consequently take place in those countries where it is most cost-efficient from the power system perspective towards the 2030 (and 2050) (renewable) energy and climate target achievement. This world is represented by the EU dominant (market-centred) policy pathway.
- On the other hand, we model the four countries analysed in detail (i.e., France, Italy, Germany, and Spain) according to their own (dominant) preferences as stated in the 2030 National Energy and Climate Plans (NECPs, described in Lilliestam et al. 2020), subsequently specified as the national dominant pathways. This world represents the *"National Preferences"* which can differ to a large degree between the countries in terms of technology choices, RES ambition, etc.

These two policy worlds—i.e., "Cooperation" and "National Preferences"—are then compared and complemented by different sensitivity analyses, resulting in scenarios with low electricity demand levels, limited availability of competing demand-side flexibility options, limited grid extensions, lower decarbonisation ambitions, and concerning the role of the EU Emission Trading Scheme (EU ETS) in enabling the decarbonisation of the energy sector.

The EU dominant pathway was taken up in the cooperation scenario, whereas the combination of the national dominant pathways forms the basis of the "National Preferences" scenario. In the "National Preferences" scenario, the renewable deployment in the rest of the EU28 countries has to be adapted to the national strategies of France, Germany, Spain, and Italy so that the overall EU target is achieved. That means that if national ambitions in those countries are lower in the national preference scenario (e.g. in the case of France), RES deployment in other countries will be stronger than in the cooperation scenario so that the overall EU target is still achieved.

Electricity demand

To cover the effect of overall electricity demand levels, we compare two scenarios with high respectively low electricity demand.

- *High Demand*: In the scenarios with high demand, sector coupling is more prominent and strong electrification of heating and transport acts as a driver for increased electricity demand. The gross electricity demand was taken from the SET-Nav "Diversification" scenario for all countries (Sensfuß et al. 2019).

- *Low Demand*: For those countries where a detailed energy policy pathway analysis has been conducted within the MUSTEC project, i.e., namely the (in terms of population and size) large EU Member States Germany, France, Italy and Spain, gross electricity consumption projections were taken from their draft NECPs whenever these countries provided them (cf., Lilliestam et al. 2020).[2,3] For the remainder of the countries, electricity demand projections are kept identical to the "High Demand" scenario.

For the year 2050, this results at the EU28 level in gross electricity consumption of 5816 to 6069 TWh in the "High Demand" scenarios and 4634 to 4672 TWh in the "Low Demand" scenarios.

Decarbonisation ambition

By default, we make the assumption that a full decarbonisation of the energy system—zero CO_2 emissions – and in particular, of the power system will be achieved by 2050 at the EU level. In general terms, this has strong implications for future technology choices (e.g. fossil CCS is no viable generation option in the power sector, as it is not fully zero-carbon) and for energy market developments. To achieve the full decarbonisation within our stylised energy system representation, a strong increase in carbon prices is assumed in modelling (75, 125, and 500 $€_{2010}$/t CO_2 for the years 2030, 2040, and 2050).

Complementary, we assess the impact of a lower climate ambition in a sensitivity analysis, assuming only a GHG reduction of 91% in the electricity sector by 2050 compared to 1990 levels instead of full decarbonisation (25, 75, and 225 $€_{2010}$/t CO_2 for the years 2030, 2040, and 2050).

(Fossil) Fuel price trends

Fossil fuel price trends, as illustrated in Table 1, are taken from IEA modelling, specifically the IEA's 450 scenario (IEA WEO 2016). These trends reflect a strong climate ambition globally. Please note that these price trends are significantly lower than the assumptions taken by the European Commission in the latest EU reference scenario: If one compares the price of oil, on average 40% lower prices are expected for the forthcoming decades. The difference in price trend assumptions is smaller for natural gas but still amounts to ca. 25% (i.e., 25% lower than in EC recommendations).

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[2] If there was no explicit demand projection available, expectations on future electricity demand are taken from the EU reference 2016 scenario (EC 2016) as derived by PRIMES modelling (adapted for the increased 32.5% energy efficiency target) to ensure maximum consistency with corresponding EU scenarios and projections.

[3] For the year 2050, Germany provided a gross electricity consumption of 464.3 TWh excluding new demand from sector coupling. This new demand from sector coupling for Germany was taken from the SET-Nav "Diversification" pathway (Sensfuß et al. 2019).

Table 1 Fossil fuel price trends

Fuel prices in €$_{2010}$/MWhth	Gas	Hard-coal	Oil	Lignite	Nuclear
2030	28.9	7.4	48.4	3.7	3.1
2040	30.5	6.6	44.5	3.7	3.1
2050	31.2	6.2	42.5	3.7	3.1

Source IEA (2016)

Please note that in accordance with the guiding principle to head towards carbon neutrality, natural gas is expected to be replaced by renewable gas by 2050. For this decarbonisation option the assumption is that the price will decline from currently (2020) 55 €/MWh to 47.1 €/MWh by 2050, reflecting first lessons learned from demo projects in the Netherlands and expert judgements concerning expected future progress.

Grid expansion

By default, we presume a strong expansion of the power system infrastructure in future years, specifically of the transmission grid. As part of the sensitivity analyses, we analyse the impact of grid expansion limits. In this context, the two scenarios with grid limitations assume limitations in transmission grid expansion in order to evaluate this effect on CSP deployment.

Cost assumptions for RES technologies

As listed in Table 2, an 11 h thermal storage system and a site-specific ratio between field and generator are assumed for the CSP plants. Investment costs for 2030, 2040, and 2050 are the average estimations of de Vita et al. (2018), ESTELA (2019), Zickfeld et al. (2012) and Sensfuß et al. (2019) adapted for an 11 h storage CSP plant. For validation, these cost trends were compared to current project costs (Lilliestam et al. 2019, 2020). Fixed operation and maintenance (O&M) costs are derived from a comprehensive literature collection by Schöniger et al. (2020, 2021). Variable O&M costs are the average of de Vita et al. (2018) and ESTELA (2019).

Figure 3 informs on the assumptions in the modelling for other RES technologies. More precisely, expected cost trends for RES technologies stem from Green-X modelling.

Table 2 Cost assumptions for CSP in Enertile in the MUSTEC project

Year	Lifetime [a]	Specific investment [€$_{2010}$/kW]	Fix O&M cost [€$_{2010}$/(kW a)]	Var. O&M cost [€$_{2010}$/MWh]	Efficiency (%)
2030	30	3525	66.7	0.046	44
2040	30	3078	53.3	0.046	49
2050	30	2554	40.0	0.046	52

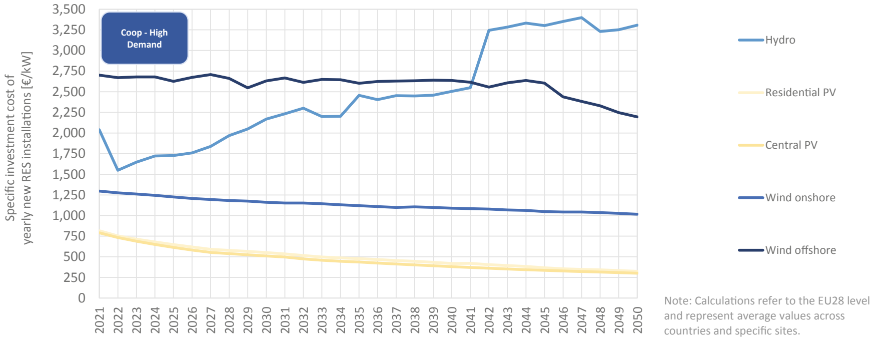

Fig. 3 Development of specific investment cost of selected key RES technologies at the EU28 level, exemplified for the "Cooperation – High Demand" scenario (*Source* Green-X modelling)

The exemplified trends in investment cost refer to a specific scenario (i.e., the "Cooperation – High Demand" scenario) and showcase the specific investment cost for a new RES installation on average at the EU28 level in a given year. As applicable from this graph, strong cost reductions are expected for key RES technologies like solar PV and wind. For hydropower, the opposite trend is observable: On average, at the EU28 level, specific investment costs are expected to increase in future years since the available future potential is comparatively limited, specifically for large-scale projects. Consequently, a tendency to invest in small-scale installations is presumed for this technology.

The general approach and the assumptions used in Green-X modelling on technology learning and corresponding cost reductions of RES technologies are briefly described in further detail below.

Thus, for most RES technologies, the future development of investment cost is based on technological learning. Two key parameters determine the development of investment cost of a certain RES technology: the deployment & the learning rate.

Assumptions on future RES deployment: As learning is generally taking place on the international level (i.e., presuming a global learning system), the deployment of technology on the global market must be considered. For the model runs, global RES deployment consists of the following components:

- Deployment within the EU 28 Member States is endogenously determined, i.e., is derived from the model.
- Expected developments in the "rest of the world" are based on forecasts as presented in the IEA World Energy Outlook 2018 (IEA 2018). For the analysis performed within MUSTEC, we make use of the IEA New Policies scenario and the technology-specific global deployment indicated therein.

Assumptions on learning rates: Complementary to future RES deployment, assumptions on future learning rates for key RES technologies (apart from CSP as discussed above) are taken from corresponding recent topical studies and are as follows:

- PV (central and residential): 20%
- Wind (on- and offshore): 7%
- Hydropower: zero—i.e., no future cost reductions are expected for this mature technology.

Dedicated support for RES versus "ETS only"

As part of the energy policy analysis, a focal assessment is conducted to shed light on the role of the EU Emission Trading Scheme (EU ETS) in reaching carbon neutrality at the EU level by 2050. Today within the EU and its Member States, a broad portfolio of policy initiatives that aims to facilitate the decarbonisation of the energy system is implemented. The EU ETS acts as an umbrella instrument to safeguard that GHG emission reduction targets are met within the sector covered, including large GHG emitters in power and heat supply and in the industry as well as parts of certain transport modes. Within the electricity sector, the EU ETS is accompanied by dedicated support instruments and various other measures like cheap loans, tax regulations etc., to facilitate the uptake of renewables and other decarbonisation options.

In our default model-based assessment, specifically within the power system analysis that aims to identify the need for CSP and other flexibility options to safeguard a reliable and affordable electricity supply in the future, carbon prices serve to account for the underlying decarbonisation objectives. For 2050 we impose as default case carbon neutrality as a constraint, causing carbon prices within the EU ETS to reach 500 €/t CO2 at that point in time. As a consequence of high carbon prices within the power system analysis, the applied Enertile model projects a significant increase in wholesale electricity prices in future years, specifically in the last years until 2050, as applicable in the graph on the left-hand side of Fig. 8.

Within this focal assessment, we evaluate how high dedicated RES support needs to be if carbon prices will not increase to these significant heights. We consequently recalculate the required support expenditures for achieving a similar RES deployment as postulated in the default "Cooperation" and "National Preferences" scenarios. This analysis serves as a sort of reality check and builds on the assumption that current policy practices are maintained, meaning that we see also in future rather a bunch of dedicated measures and instruments to facilitate decarbonisation at the various ends instead of solely one single instrument—i.e., the EU ETS. Table 3 informs on the assumed carbon price trends used in this focal assessment. The default high carbon price trend builds on own assumptions and acknowledges the findings of EC (2018), whereas the alternative low carbon price trend is based on the latest PRIMES reference scenario of the EU (EC 2016).

Data Availability

For increasing transparency in the approach used and the underlying data and results, key modelling data is publicly available at https://zenodo.org/record/3905045.

Table 3 Assumed carbon price trends in the focal assessment on dedicated support as an alternative for high carbon prices

Assumptions on carbon price developments (in the EU ETS) in €$_{2010}$/t CO_2	2030	2040	2050
Default assumptions (*high* carbon prices)	75.0	125.0	500.0
Alternative trend (*low* carbon prices)	31.0	46.3	81.5

Source Own assumptions and EC (2016)

3 Results from the Model-Based Analysis on the Need for CSP

3.1 The Uptake of Renewables for Deep Decarbonisation

In the last 13 years, the expansion of renewable energies in the EU28 has more than doubled. This impressive trend must be maintained in all scenarios: The deep decarbonisation as a guiding principle implies an increase in the RES shares in gross electricity demand to around 56% by 2030 and to at least 90% by 2050: The RES shares fluctuate from around 90% by then ("National Preferences", assuming continued heavy use of nuclear power in France) up to around 97% ("Cooperation", assuming that no new nuclear facilities are being built across the EU). In absolute numbers, the associated strong increase in electricity consumption even means a strengthening of RES developments in the coming years compared to the historical record. Electricity generation from renewable energy sources must at least double within the next twelve years and more than quadruple by 2050, as shown in Fig. 4

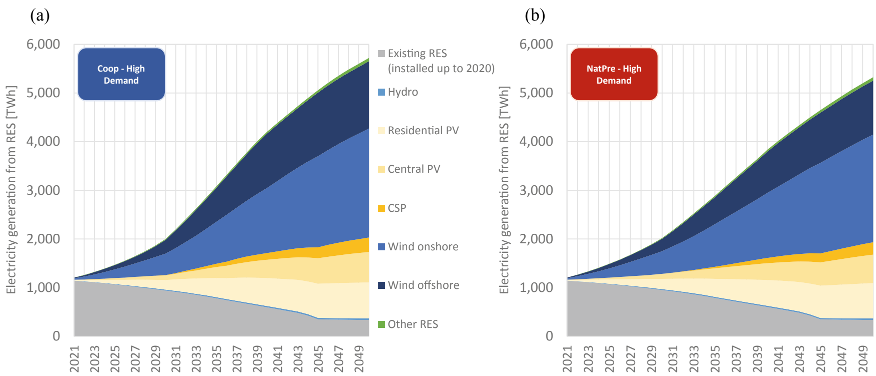

Fig. 4 Technology breakdown of the development of electricity generation from RES up to 2050 at the EU28 level according to the "Cooperation – High Demand" (**a**) and the "National Preferences – High Demand" scenario (**b**) (*Source* Green-X modelling)

key scenarios ("Cooperation" versus "National Preferences").

According to our modelling, the lion's share of the new generation will come from variable renewable energies. Key trends in technology-specific developments are that onshore wind dominates the picture—both up to 2030 and 2050. Offshore wind energy will account for the second largest share of the total use of renewable energies in the coming years, followed by photovoltaics, where private and central PV systems are expected to increase significantly. In our model, CSP is the fifth largest contributer to RES generation and serves as a "gap filler" for the system flexibility of the EU electricity system, which is based on large proportions of variable renewable energies - as identified in the electricity system analysis. Other technologies such as hydropower, biomass, geothermal energy, tidal currents or wave power will only show comparatively small contributions in the coming years under the underlying framework conditions in which the most cost-effective options are prioritised in the modelling.

3.2 The Role of CSP in a Decarbonised European Electricity System of 2050

Our modelling results show that in a future European electricity system, there is a clear need for dispatchable CSP, driven by the political goals of carbon neutrality and full decarbonisation. But the need for CSP competes with other carbon-free technology options that may provide the required flexibility system. Consequently, the amount of CSP generation at the EU level by 2050 varies across the assessed scenarios. As part of the electricity grid analysis, we, therefore, examined the influence of important energy policy decisions on the overall role of CSP in the EU electricity system until 2050, when the technology achieves its cost-cutting goals. In particular, we analysed how cross-border cooperation ("Cooperation" versus "National Preferences"), sector coupling, electricity demand levels ("High Demand" versus "Low Demand"), and infrastructural developments/requirements ("Limited Grid") affect the market acceptance of CSP in the EU. In all scenarios, we find that a sharp increase in electricity generation from CSP will contribute to cost-optimal future electricity systems, with EU-wide CSP generation from 5 TWh in 2018 to increase by a factor of 20 to 60 over the next 30 years. For the year 2050, this implies an EU-wide CSP generation ranging from 100 to 300 TWh (see Fig. 5).

Our results show that, in particular, the degree of cooperation between the countries, the volume of demand, and the number of available connections are important determinants for the introduction of CSP, the respective effects of which are discussed in more detail below.

With regard to the question of whether cooperations between European countries lead to a higher expansion of CSP power plants, our modelling results are ambiguous. While in the case of very high electricity demand, CSP generation in the "Cooperation" scenario is slightly higher than in the "National Preferences" scenario, this

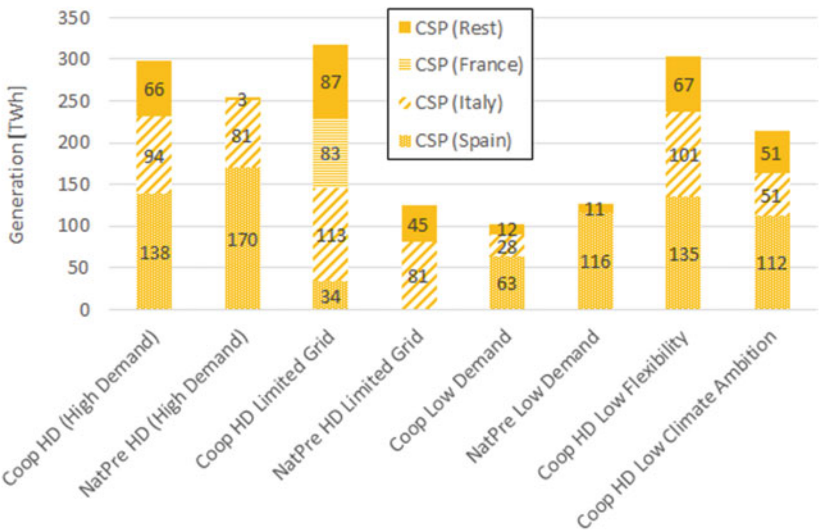

Fig. 5 Electricity generation from CSP in the EU28 in 2050 for the different scenarios calculated for this analysis (*Source* Enertile modelling)

tendency is reversed when demand is lower. In a world with very ambitious decarbonisation goals, however, high demand for electricity is more likely, which can improve the prospects for CSP.

In addition, our results show that higher electricity demand increases the generation gap for CSP. Since CSP is more expensive than other renewable technologies, CSP capacities are increasingly being installed when the potential of other renewable technologies such as wind and PV is already being exploited to a greater extent.

Since they hinder the use of fossil fuel power plants, high climate policy ambitions are a very important driver for the introduction of CSP. Firstly, as a backup of fluctuating renewable energies and, secondly, as a supply of electricity demand that exceeds the realisable potential of other renewable energies. Hence, CSP, with its renewable dispatchability benefit, becomes more important under such conditions.

Finally, a highly developed transnational power grid proves to be an ambivalent factor in the development of CSP. On the one hand, interconnectors are a trailblazer for CSP, especially since the areas with the greatest and cheapest potential for CSP production are on the European periphery (Spain, Portugal, and Italy). Due to their peripheral location, Spain and Portugal, in particular, are dependent on a strong electricity grid coupling to the rest of Europe in order to export larger amounts of electricity from CSP (if the conversion of electricity into hydrogen, for example, with subsequent international trade is less efficient than direct electricity trading locked out). On the other hand, a strongly expanded European power grid smooths the fluctuations in wind power and PV feed-in so that the need for additional flexibility on the supply side, including CSP, decreases. In contrast to the above, more limited grid interconnection hinders the introduction of CSP in Portugal and Spain, while it favours the use of CSP in other countries like France or Italy – because it limits the import of electricity from neighbouring countries and the system flexibility provided by the grid, thereby the need for disposable CSP is increasing.

Figure 5 compares the generation of CSP in the considered scenarios and sensitivities. The two main scenarios, "Cooperation" (Coop) and "National Preferences" (NatPre), assuming high demand growth, have a CSP generation of 300 TWh respectively 250 TWh. Here, the generation of CSP in Spain is highest with 138 TWh respectively 170 TWh. As discussed previously, the scenarios with low demand and the "National Preferences" scenario with a limited grid show the highest deviation for the generated CSP electricity.

3.3 Strong Investments into CSP and Other RES Technologies Are Needed in Forthcoming Years

Strong investments in RES technologies are required to make the transition to carbon neutrality in the EU electricity sector. Average annual investments for the key scenarios analysed range from € 91 billion ("National Preferences") to EUR 100 billion ("Cooperation"). Investments are slightly higher when the grid is restricted (€ 96 to 106 billion per year) and lower when demand grows less than expected (€ 64 to 72 billion).

Similar observations can be made for CSP in general: In the scenarios that follow a policy path of "Cooperation", the average annual investments in CSP range from 8.0 to 8.8 billion with low demand growth. The corresponding figures for the "National Preferences" scenarios are € 6.4 billion for the default case with high growth in demand and € 2.8 billion for the scenario with low growth in demand. Compared to the total investment volume that needs to be invested in renewable energy in the electricity sector, these numbers mean that, on average, about 7–8% of that is for CSP if there is high demand growth and the goal of carbon neutrality by 2050 in energy and climate policy is taken seriously. Nevertheless, around 4% of total annual RES investments would go to CSP if sector coupling and thus electricity demand did not increase as expected.

3.4 Support is Needed to Facilitate the Strong Uptake of CSP and Other RES Technologies—But New RES Installations Are Significantly Cheaper Thanks to Technological Progress

In order to model the required support for CSP and other RES, a common approach is taken for the RES policy framework, which is intended to facilitate RES uptake: It is assumed that (technology-specific) auctions for sliding feed-in premiums will be carried out across the EU Member States in the coming year on a pay-as-bid principle.

The results show that to enable high CSP shares in 2050, dedicated support is required in the short to medium term. The average (2021–2050) annual support expenditures for CSP in the analysed scenarios range from € 0.4 billion (both scenarios of "Low Demand") to € 2.0 billion ("Cooperation – High Demand" with or without less (demand-side) flexibility). This corresponds well to the underlying CSP deployment trends, and specific support for CSP (per MWh RES generation) is consequently hardly affected by analysed changes in input parameters like grid limitations, demand flexibility, etc.

However, the majority of the identified RES-related support expenditure up to 2050 is intended for existing RES, which were built in the years up to 2020, as they caused higher costs. Due to technological advances and projected rising prices in wholesale electricity markets, support for new renewable energy sources (which will be installed after 2020) is expected to decline sharply over time. A key element in achieving this decrease in the promotion of new RES systems, especially for variable RES such as wind and photovoltaics, is the expansion of the cross-border transmission network, as this facilitates RES integration and the compensation of under- and oversupply of variable RES infeed across national borders.

Figure 6 compares the resulting average (2021–2050) yearly RES-related support expenditures across assessed scenarios. This graph shows a comparatively broad spectrum for the average yearly support expenditures, ranging from € 10.2 to 29.2 billion. Expenditures are lowest in scenarios with low demand growth and highest in the case of imitations in expanding the cross-border transmission grid.

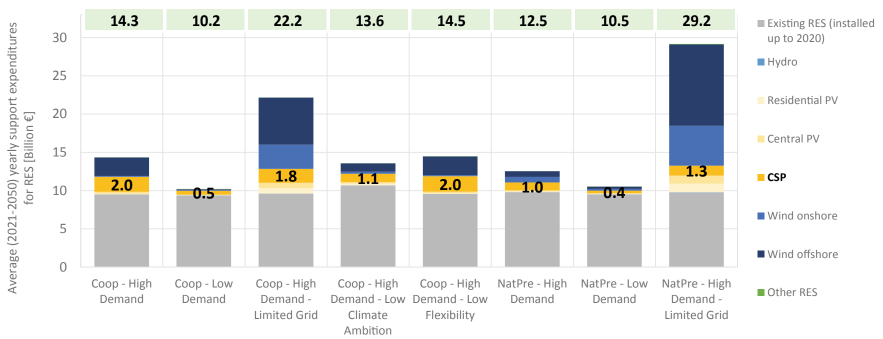

Fig. 6 Comparison of the resulting average (2021–2050) yearly support expenditures for RES technologies in the electricity sector in the EU28 in different scenarios (*Source* Green-X modelling)

3.5 *Dedicated Support as Promising Alternative to High Carbon Prices*

As the default case, cf. Table 3, high carbon prices in the EU ETS of ca. 500 €/t CO_2 by 2050 are presumed in modelling in order to facilitate the decarbonisation of the electricity sector. In a focal assessment, we evaluate how high dedicated RES support needs to be if carbon prices will not increase to these significant heights but peak at 81.5 €/t CO_2 by 2050 instead (cf. Table 3). This serves to shed light on the role of the EU ETS in reaching decarbonisation goals within the electricity sector. We consequently recalculate the required support expenditures for achieving a similar RES deployment as postulated in the default "Cooperation" and "National Preferences" scenarios presuming high carbon prices.

The comparison of average yearly support expenditures, as shown in Fig. 7 (left), indicates that support costs triple if the current trend and policy practice of using a bunch of dedicated policy instruments to facilitate the energy transition complementary to the "umbrella tool" EU ETS is pursued in the years up to 2050, as a consequence of the comparatively "Low Carbon Prices" within the EU ETS. The picture changes, however, from the perspective of an electricity consumer if we add to our comparison the price changes in the wholesale electricity market: As applicable from Fig. 7 (right), consumer costs in specific terms (per MWh electricity consumption) that take into account wholesale prices and RES-related support expenditures on average throughout the whole time period 2021 to 2050 are lower in the alternative cases where "Low Carbon Prices" are presumed. Thus, despite the significant increase in dedicated support for RES, electricity consumers will pay 19% ("Cooperation") to 21% less ("National Preferences") if the current policy practice of combining the EU ETS with strong sectoral policies that provide dedicated support to RES (and possibly also other decarbonisation options) is maintained in future years. Under

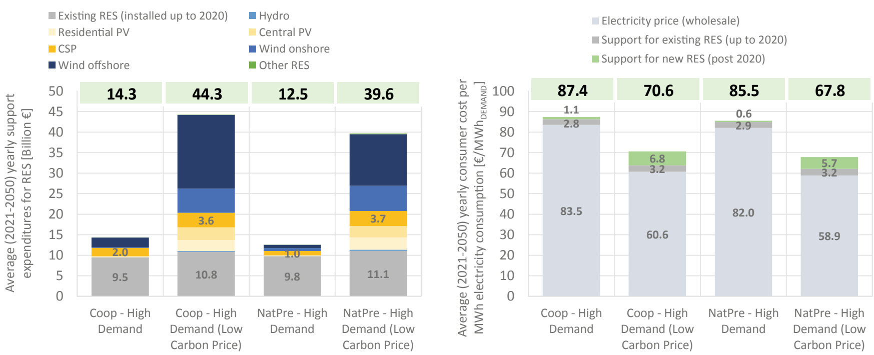

Fig. 7 Comparison of the resulting average (2021–2050) yearly support expenditures for RES technologies in the electricity sector (left) and of the average (2021–2050) consumer cost in specific terms (per MWh electricity consumption) (right) according to selected assessed scenarios (*with default* and *with low carbon prices*) (*Source* Green-X modelling)

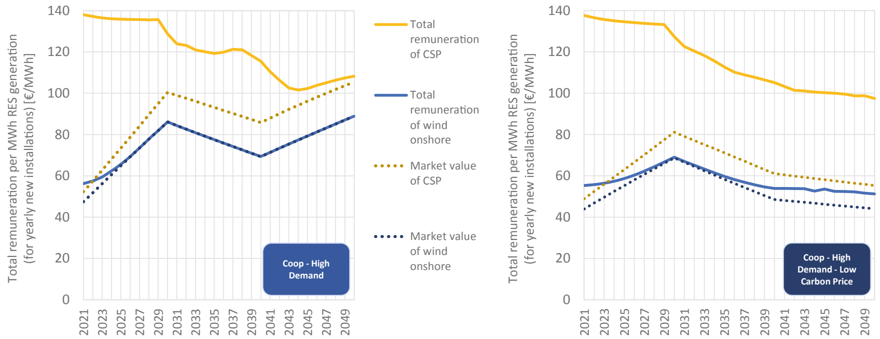

Fig. 8 Comparison of total remuneration per MWh RES generation of CSP and wind onshore according to selected assessed scenarios—*with default* ("Cooperation – High Demand" (left)) and *with low carbon prices* ("Cooperation – High Demand – Low Carbon Prices" (right)) (*Source* Green-X modelling)

these circumstances, targeted support can be provided to individual RES technologies, for example, via auctions for sliding feed-in premia (cf. del Río et al. 2019), in accordance with technology- or even site-specific requirements. Such a policy approach helps to avoid overcompensation for "low hanging fruits" like onshore wind or solar PV.

To clarify that, we depict the temporal development of the total remuneration per MWh electricity generation in Fig. 8, exemplified here for key two technologies, namely onshore wind and CSP, according to both assessed variants of the "Cooperation" pathway, i.e., with default ("Cooperation – High Demand") and with low carbon prices ("Cooperation – High Demand – Low Carbon Prices"). The key results are:

- For onshore wind, the comparison of both variants makes clear that on average total remuneration, and accordingly also the consumer burden, is 23% lower in the case of "Low Carbon Prices" (compared to high ones under the default "ETS only" case). The difference is in early years small and in later years close to 2050 significant, peaking at a 42% cost saving by 2050.
- For CSP, the cost savings are smaller—i.e., on average, they amount only to 4%—but the general tendency is the same. More precisely, under the default case of high carbon prices, a slow decline of total remuneration is observable in the early years, followed by an overage steeper one post 2030, and beyond 2043 remuneration increases again. The variant of "Low Carbon Prices" shows an (almost) identical trend and also comparatively similar heights of remuneration compared to above in the early years until 2030, but beyond that point in time, a steady downward trend of total remuneration is observable, leading to cost savings of about 10% by 2050.

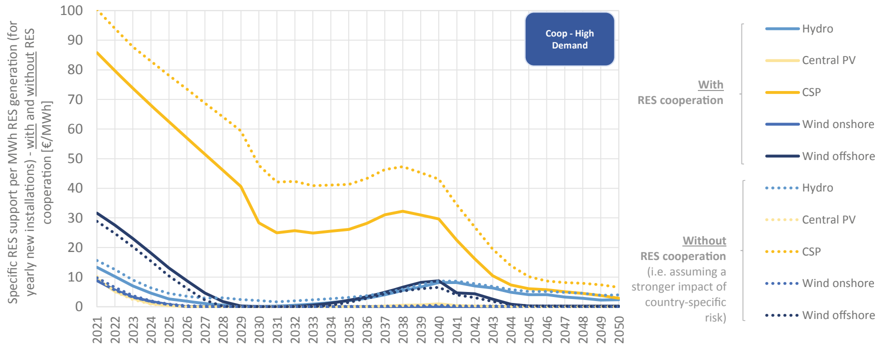

Fig. 9 Development of the specific support per MWh RES generation up to 2050 on average at the EU28 level according to selected assessed scenarios ("Cooperation – High Demand", with and without RES cooperation ("High Country Risk")) (*Source* Green-X modelling)

3.6 There is a Need for and Positive Impact of RES Cooperation on the Cost of the Uptake of CSP and Other RES Technologies

Figure 9 shows how RES cooperation affects the need for targeted support at the technology level, with reference to the EU28 on average. More precisely, this graphic shows the future development of the specific funding per MWh of RES generation up to 2050 according to two variants of the "Cooperation - High Demand" scenario, i.e., the default case assuming RES cooperation and the sensitivity case assuming no RES cooperation and, consequently, the impact of (in some countries) "High Country Risk". For CSP, a strong impact of the RES cooperation is becoming apparent: If there is no RES cooperation funding, if there is a "High Country Risk" in many southern European host countries of the expected future CSP developments, significantly higher specific funding is required.

At the aggregated level of the EU28 for all renewable energy sources, a clearly positive influence of the RES cooperation, in particular the gradation of the country risk in financing, on the RES-related support expenditure can be ascertained. More precisely, the funding costs at the aggregated EU level would increase by 5–11% across the EU according to the scenarios assessed without an alignment of the country risk in project financing. This suggests that large differences in financing conditions between EU countries, as we still see them today, are less likely to favour the decarbonisation of the EU's electricity sector.

4 Conclusion and Discussion

Based on the analyses carried out, we have identified the following key drivers and political decisions that are required for an effective CSP introduction in Europe in the coming years up to 2050:

- Thanks to the increased demand for CSP and the expected reduction in financing costs due to the cooperation policy, RES cooperation can act as an important engine for CSP. This is confirmed by modelling in which the CSP utilisation is significantly higher in scenarios that assume strong RES cooperation in combination with strong growth in electricity demand. In these cooperation scenarios, it makes economic sense to invest in CSP in the long term.
- There are different niches for different flexibility options. With flexibility reduced by 50% through decentralised heat storage (connected to heat pumps) and e-mobility, the need for dispatchable CSP is hardly affected, as this is required in both cases due to its operating properties.
- If exporting countries decide to expand and diversify their transmission and connection capacities beyond EU regulations, they can better utilise the full capacity for the use of dispatchable CSPs.
- Complete decarbonisation of the energy system in line with the Paris Agreement, which is the aim of EU policy, requires a sharp increase in sector coupling and thus in electricity demand. This is a major driver for an increased spread of CSP in Europe in the coming years.
- CSP needs effective price signals that value dispatchable and CO_2-free electricity generation. When market design guidelines ensure these price signals without considering CCS, CSP can play an important role.
- The continuation of current practices of combining the EU ETS with strong sectoral policies that provide dedicated support to RES (and possibly also other decarbonisation options) appears cost-effective for deep decarbonisation, specifically from a consumer point of view. Targeted support can then be provided to individual RES technologies, for example, via auctions for sliding feed-in premia, in accordance with technology- or even site-specific requirements. Such a policy approach helps to avoid overcompensation for "low hanging fruits" like onshore wind or solar PV.
- Technology cost reductions for all CSP components are necessary to keep this technology competitive and available for the transformation of our power systems. Since the installed CSP capacities are relatively small, measures are required to provide targeted support for CSPs that can promote high learning rates.
- CSP and PV can perform complementary tasks that must be addressed through a renewable energy policy. Competition-specific auctions can help assess the system contribution of various technology options and assess the dispatchability of CSP. According to our modelling, both PV and CSP are required in the electricity system by 2050.
- National or international measures that bring about the phasing out of nuclear energy (and/or coal) create a need for alternative dispatchable technologies that

can be covered by CSP. National acceleration of the transition that aims to reach fully renewable systems as early as possible increases these flexibility needs accordingly.

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ESCO and EPC Models for Energy Efficiency Transformation

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Abbreviations

ÇŞB	Ministry of Environment Urbanization and Climate Change
EVÇED	Efficiency and Environment Department
EVD	Energy Efficiency Consultancy Firm
ESCO	Energy Service Companies
EMRA	Energy Market Supervision Agency
EVEM	Energy Efficiency Center
ECC	Energy Conservation Center
ESC	Energy Sales Contract
EPC	Energy Performance Contract
Mtoe	Million tons of oil equivalent
OTGEPC	EPC Guaranteed Approved Savings
PGEPC	Guarantee Energy Performance Contract Sharing
TSE	Turkish Standard Institute
TGEPC	Energy Performance Contract with Saving Guarantee

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UETM The National Energy Conservation Center
YEGM General Directorate of Renewable Energy

1 Introduction

Current energy crisis that the world is witnessing with a persistent increase in energy prices all over the globe is impacting many countries including Turkey, with energy industries inability to compete with the current demands because of the carbon sanctions a solution must be created to get rid of carbon sanctions. To bypass this crisis our solution is a transition to green renewables and a transition to a "green sustainable economy" such agreement should be viewed comprehensively and urgently since the current deficit in energy supply is largely due to energy imports while knowing that the most energy dense sector is the industrial sector, followed by a high energy consumption in building which accumulated at m^2kWh/year and surpassed other countries consumption. Providing that we are in a country that all time high records of carbon emissions have been recorded before Covid-19 pandemic hit, for these reasons mentioned, a transformation towards energy efficiency should be planned and implemented as soon as possible in turkey. After the pandemic all sectors and in our case the energy sector has experienced a decrease in public resources with additional financial difficulties due to the different sectors which have been impacted by the pandemic, the appropriate and necessary technical, administrative, and financial models-mechanisms have not been formed yet in turkey, which caused the widespread problem of availability regarding energy efficiency applications. The lack of a reliable energy efficiency models has created financial problems in the face of investors and resulted in a non-healthy solution for the progress of the desired energy efficiency plan. a solution is to crate and develop a sustainable energy efficiency mechanism that follows a model in accordance with the available infrastructure in turkey, which when it succeeds it will be adapted as a successful example to be followed in the world.

2 Corporate Process

The National Energy Conservation Center (UETM) was established in 1993 under the Electrical Works Survey Administration. "**Turkey Energy Efficiency Strategy**" was announced first in April 2004, followed by the "**Energy Efficiency Law**" that was published on the 2nd of May 2007. And 2008 was declared the "Year of ENVER". Which was about the regulation on increasing efficiency in the use of energy resources, it was published on October 25th, some changes affected it on October 27th, 2011, where it entered action. And on the 5th of December 2009 the "Building Energy Performance Regulation" was deployed, followed by the "Energy

Efficiency Strategy Document" which was also published after various revisions. The article 89 of the "**Decree-Law No. 662**" published in the official newspaper dated November 2nd, 2011 the "**Law on the organization of Electrical work survey administration**" dated 14th of June 1935, numbered 2819 was repealed, the same law "**General Directorate of Renewable Energy (YEGM)**" Was established with a Decree-law appointed by a judge. Finally, the General Directorate of Renewable Energy (YEGM) was abolished and replaced by the "**Energy Efficiency and Environment Department (EVÇED)**" with a presidential decree law No. 27, published in the official newspaper dated 10th of January 2019. Despite the lengthy period that passed since the first "Energy Efficiency Strategy" with "Laws and regulations" many institutional changes occurred that weren't sufficient enough since no efficiency practices, infrastructures capacity, and development studies were made even the laws and regulations in turkey regarding the energy efficiency matter, which all have not been realized at the desired level until this day. In 2021, both the communiqué on energy performance in public buildings (published in the Official Gazette of April 15, 2021) and energy efficiency (KABEV) applications in public buildings were initiated by the Ministry of Environment, City and Climate Change General Directorate of Building, which has been renamed (formerly the Ministry of Environment and Urbanization). Turkey, which ratified the Paris Climate Agreement in the Parliament in 2021, also published the Green Reconciliation Strategy Action Plan in the same year, becoming involved in the process of action and adaptation of climate change in the world and especially in the EU. In 2053, it made a net-zero commitment.

3 Global Situation

The USA, China, Japan, and the European Union started their energy efficiency practices in the 1980s which they developed due to the energy crises not to mention the increasing price of energy resources, and the widespread movement to protect the environment where serious energy efficiency effectiveness and cost reduction on energy savings have been achieved. On top of all the gains achieved, they increased their targets to achieve 20% more energy efficiency which set to launch in 2019–2020, on the other hand, many European country's obligations were to construct zero-emission/energy buildings were introduced to the public sector.

4 Starting Point and Plan to Be Followed Publicly

One of the most important challenges for Turkey to overcome are financial challenges related to the current energy crisis, states and governments should point their attention to working on the energy infrastructure, increasing capacity both industrially, and providing enough of a workforce to work on future projects. While also creating an incentive mechanism to attract investors both privately and publicly. For solving such a problem, a more sustainable, environmentally friendly, and energy-efficient grid must be a priority target to be achieved. The first step is to announce the year 2022 as the year of "**National Energy Efficiency Mobilization**" and address the issue of energy efficiency both short and long term, and it should be a priority as a stable and sustainable state policy, which doesn't depend on government, ministries, and institutions that change frequently so continuous progress can be achieved. Another issue the transformation to energy efficiency should also be planned, coordinated, and implemented with the "**Kyoto Protocol, Paris agreement and urban renewable energy transformation legislation**", for energy conversion to work optimally both renewable energy and energy efficiency should be integrated for effectiveness. After the "green agreement" in the EU, especially the energy transformation and energy efficiency-related legislative changes, they should be followed up and updated, and reorganized. The current "**National Energy Efficiency Action Plan 2017–2023**" targets should be revised and brought forward with parts that have not yet been implemented are to be activated and forced into action. In this context, "Provincial Energy Management Units" should be established through governorships in each province and transformation should be started first from public buildings. All metropolitan and district municipalities should prepare a "Sustainable Energy and Climate Action Plan (SECAP)" in line with the objectives of the EU Green Agreement, The Paris Climate Agreement, and commit to 40% emissions reduction by 2030 and start the actions with energy efficiency transformation. A portion of the money paid in energy imports are imported with zero-interest loans, discounts on VAT, and reduction in electricity prices, by developing a new financial mechanism, billions of dollars can be made in a few years' timelines, both in the industrial sector and in buildings, as of now a lot of saving potential is already wasted each year if a new mechanism is deployed the wasted money can return itself and remain in our country, to obtain such measure the development of a sub-industry R&D, "**Energy Efficiency Consultancy (EVD)"** and **"Energy service companies (ESCO)**", that will lead to an increase in energy management, innovation in engineering and employment. Which all can be linked together as a chain-like system for an economic recovery plan throughout the country, where growth, development, and sustainability are provided through these sub-industries, which all will help improvise all the negative effects that the pandemic had impacted in all links on all levels finically, energy sectors, employment, and even the ongoing climate change crisis that we are experiencing and here's were "Green Economy" and "Energy Transformation".

Instead of taking place as a "Presidency" under the name of "Energy Efficiency and Environment Department" that is affiliated to the Ministry of Energy, which is primarily responsible for ensuring and improving energy efficiency, it has been reorganized as a separate "General Directorate of Energy Efficiency-Institute-Central-Agency". Such a configuration would be more accurate. Globally and within turkey energy sectors will not be able to bear another five or ten years. In addition, regardless of the name of these structures, their number in turkey are very few to have an impact as of now, although they will work with great efforts and experienced, dedicated staff it will not be enough, it must be ensured that capacity is rapidly created, developed, and improved and if necessary, energy efficiency centers should be created both regionally and locally. The "**Energy Efficiency Coordination Board (EVKK)**" includes the relevant professional chambers, sectors associations, and financial institutions, effective structuring in sub-commissions will become widespread in this form more actively and frequently, it should form the infrastructure of the "**Energy Efficiency Center (EVEM)**".

Solution 1

Establishment of Energy Efficiency Center (EVEM) and a Public SUPER ESCO

Many financial institutions that grant credits as the European Union, Investment banks, World Bank, IMF, and private financial institutions, etc. They come to our country to provide credit and support our applications on energy efficiency and renewable energy, we also have our financial resources, these resources must be well managed, coordinated, and transferred to the right prioritized projects so resources efficiency must be ensured. ADEME in France, DENA and "**Berlin Energy Agency**" in Germany, "**NL Agency**" in the Netherlands, "**State Energy Committees**" in the USA, "**Energy Conservation Center (ECCJ)**" in Japan, BECON in China and many other institutions in other countries, it would be very important for to assume a similar functionality across all centers. The private sector, universities, and representatives of the relevant sectors to energy efficiency will have their place which will be above independent ministries, institutions, and organizations. Mechanism models will be created that will carry out all applications in the upcoming energy efficiency industry as in buildings and transportation all from a single source, later on, after this model is active all public and private institutions will hat to comply with the sanctions, rules, and standards created by the following agencies "**Public Procurement Authority (KİK)"** and "**Energy Market Supervision Agency (EMRA)**", which are partially similar to the "**Turkish Standard Institute (TSE)**". This can be a new model with management from national institutions with semi-public/private qualifications. The "Energy Efficiency Center EVEM" will be developing mechanisms and methodologies for identifying and solving problems related to energy efficiency from a single source as we mentioned above.

Providing technical information and finance implementations and coordinating all of it across boards, institutions, and organizations that are directly or indirectly active in the fields of energy efficiency, and present the solutions, practices, and indicators that it has created to the public.

Sharing and evaluating the developments in this field both nationally and internationally and taking a leading role in the government and state policy-making process, which will be a multilateral process including (private sectors, universities, and the public) to provide accurate information to decision-makers. Relevant industry representatives, universities are managed by a board of directors consisting of representatives of relevant chambers, associations, and NGOs in all related ministers as (Energy, Forestry, Environment, Water and Urbanization) which are all summed under the "**Ministry of Environment Urbanization and Climate Change (ÇŞB)**", with other related institutions such as KIK, EMRA, BDKK, etc. it will also be in coordination with other organization that is called Executive Organizations. For example, a public Super ESCO should be established by EVEM or by the Presidency side, for implementation purposes take India and Dubai as an example and how they did a direct energy transformation in the public sector, Super ESCO can be created immediately by transforming existing institutions such as development and investment bank, ÇŞB (Ministry of Environment Urbanization and Climate Change) and general directorate of Construction, etc. Additionally, for continuous control on financial support, a new form of the existing public banks should be established and named the "**Energy Bank**", the national bank can be partially converted into an energy bank too. An energy efficiency granted fund should also be established from the energy efficiency savings that are obtained from the public sector plus the cuts as TRT and energy shares, in this fund Super ESCO and ESCO EPC applications should be used for a guarantee, credit, collateral, incentive, and insurance purposes.

The main duties of EVEM are to be determined by the following

- In all areas of the country's economic sectors, environment, international legislation, and sanctions while keeping the current structure of competition in the industrial and transportation sector in mind, new measures will have to be set that will be beneficial for the development of energy use, production and consumption in accordance with the principles of "**Energy Efficiency Savings**" across these sectors, to carry out all sorts of legal administrative, financial and technical studies that will ensure the implementations of these measures.
- After the establishment of SUPER ESCO it will conduct training, consultancy, and implementation studies, including development and implementation and monitoring-measurement-evaluation services, all of that to determine the techniques, methods, and approaches that will increase energy efficiency in public and private sector institutions and workplaces.
- With SUPER ESCO to be created regarding energy efficiency applications while coordinating and monitoring measurements of public tenders to ensure energy efficiency increasing project (VAP), energy performance contract (EPC), and measurement and verification (M&V) all from a sole source.
- To also establish relations and cooperation with public and private sector workplaces (workers/employer) and specialized organizations such as scientific and training institutions, supervised by professional chambers, sector associations. Following agencies and organizations established for similar purposes in foreign countries.
- Established training, consultancy, and studying the use of the right applications, including determining techniques and methods that will increase energy efficiency in public and private sectors, institutions, and workplaces. Researching, modeling, developing, and implementing these monitoring measurement services in finance will boost their application possibilities
- To assist in the establishment of efficiency-related associations, regional centers, and to cooperate intensively with these associations and agencies
- Creating, providing, and controlling all kinds of required supports such as national and international energy efficiency incentives, loans, funds and ensuring the most accurate and effective use of these resources managing and monitoring them according to country and sector priorities.

Solution 2

Energy Performance Contracts (EPC)

- EPC is a model in which energy efficiency increasing projects are financed with a special (saving-efficiency) fund provided by the energy efficiency investment and improvement program that are to be made. Such agencies that are enrolled in the contract will guarantee their services without extra money out of pocket and the risk are on the "**Energy Efficiency Consulting Firm (EVD) and/or Energy Service firm (ESCO)**", there is no financial and application risk during the contract period, it's a "win–win" model, that is used in US public and commercial buildings along with the EU and Asian countries. Guaranteed EPC (Saving Shared EPC) can be done either by the company's financing or by ESCO and other financing banks.
- In the public sectors very, important steps have been taken because of the necessity of energy management, the establishment of ISO 50001 Energy Management System (EnMS), with an energy efficiency survey project to carry out efficiency-enhancing practices with "**Energy Performance Contracts (EPC)**", so to do that the law was amended, and the relevant detailed implementations and procedures were published in the official newspaper on April 15th, 2021. However, the EPC needs to be coordinated with the public procurement law, the Turkish commercial code, the Turkish Legal system, and the Turkish Banking-Insurance system. Meanwhile, an independent 3d-party expert mechanism should be established so it can resolve any problems in case of any disputes.

4.1 ESCO Model

The most important feature of these models is the energy efficiency applications that is supplied by an energy service provider company (**ESCO)**, which provides both financing and technical performance guarantee, the model will first determine the current energy consumption so it can create a baseline, according to this baseline it will compute an energy study and calculation specifically in the required field inputs, so it can realize the guaranteed potential energy-saving and performance with a certain contract period, such contract takes full responsibility of this project including the operation, product management, and system energy and performance. Whether this energy performance contract is realized or not, is determined by the "Measurement and Verification (M&V)" method, which works accordingly to the before and after energy saving rates. In accordance with the energy performance contract, any sanctions payments if exists are terminated. If necessary or upon the customer request ESCO can also provide an "**Energy Sales Contract (ESC)**" in addition to the "**Energy Performance Contract (EPC)**", ESCO can also establish a **Pv powered Cogeneration/Trigeneration** and can even buy/sell Electricity, and natural gas from available power distribution companies (Fig. 1).

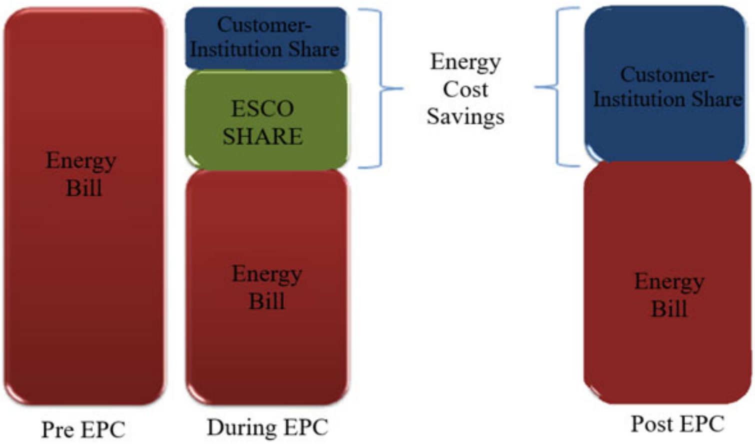

Fig. 1 ESCO model (SHURA 2021)

The main benefit and purpose of the EPC model in the energy efficiency transformation field is the repayment of the investment with the funds from the savings obtained over time, regarding who makes the investment whether it is ESCO or the institutions/facility owners, when EPC is in a fixed contract for ESCO, to guarantee the potential energy efficiency savings because of the detailed study carried out in a facility or institution with them providing savings and investments for the projects that are to be made (Fig. 2).

In ESCO-EPC Model Solution; especially "Energy Performance Contract (EPC)" and "Energy Sales Contract (ESC)" etc. There is a wide variety of investments models and applications in different countries such as.

4.2 Sub Models of ESCO-EPC

Energy performance agreement with saving guarantee (TGEPC): is a financial investment which is done either by the owners of the facility of or through a third-party financial institution, if technical energy performance is a risk in the facility/institutions then so is it in ESCO. This type of model is used widely in many countries around the world, especially in public buildings and in countries with a strong ESCO structure, on the other hand in our country since the "Saving Guaranteed EPC" fee is to be paid to the ESCO as per contract, the public own annual energy budgets can be used as a part of the institutions current budget so funding can be made more accessible, depending on the EPC contract in the public sector; the amount of needed material equals the amount of the investment needed, which can be paid during the contract periods annually/monthly funded by external loans and the remaining part from the public's budget, sharing risks with the customer is the

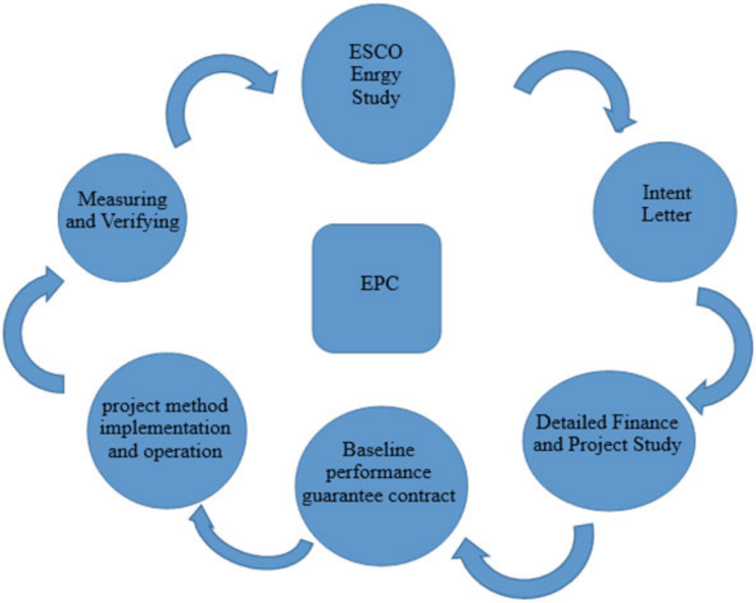

Fig. 2 EPC flow process (SHURA 2021)

biggest advantage but an important disadvantage is that it is not preferred in public and private sectors that have financial difficulties which leads ESCO not to push too hard to achieve maximum savings since it doesn't take risk in this case (Financial risk) (Fig. 3).

Guarantee Energy Performance Contract Sharing (PGEPC): in this type of contract, both investment and technical application risks in energy-saving performance entirely belong to ESCO, now since ESCO also make the investment, it receives all or part of the savings obtained during the contract period, and it is one of the most suitable solutions for the public and private sector, ESCO also assumes both technical application risk and financial risk in order not to take any risks, ESCO also undertakes and supervises the maintenance and operation during the performance guarantee application. ESCO can make investments and EPCs using its resources if available. a third party can use the investment material as credit for financing, and the rest of the progress payments can be obtained as mentioned before through monthly/annual payment contracts that are to be obtained from savings. ESCO can also provide all or part of the EPC values as a loan from external funds acquired from banks. ESCO may also grant contracts to the material investments as a part of the EPC which is to be conducted by the device manufacturers and suppliers. ESCO can also grant these manufacturers and suppliers a similar performance guarantee according to the performance guarantee given to the institution. A strong financial and engineering structure by the private sector is provided by ESCO which is an advantage since it is more suitable for customers with difficult access to finance, and

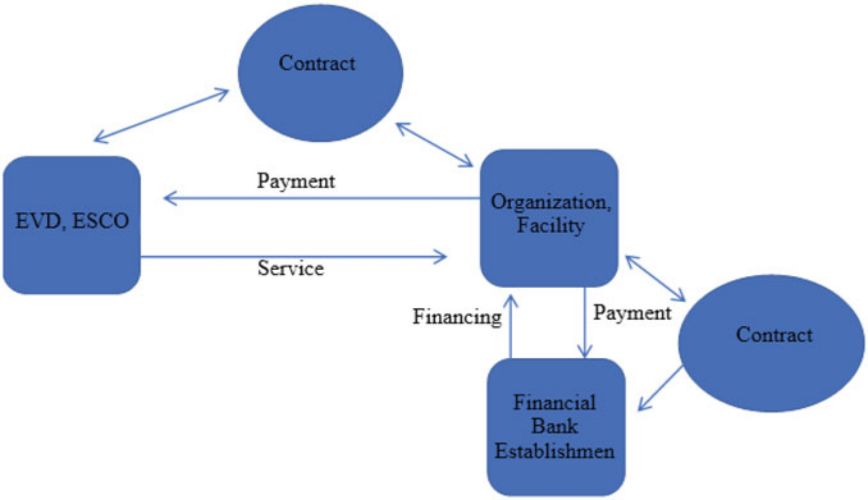

Fig. 3 TGEPC flow process (SHURA 2021)

it is more applicable by large ESCO companies, and it is more suitable for projects with long returns which is the most important advantage here. Variable input process which its applications in industrial facilities are connected to production requires the risk and measurement verification (M&V) which is one of its disadvantages (Fig. 4).

Partial Savings Guarantee and Partial Savings Sharing with EPC: this can be preferred for ESCO-driven institutions and a model where risks are shared in terms of financing that can be applied both in public and private sectors. Part of the investments and implementations of ESCO is covered by the institutions as EPC with their

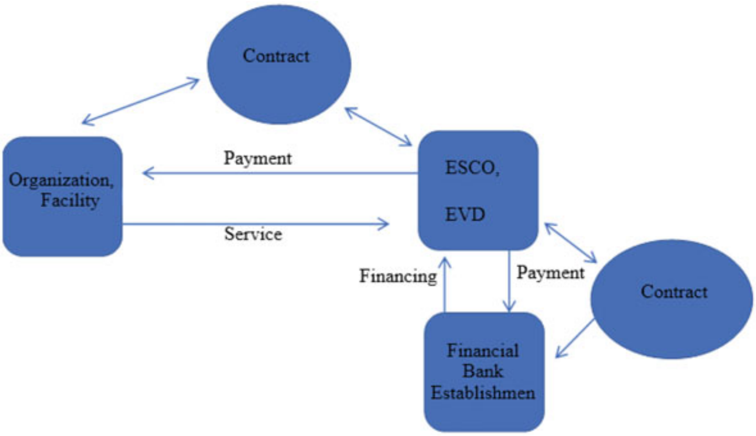

Fig. 4 PGEPC flow process (SHURA 2021)

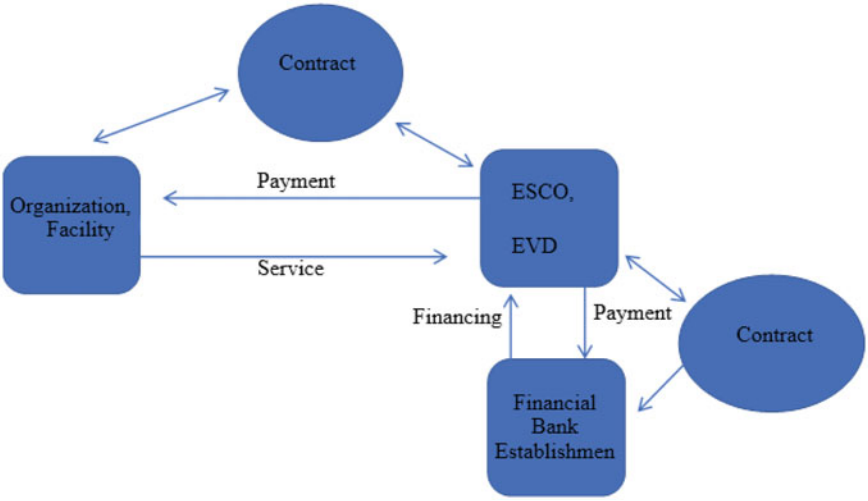

Fig. 5 OTGEPC flow chart (SHURA 2021)

savings guarantee, the remaining parts are shared between the parties according to the agreement during the EPC contract.

EPC Guaranteed Approved Savings (OTGEPC): this is a model in which ESCO first finances an amount of the project cost and then carries the obligation to repay the lender for this investment, in this model the facility/organization commits to provide ESCO with an advance of approximately 50% of the project and repay the remaining investment financed by ESCO monthly over the period (1–2 years) at the project completion date. Payments are finalized after confirmation of expected savings from the project (measurement and verification M&V) (Fig. 5).

Super ESCO Model: New public institution or an institution with suitable infrastructure is created to make energy efficiency transformations in the public giving them the authority to do so, all funds, resources, and practices related to energy efficiency transformation are managed here. Tender specifications, performance contracts, baseline formation studies, tender process, belief process, implementation, measurement and verification (M&V), monitoring, and finalization; are all conducted under Super ESCO and other private ESCO sectors. Instead of establishing a new "**Energy Agency**" and-or "**Super ESCO**" in the public in our country; If institutions can be formed as a Super ESCO, together with the Bank of Provinces, TKB, TSKB, TEMSAN, etc., or some of them; energy efficiency transformation in the public can begin quickly. Then, similar models can set an example for the private sector and initiate and accelerate energy transformation. Dubai Model named (ETIHAD) which is a Super ESCO is an institution that provides renewable energy loans and has evaluations in engineering infrastructure, for example, it can be assigned as Provincial

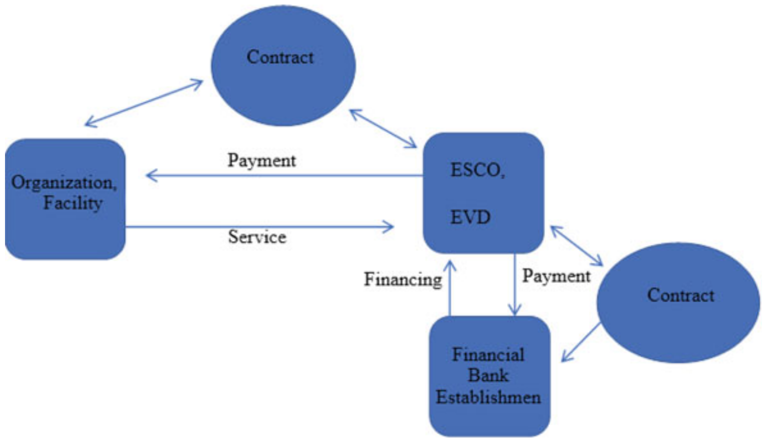

Fig. 6 Super ESCO flow process (SHURA 2021)

Bank or TKB. It can make and make public tenders, specifications, contracts monitoring, and measurement and verifications with ESCOs in the market. It can receive, manage, and use EV and YE financing from funds and even from the public (Fig. 6).

Energy Sales Contract (ESC): ESCO undertakes the energy management of the entire institution, it establishes and operates itself for a certain period, and sells energy (electricity, natural gas, hot water, steam, cooling, etc.) for a certain period, Similar practices are conducted in Germany and many countries in Turkey.

Savings Competition Model: It is an EPC model that ESCO will win after the energy studies of public buildings and-or commercial buildings, tendering on the amount of annual savings that can be obtained in facility-institution and giving the shortest return on this amount of savings and-or more as the contract period. This EPC model: Savings Can be Guaranteed EPC and-or Savings Sharing Guaranteed EPC. In our country, the ESCO, which makes the most optimal offer for saving MW, kW, or CO_2 regarding (maximum amount of savings, price, turnaround time) will win over the minimum amount of savings predetermined for a public or private facility/institution, and the Public will provide incentives according to a certain MW, kW and-or CO_2 ratio according to the total amount of annual support available to the Public; It could be a similar model to the one in Germany and Sweden. However, the Ministry of Energy and Natural Resources may prefer that the investment are to be made by the ESCO and that savings be shared, and no money is spent from the public current energy budget, especially and if possible because public resources are also limited and must be used for other purposes. Until the ESCO-EPC Model is seated, it can be considered as an EV support and incentive mechanism.

Guaranteed EPC Partial Savings and Partial Conventional Method (EPC Model Recommended by the World Bank to the General Directorate of MoUE)

- Studied and detailed report on the potentials for energy savings are created, which is prepared by (**Ministry of Environment Urbanization and Climate Change MoUE**) to EVDs and potentials for energy saving are created.
- According to these potentials, the design project construction tender file indicated to the minimum energy savings (e.g., 30%) is prepared by the tender to the consultants and project companies and optimum RE/EE measures are determined.
- Undertakers (ESCOs, EVDs, construction firms, consortiums) are tendered to submit their offers, including alternative ways in which energy to be saved can be maximized cost-effectively.
- Evaluation of proposals: Technical feasibility, minimum or more energy savings selection is made according to the highest “net present value (NBD)”.
- According to the realized energy-saving value (by the project unit subject to confirming) payments are made.
- Payments are made in the form of fixed (input) and performance-based payment mix.
- Detailed technical design/project is given a 10% advance (subject to approval by the project unit).
- If the building refurbishment is completed in accordance with the approved technical design project and specifications: 50% payment is made.
- 1–2 weeks (for 5% validation of ± the “Net Present Value” committed in the offer) performance test: 20% payment is made.
- 10% is paid after 6–12 months to ensure performance and savings.

Areas Supported by Energy Efficiency for Electrical System Transformation

ESCO; Since it will maximize energy efficiency savings in plants with “Energy Performance Contracts (EPC)” and make “Energy Sales Contracts (ESC)” within the scope of energy sales with investments such as Cogen-PV, it will ensure total and maximum energy efficiency in the plant/enterprise. Therefore, the ESCO model will also make the most of the fundamental contributions to the increase and spread of distributed energy production such as white certificate, demand-side management, to different new business and financial models, digitalization, etc., which are all elements of other electrical system transformations. Without an ESCO-EPC model that manages both production and consumption, which performs an integrated energy efficiency saving management, it is unlikely that many different energy transformation solutions and applications whether are financed or not will integrate or be sustainable, healthy, and successful. Further environmental and financial costs for energy generation, transmission, and distribution investments will contribute significantly to reducing finance and improving the efficiency, and problems of the existing electrical system. Thus, since it also provides the reduction of excessive electricity consumption/loads, preventing financial crashes in transmission and distribution systems will help to reduce additional maintenance and operating expenses, indirect reduction of financial, material, fatigue, renewals and relief of the energy production, distribution, and transmission system.

In Which Areas of the Electrical System does it Apply to?

ESCO-EPC-ESC models, "Transmission System Operators (TSO) and Distribution System Operators (DSO), are applied on the demand management side from production, distribution, transmission, and end-user, in reducing, managing, and financing each electric and electro-mechanical device for electricity and energy consumption. In addition, apart from the reduction, control, and management of electricity consumption; it is also applied in the production and investment of greener, efficient, and renewable electricity heat generation.

What area of the electrical system does it affect?

TSO-DSO affects the reduction or displacement of production, distribution, and transmission to end-user investments. It also provides demand-side management control, demand shifting, shaving demand, reducing demand. In addition to the existing electricity and natural gas system, distributed energy positively affects the dissemination of applications.

How does it help energy efficiency?

Since both financial and technological risks are taken with ESCO-EPC-ESC models, maximum engineering technological applications will be made to achieve maximum savings (to share all or part of the monetary value of the savings obtained), maximum energy efficiency conversion will also be achieved. At the same time, since partial device replacement, etc. cannot be achieved in energy efficiency applications and only within the scope of ESCO-EPC, energy efficiency conversion of an entire plant can be performed; the total savings and efficiency to be achieved will be greater. Energy efficiency transformations focused on product system sales, which do not provide energy-saving performance. It does not save as much as EPC, because it only focuses on some projects that are easy to implement and where material sales and profits are high. Thus, very little of the maximum savings' potential is recovered. Therefore, in Turkey, which has great savings potential, maximum and real energy efficiency can only be achieved by the fact that the ESCO-EPC-ESC model and financial mechanisms are formed in accordance with holistic, accurate, and sustainable country conditions.

"Energy Efficiency Consultancy (EVD)" companies in Turkey.

- "Detailed energy efficiency studies"
- "Efficiency-enhancing project (VAP)"
- "Energy management (EM)"
- "Energy management training"
- In addition to preparing an "energy identity document (EKB)", it will contribute to the increase of efficiency by making the application project and engineering, purchasing, commissioning, measurement, and verification of the prepared VAPs. In addition, apart from EPC, the use of new energy sources with ESC in place

is also inefficient, as there is no loss/leakage production so both production and consumption efficiency, i.e., “total efficiency”, will be increased.

5 Facilitators, Restrictions, and Requirements, What Are the Facilitating Approaches?

- Diversification of financing sources, such as leasing organizations, where there are resources that can simplify the issue of collaterals.
- Allocation of resources that can be used through energy efficiency specific, organizations and ESCO’s.
- Use of climate packages by contracts from outside suppliers regarding the sustainable city, energy efficiency, etc., and providing loans and funds to be developed for EPC applications guaranteed savings in the public and private sectors, such as WB, EBRD, AFD, etc.
- Implementing a mortgage like a model in energy-efficient housing conversions.
- Not specified on the legal infrastructure of EPCs, mediation, etc.
- "Energy survey report” and “occupational liability insurance-performance insurance” for the application project.
- It will help to provide “bail insurance” by ESCO for savings performance guarantees in the application and to provide that “bail insurance” against the bankruptcy and payment difficulty that may encounter the owner.
- This insurance system will guarantee the responsibilities of the parties to each other. In this financial security environment, important institutions and banks will make it easier to obtain loans. The important thing is that there are no gaps in financial responsibilities between the parties and the bank can see spot any issues. On the other hand, for the owner who invested himself, there is no need for assurance for bankruptcy, etc. This 3-way insurance system can be shaped according to the EPC models applied, especially since advances in energy monitoring, measuring, verification, management systems, meters, sensors, ICT, and IoT are essential for ESCO-EPC applications since they are highly helpful technologies and approaches for implementing the solution.
- New LED systems, efficient heat pumps, HVAC and pump motors, PV and Cogen systems also make great contributions to the solution as technologies that ensure performance guarantees in EPC applications.
- In addition, new business services and models developed by TSO-DSO and IT companies due to competition, roof PV applications, transition to distributed energy and smart grid, etc. approaches also mature and help the ESCO-EPC implementation process.
- Energy funds, voluntary agreements, VAP, savings competitions, 5. Zone-Kosgeb incentives, roof PV offset mechanism, white certificates, ISO50001 energy management system, energy efficiency clusters, demand-side management, distributed energy systems, legal obligations, and 15% public savings targets

by 2023; are approaches that contribute to the implementation of the ESCO-EPC solution.

What are the restrictions for such implementation?

- Financial difficulties in the public and private sectors.
- The communiqué on the filling of the "Energy Efficiency Law" amendment regarding EPC has just been published on April 15, 2021.
- EPC models have not yet been determined and clarified.
- Uncertainty of what the "Baseline" and "measurement and verification (M&V)" mechanism will be.
- Energy efficiency project financing as in renewable energy on the bank's side and the absence of a credit mechanism that belongs only to energy efficiency.
- Failure of the facility or ESCO and the absence of possible credit, technology, and performance risk insurance in case of bankruptcy.
- Failure to create a competent and effective public institution with only EV transformation (a strong central agency or Super ESCO, etc.)
- "Demand-side management (DSM)" has not yet been initiated in the electricity distribution, transmission, and retail sectors.
- Lack of strong ESCOs,
- Public investments from their budgets, current expenditures from the central budget, and the benefit of saving are not visible.
- Not spreading awareness, energy management, and energy studies to the public.
- Not knowing the credit, incentive, and support mechanisms fully and not being able to implement them easily.
- In applications for public buildings:
  - Uncertainties and information deficiencies regarding the building inventories of public institutions.
  - Public institutions make their investment expenditures from their budgets and current expenditures from the central budget. Energy efficiency is not among the priorities because they do not see the benefit of saving.
- Lack of special incentives for energy efficiency applications in industry.
- Lack of support mechanism for energy efficiency for public buildings.
- The last building census in Turkey is from 2000. Providing building census and energy consumption data to make healthy assessments of building potential.
- Lack of research and focus on energy efficiency in transportation.
- Energy efficiency investments are prioritized on a segment, region by region basis, socioeconomic also research for the setup of effective support mechanism and lack of impact analysis.

What are the requirements for such implementation?

- As a good example, the different ESCO-EPC models mentioned above should be tried in pilot projects in the public and private sectors. The most suitable and working repeatable models should be designated as legislation and tender method and applied for energy efficiency transformation throughout the country. For example, different EPC pilot applications can be made in the public and private sectors with the German DENA with the World Bank concerning the agreements and projects between the Ministries of the two countries. The relevant Ministries can be included in the process and the legislation, specification, contract, and tender implementation processes can be developed.

- Large ESCO's created by large energy companies or technology companies can be directed towards large investments, while local ESCO's with high engineering experience can be concentrated in small-scale businesses while Small EVDs and implementing engineering companies need to come together and form a large ESCO to provide better solutions
- If the "Energy Efficiency Learning Network" etc. can be created by the public, NGOs, and sector in the industry, private sector, and public municipalities internationally or nationally, it can be ensured that the facilities and institutions that are members of this network learn ESCO-EPC solutions, share good examples, and increase the demand for EPC solutions.
- To manage and prioritize loans and other future funds, a domestic/national bank such as Halkbank, Vakıfbank, and Ziraat Bank, etc. can be authorized and specialized in energy efficiency loan and financing.
- Through an "Energy Efficiency Fund" to be established by the Presidency of Budget and Strategy and the Ministry of Treasury and Finance; Some of the savings obtained from energy efficiency transformation in the public sector can be supported by TRT share, energy fund, etc., energy-saving competitions, "efficiency-enhancing projects (VAPs)" and public EPCs.
- Financial support mechanisms can be developed and increased by transferring outsourced and national resources to the "Energy Efficiency Fund" to be created. This fund also regarding a risk that will occur during implementation can be used as insurance.
- "Credit Guarantee Fund (KGF)"; In EPC applications to ESCO's, can provide the necessary credit guarantees in accordance with the savings to be obtained under favorable conditions. BDKK can pave the way for banks to provide energy efficiency (EE) project financing in energy efficiency transformation projects by accepting the savings guarantee to be committed by ESCO as a loan, collateral, mortgage, and ESCOs.
- Banks can create units specializing in ESCO-EPC, EE project finance, credit, and performance risk insurance.
- Applications such as BSMV, KKDF, and interest deduction, reducing credit risk weighting in the calculation of capital adequacy ratio can be provided.
- Financial literacy and awareness campaigns and training can be given to sectors and users to understand the benefits of energy efficiency projects.

What is the relationship with other Energy Efficiency Solutions?

- Other solutions of energy efficiency transformation; Demand-side management, smart energy monitoring system (IoT, smart meter), energy-saving competition, white certificate, energy studies, energy management, energy efficiency, and competition tenders, one of the most important solutions that trigger, increases, and creates distributed grid integration is the ESCO-EPC model.

- ESCO-EPC-ESC: will use these solutions, which will help transform digitalization, IoT, ICT, and the service sector; it is also a new and most important business and financial model. In this respect, it is the most effective model and method that will create synergy and be the catalyst with all other solutions
- However, energy production, transmission, distribution, and retail companies still make money on the sale of electricity as much as kWh amount in Turkey. Maximum electricity savings and distributed electricity generation-oriented investments and solutions of EPC-ESC models; unless there are public subsidies, obligations, sanctions, TSO-DSO demand-side management will also clash with some of its solutions.
- ESCO-EPC application; VAP, Voluntary Agreements, grants, incentives, and further promotion and crediting of Renewable Energy applications can create a constraint. These are the sectors that are accustomed and waiting for incentives that may not be sympathetic to the self-paying EPC model by committing to guaranteed savings using either its equity or credit. It can only expect the investment to be made by the ESCO, which may restrict ESCO practices.
- If the Savings Competition Model, an EPC finance model similar to VAPs, is implemented (in which the State purchases the savings obtained by competing institutions and facilities within a certain budget); it has a certain leverage effect. However, to benefit from this model, all institutions and facilities may delay or delay their investments if they do not win their investments or competitions.

In addition, ESCO has relations with other financing models that support energy efficiency as follows.

Leasing Model

Leasing is a contract between the owner of the asset and the user which in exchange for a rental payment the tenant has the right to use the energy-efficient compressor, cooling group, Cogen-trigen, Pv, etc. facilities for a certain period (basic rental period). The rent is usually paid annually to the leasing institution. The tenant can be an ESCO or a customer (building owner). At the end of the rental period, ESCO or the customer purchases the device, the facility and puts it into ownership at the settlement price. Currently, some Cogen-trigens, generators, and recently cooling groups are leased by manufacturer groups similar to this model. According to the laws and regulations of the belief rental in our country, the total rental period cannot exceed 80% of the economic life of the equipment. According to the laws and regulations of leasing in our country, the total rental price cannot exceed 90% of the market value of the equipment.

White Certificate Model

With an application such as “carbon offset and carbon deflation”, which is available in India, the amounts of savings obtained especially in the facilities to the industry can be certified and sold on the free market. Energy efficiency investors receive an additional contribution and support. The amount of savings obtained because of the savings competition model in our country; With the “White Certificate”, a sales mechanism can be established for companies that do not and cannot save energy.

Integrated Model: Energy Sales Contract with (ESC) and EPC

ESCO; owns energy supply facilities or has the right to sell energy to the customer. To the same customer, it can also do EPC with ESC. Or the ESCO undertakes the installation, operation, and maintenance of refurbished power generation facilities in the customer’s facility. The customer pays the fee to ESCO via the kWh, m^3, which is calculated by the formula that is bound by the contract. ESCO can also make energy efficiency transformations in the plant/institution with EPC.

Purchase of Goods and Services Model with Public Current Energy Budget Within the Scope of Existing Law 4374

Until secondary legislation is formed, it is possible to model and implement some of the energy efficiency transformation investments in a mixed way as a service according to the return time of the investment within the framework of the current legislation. General Communiqué of Public Procurement Md/63.1; the repairs related to the construction work are described as construction. If we accept maintenance and repair of EPC according to Law Md/4.

22/b: Due to special software-software for monitoring and managing the improvement; by exercising a special right (energy monitoring and management system, etc.).

Or 22/c: After the work is done, with the existing goods and automation system, EPC can be made using contracting up to 3 years from the first purchase place to ensure technological compliance. However, shared EPC cannot be done. Because the purchase of goods and services must be fixed (for the public to be able to contract and pay at a certain price).

Providing Finance Through ESCO-Technology

Here, powerful ESCOs provide EPC investment financing either with their financing or with loans from banks, or other 3rd financing providers. ESCO invests in project partnership/solution partnership with other ESCO and technology manufacturers, providers, providing financing needs.

Financing by INVOICE

Energy production, distribution, and retail sales companies can make credit-EPC agreements, especially with residential, industrial, and commercial customers. DSO-TSO’s can make the investment with the ESCO Model, and they will be able to pay the monthly normal electricity bill, the savings are to be obtained through the investment by adding the invoice, collecting according to the return time of the investment. Especially energy-efficient white goods, lighting-LED conversion, insulation, air conditioning, and boiler conversion can be used for EPC, etc.

Table 1 Sectoral application area of ESCO-EPC sub-models (SHURA 2021)

	Areas of application				
Model	Public building	Municipality	Commercial facility	Industrial	Residential
EPC with savings guarantee	X	X	X	X	
EPC with sharing guarantee	X	X	X	X	
ESC	X	X	X	X	X
ESC + EPS	X	X	X	X	
Cconfirmed savings	X	X	X	X	
(EPC) sharing guarantee + (EPC) Savings guarantee	X	X	X	X	
Super ESCO	X	X			
Savings contest	X	X	X	X	
Partial EPC + conventional method	X	X	X	X	
EPC + ESC	X	X	X		

Energy Efficiency Service Model

Not Capex, but through Opex by ESCO to the customer; Lighting conversion, energy monitoring system, pump/motor, and Pv system, etc. can be established with a fixed monthly service fee for periods such as 24 months/36 months/48 months, etc. Within the scope of new business models, energy sales companies, telecom companies, energy monitoring, and management system companies, facility management companies can enter energy efficiency transformation applications with such energy service model (Tables 1 and 2).

6 Review of Good Practices

Germany Digital Energy Sales Contract (Thermondo Case) in

By installing boiler heating and hot water system in the residences with the method of subscription-rental over the Internet. Energy sales service method through invoice has been implemented since 2016. Minimum per dwelling: 5% more heating energy savings.

Table 2 Applicable ESCO-EPC models and required tools (SHURA 2021)

	I					
Model	Advantage	Disadvantage	Required institutional structure	Required legislation	Required financial tools	Applicability (scoring 1–5)
EPC with savings guarantee	Easy, low risk	Less preferred	Creation of a public institution	Secondary legislation and legal-banking legislation amendment	Creating project finance + insurance	4
EPC with sharing guarantee	Highly preferred	Difficult and high risk	Creation of a public institution	Secondary legislation and legal-banking legislation amendment	Creating project finance + insurance	3
ESC	Easy, and applied immediately	Decrease in revenue of DNO/TSO	Creation of DSM infrastructure of energy sales companies	Formation of heat and Cogen law and demand-side management	Establishment of state aids	5
EPC + ESC	Easy, and applied immediately	Persuading to the customer	Creation of a public institution	Secondary legislation and legal-banking legislation amendment	Creating project finance + insurance	4
Confirmed savings	Easy, low risk	Persuading to the customer	Creation of a public institution	Secondary legislation and legal-banking legislation amendment	Creating project finance + insurance	4

(continued)

Table 2 (continued)

	I					
Model	Advantage	Disadvantage	Required institutional structure	Required legislation	Required financial tools	Applicability (scoring 1–5)
(EPC) sharing guarantee + (EPC) savings guarantee	Easy, low risk	Difficulty in preparing the O&D and contract	Creation of a public institution	Secondary legislation and legal-banking legislation amendment	Creating project finance + insurance	3
Super ESCO	ESCO-EPC model is easy for the public	Difficulty in the formation of the institutional structure	Creation of a public institution	Secondary legislation and legal-banking legislation amendment	Creation of public finance	5
Savings contest	Easy for the public to implement	Providing the budget-incentive	Creation of a public institution	Secondary legislation and legal-banking legislation amendment	Creation of public finance	4
Partial EPC + conventional method	Easy for the public to implement	Providing the budget-incentive	Creation of a public institution	Secondary legislation and legal-banking legislation amendment	Creation of public finance	5

Germany Savings Competition Model (Step-up)

Starting in 2016, all companies can apply for funds, regardless of their legal form, from family businesses to large industrial companies. The requested funding is based on expected CO_2 savings (“subsidy-euro” per kWh and CO_2 savings per year). The higher the savings or the lower the subsidy requested, the greater the chance of funding and the competition is won. The duration of the program is a maximum of 3 years and there is a maximum funding rate of 50% of productivity-related costs (additional investment costs, auxiliary costs, and costs for preparing or approving the necessary savings concept). This puts a maximum upper limit on the production quota as each applicant can decide for themselves which funding rate to apply to this upper limit from a competitive point of view for the productivity project. The 10-year pilot envisions energy savings is 1446 GWh.

Germany-kFW Energy Efficient Building Finance Support Model

Since 1996, tenders and applications have been made with EPC, which is managed by BEA and guarantees savings in both public and private buildings. Bea’s operational costs were first covered by the German Government and now continue as an energy agency providing its own financial needs. Within the scope of this project, approximately; 26% energy saving was achieved. Only in 2013, it reduced CO_2 emissions by 70,000 tons.

Ireland-Tax Reduction Model

Since 2008, approximately 17,000 products in 52 different technologies had tax breaks applied to companies that use and sell them. In public institutions, the use of these products is mandatory. Expected energy savings in 2020; will be 185 GWh.

India Energy Saving Certificate and White Energy Certificate Trading Model

Starting in 2012, it has been compulsory in 478 Factories in 8 different industrial areas. Every year for 1–2% energy reduction target, they can achieve their goals by obtaining energy saving certificates. Between 2012 and 2015 6.6 Mtoe energy savings were achieved and 26 Mton CO_2 emissions were reduced.

Energy Efficiency Fund Model for the Chinese industry

Since 2006, incentive efforts have been made by creating a fund for 1000 most energy-consuming industrial plants in China, and then for the 10,000 companies that consume the most energy, by 2011 approximately 10,000 of funds are created for the company between 2011 and 2015; 250 Mtoe/2900 TWh energy savings are achieved.

Dubai-Super ESCO ETIHAD Model

Etihad Super ESCO, was established as a public institution in 2013, It works towards energy efficiency transformation with the ESCO-EPC model of public buildings in Dubai. Etihad Super ESCO manages public funds and resources and all tenders and payments. It also makes energy-efficient building transformations in the public by tendering to nearly 30 approved ESCO Companies with the “Shared and Saving

Guaranteed EPC Model", as well as "measuring and verifying (M&V)". To date, more than 9000 public buildings have been transformed into energy efficiency, average: 25–31% savings have been achieved.

Current applications in Turkey

There are 45 Energy Efficiency Consultancy Companies (EVDs) authorized in accordance with the Energy Efficiency Law and legislation in Turkey. Of these, 16 are industrial and 29 are authority buildings. As of 2021, there are 45 EVDs operating in Turkey. Of these, 29 are authorized for the building sector, 16 for industry, and 8 for both sectors. Approximately 70% of EVDs are in Istanbul, while others are distributed to other cities such as Ankara, Izmir, Bursa, Antalya, Kayseri, Kocaeli, etc. Evds are usually private enterprises in Turkey. İlbank, İstanbul MM Enerji A.Ş. ve Ugetam are public enterprises only. EVDs; they must obtain and renew their authorization documents and certificates through EVÇED affiliated with ETKB. EVDs provide services such as energy identification documents, detailed energy study, energy management, and energy management training. Studies are mainly carried out in public buildings, industrial facilities, and hospital-hotel-AVMs. However, existing EVDs are not yet available; Like ESCO's, they cannot invest and implement, i.e., EPC. Even if the legislation is ready, if EVDs cannot become stronger or merge into ESCO's, ESCO-EPC applications will be able to they can serve as subcontractors in measurement and verification issues. When ESCO-EPC applications start to become widespread in the public sector, especially large distribution and transmission companies/service providers and large superstructure construction firms will take part as players in the sector as ESCO. ESCO and EPC 2021 have been implemented with a public project in Turkey. In the private sector, there is no legal restriction. However, since the ESCO-EPC Model and its mechanisms are not yet fully formed, partial applications can be made in the private sector.

EPC and ESC Examples in Turkey

PILOT EPC Application Before Legislation and Releasing Them in the Public

IBB Energy Inc. Istanbul Hasan Dogan Sports Facility Savings Guaranteed Lighting EPC application; it is a work done before the second amendment of the legislation in the public, for the first time in the public, basketball court lighting improvement was made at Energy Inc. Hasan Dogan Sports Facility in this project, which was made as "EPC with Guaranteed Savings" and tried with existing regulations. The specifications were created by Venesco, an Advisor to Energy Inc. As Turkcell Super ESCO, Philips undertook with Endoks. After the application, "measurement and verification (M&V)" was done by Venesco. Lighting systems return time is approximate: 4.6 years, savings to be obtained are determined as 77%, investment is 67,500 TL. However, since the Municipality can contract for a maximum of 3 years, the portion of the investment corresponding to 3 years was modeled as the purchase of maintenance services, and the portion against 1.6 years was modeled as the purchase of goods.

Public Application of EPC

The first ESCO-EPC Tender for Public Energy Efficiency (KABEV) in Turkey was held for a public school in Bursa in early 2021, the contract was signed, and its implementation was started with the World Bank and the Ministry of Environment, Urbanization and Climate Change Building Works Directorate.

Industrial Application of EPC

ESKON Energy Paper Factory Savings Shared EPC Project: Waste Heat Boiler and Thermal compressor application; annual committed savings: $326,022 (~ $27,000 per month). Investment Amount: in USD 370,000 and Deal Duration: 24 Months. Contract Savings Sharing Terms: 65–35%. Annual Savings After Project: USD 378,640.

Commercial Application of EPC

TURSEFF-JOHNSON CONTROLS-ISTANBUL CAROUSEL SHOPPING MALL Savings Guaranteed EPC Project: EPC Financing was given to Carousel Mall by Turseff-Vakıfbank in 2014. In the “EPC With Savings Guaranteed” application by Johnson Controls ESCO; A 14% savings commitment has been made. This project will have a total investment of USD 3.5 Million and a return in 6.8 years; It is one of the first applications in Turkey.

Commercial Application of ESC

TURSEFF-ESKO-Istanbul Florence Nightingale Hospital Energy Sales Contract (ESC): A 100% loan financing for the Cojen application was provided by Turseff to ESKO Company. ESKO took over the investment and operation of 592,000 Euros. ESKO; provided 10 Years of electricity, hot water, and steam that gave the sale price to the Hospital with a guarantee of purchase, 15% below the market price.

World Bank: Turkey Small to Medium Enterprises Project. Credit No. 82430; GEF Grant No: TF14582

In 2016, Turkey received a grant from the Global Environment Fund (GEF) through the World Bank for the Small and Medium Enterprises Energy Efficiency Project (SME EE), the grant would be used to support energy efficiency projects used in the energy performance contract of energy service companies (ESCO). Within this framework, the energy savings requested by the World Bank would be met at a minimum rate and, if appropriate, the project could be financed by Vakfbank, Halkbank, and Ziraat Banks within the scope of the SME EE project under the following conditions, and the total energy efficiency would be eligible for grants of up to 10% of the investment cost or up to USD 100,000, whichever amount is lower. The projects in question should have saved at least 20% energy or resulted in a 20% reduction in the energy consumption of a particular system that uses energy. In addition, in the energy performance contract; At least 30% of the final payment to ESCO, supplier, or leasing company; based on the approval procedures agreed with the customers and banks, it can be paid if it is confirmed that it has occurred at the rate promised in the contract (not less than 20%), otherwise this amount (30% of the contract amount) will not be paid. However, very few projects have been made within the scope of this project.

Recommendations of Previous ESCO-EPC Model and Financial Studies

WB

In 2015, "ETKB IPA12/CS04 Consultancy Services for Energy Efficiency New Bank Products and Financial Methods Report" and "ESCO Development Roadmap" were prepared for ETKB with the support of the World Bank. In these reports, evaluations and recommendations on different ESCO-EPC Models on EV Finance were presented comprehensively.

ECONOLER

In 2016, he prepared many workshops and reports for ETKB within the scope of "Preparing the Roadmap for the Energy Performance Contract for EVD and Developing Case Analysis". He prepared EPS User's Guide and EPC Contract samples for SMEs, with more studies and recommendations that were made on rental models with "Guaranteed and Savings Shared EPC".

TURSEFF

Within the scope of the 265 million USD Sustainable Energy Financing Program provided by the EBRD, high-capacity buildings, financing model studies, and EV-EPC projects were supported. In this context, the first EPC experiences were implemented in Turkey with the TURSEFF-ESKO-Istanbul Florence Nightingale Hospital Energy Sales Contract (ESC), the ESKON Energy-Paper Factory Savings Shared EPC Project, TURSEFF-JOHNSON CONTROLS-ISTANBUL CAROUSEL AVM Savings Guaranteed EPC Project.

Frankfurt School of Finance and Management

In the "National Energy Efficiency Financing Mechanism Roadmap and Support for the Establishment of a Competitive Energy Efficiency Tender Mechanism in Turkey-2019 Project" prepared for ETKB; It is recommended to establish a Super ESCO or energy agency, by presenting models from Countries such as Ukraine, France, India, etc.; They propose the establishment of a national energy fund in Turkey and the transfer of these loans through Super ESCO, ESCOs, Development Agencies, Energy Agency, Banks through this fund. In addition, through the savings competition model, as 3 separate tender models:

1. For small-scale projects: the appropriate set of certified equipment at a certain price is made by taking credit directly from banks.
2. For medium-sized projects: incentives for CO_2 savings per kWh under key performance indicators (KPI) with the principle of "first-come, first-time", within the scope of the specified budget held by the State.

3. For large-scale projects: it proposes to introduce incoming projects into the competition within the scope of the specified annual budget: starting with the highest KPI (lowest price and highest CO_2 reduction per kWh).

ESCO-EPC Potential and Investments in Turkey

An average annual investment of USD 0.6 billion in energy efficiency between 2002 and 2018 is projected to increase to USD 1.4 billion between 2019 and 2030 (2×). The global market size for energy efficiency applications is $236 billion and the ESCO market is $28.6 billion. Based on these sizes, the potential market size of energy efficiency for Turkey is estimated at $2.36 billion with a 1% share estimate, and the ESCO market potential is estimated at $200–250 million. Although no registration system can track all energy efficiency investments, it is estimated that the current market size is around $170–200 million, including equipment sales, based on the business volumes of energy efficiency consulting companies and technology companies, and the volume of the model in which energy efficiency applications are carried out through consultancy services is estimated to be around 20–25 million dollars. These calculations are based on the activities of leading technology supplier companies, including engineering and consultancy services, direct energy efficiency, investments in equipment such as steam and heat boilers, electric motor replacement, «Efficiency Enhancing Projects (VAP)» and business volume and energy studied data. In the period 2002–2018, energy efficiency investments in the industry were mainly carried out by large industrial organizations, most of them did not use external financing, some of the investments were not privatized under the heading of "energy efficiency", and within the scope of larger investment plans. There is an industrial infrastructure in Turkey that has reached a certain level of maturity, which had a high sectoral diversity and has high energy efficiency potential. However, in the 2000s, rapid economic growth increased the need for investments in rapid development, capacity increase, and modernization in the sectoral composition of the industry, and energy efficiency-oriented investments were seen to be made by factors such as environmental legislation and the provision of appropriate financing sources. Experience from industrial projects, VAP, and energy studies indicates that the potential for energy efficiency increase is high, and priority areas are steam boilers, heating systems, and electric motors. The ESCO-EPC model will play a key role in meeting the financing needs, which will increase at a similar rate.

7 Recommendations for Successful Implementation

Finishing the work on setting rules for energy efficiency applications

In the financing of energy efficiency applications, it seems necessary to clarify the conceptual and application-oriented framework and to determine the rules of the

Table 3 Gap analysis (SHURA 2021)

	Subheadings	GAP
Politics	Law, legislative changes	EPC secondary legislation, measurement and verification mechanism, preparation of EPC specification contracts, EPC insurance mechanism, and BDKK project financing barriers, and the absence of arbitration mediation mechanisms
	Implementation of the national energy action plan	Failure to start piloting some of the topics in the action plan such as EPC demand-side management, etc.
	Super ESCO/agency	The lack of a fully competent and responsible institution in the public
	Presidential-sponsored national energy efficiency transformation campaign-obligation	The circular, issued on August 12th, set a target of 15% energy reduction in public buildings by 2023. However, this has not yet been filled out
Technology	For commercial and industrial transformations	Some technologies for energy efficiency are imported and can be expensive. However, as supply increases, both costs are reduced, and they become available to domestic arge and to sub-industries. Some of the technologies such as lighting, PV, Kogen, heat pump, solar wall, solar collector, energy monitoring systems have now become partially produced competitively in our country, but there is no domesticity and insufficient R&D support for them
	For municipal transformations	Electric vehicles, storage systems, smart traffic, biogas, energy from garbage, etc. technological systems are not yet produced in our country and there is no arge support for them

(continued)

Table 3 (continued)

	Subheadings	GAP
Methodology of vehicles development	*Financial vehicles*	Support, bank, loans, grants, cooperatives, leasing, funds, insurances, lack of EPC-ESCO financial models. The fact that a national bank has not been commissioned to do so, and that the EV loan mechanism has not been developed. Lack of EV project funding. The fact that collateral mechanisms such as KGF have not been activated in the EV
	Technical vehicles	The development of ESCO, super ESCO tools, demand-side management tools, etc. is incomplete
	Administrative vehicles	Cooperative law, consumption demand consolidation, discounts (VAT, environmental tax, property tax, electricity prices, etc.), GCC tender methods, state material office special unit prices-poses are missing
Monitoring, reporting, and verification systems	• *ÖDES* measurement, evaluation system establishment, and establishment of ISO 50001 EnMS and energy monitoring management system, measurement and verification protocol	There is no system where both the energy efficiency action plan and the results of the energy efficiency transformations are monitored, measured, and evaluated. It is very important to establish such a unit and system. Especially in the transformation of energy efficiency in the public; although the establishment of "ISO 50001 EnMS" and "energy monitoring and management system" in facilities is the cheapest and fastest solution, it is not used. It was mandatory to install 10,000 m^2 in public and 20,000 m^2 in the private sector by the end of 2023, but it is progressing slowly

(continued)

Table 3 (continued)

	Subheadings	GAP
Need for institutional change	Establishment of a new energy efficiency agency-institution or creation of super Esco	There is a gap because existing structures are effective and inadequate as legislation. Although there are units within many institutions such as the Ministry of Industry, Ministry of Transport, Ministry of Environment and Urbanization, Ministry of Energy, Presidency, etc., a successful energy efficiency transformation cannot be initiated. Therefore, it is necessary to establish a public super ESCO similar to the Berlin energy agency and/or Dubai Etihad ESCO, whose main task is this. There is a need for an institution that manages and oversees all public transformation, financial resources
Market design	**Public municipality commercial-sector industrial-sector residential**	If the transformation of energy efficiency in the public sector, especially from municipalities, can be started with ESCO-EPC models, and a transformation begins in the private sector, industrial sector, and housing sector in Turkey, and the gap in applications decreases. Such financial model consists of technologies, employment, business models, and companies-sector transforms. For market creation, there are shortcomings and gaps in the development of separate ESCO-EPC and financial models for public buildings, municipalities, industrial-commercial facilities, and housing. Big players on the market; energy distribution companies and construction companies have not yet entered this transformation process. Banks and investors also do not yet see energy efficiency saving as a separate commercial product due to the in illegibleness of the country's markets rates and economic outlook

mechanism used. Actions to clarify the framework are needed in topics such as collateral, mediation mechanisms, and energy performance contracts, the creation of independent accredited organizations for measurement and verification. The use of energy performance contracts as collateral, the creation of independent accredited organizations in measurement, verification and the creation of an ESCOs-based structure, the development of mediation mechanisms for resolving disputes between the parties to investment and financing, and the development of mechanisms for minimizing technical and commercial risk are the main elements of the framework. Although the relevant public regulations are being made, there is also a need to improve the applications. In this respect, it is seen that the pilot application of public buildings will play an important role in the establishment of the model. International financial institutions and international collaborations provide capacity-building support; local financial institutions will be able to provide support in developing energy efficiency practices, especially the use of energy performance contracts as collateral, and in the establishment of the ESCO model.

Guarantee of energy performance contracts in financing

The ability to obtain energy performance contracts as collateral, in which the savings/benefits to be provided in the financing of energy efficiency investments/applications are committed, will play a role in increasing and facilitating financing. It is necessary to make facilitating arrangements in banking legislation that the savings can be guaranteed as collateral, to strengthen the legal infrastructure for the legal validity and applicability of energy performance contracts, and to develop standard contracts in accordance with Turkish conditions by taking advantage of international experience. In addition to the capacity-building support of international and local financial institutions, it is especially important for international technology supplier companies to convey their international experience and for energy efficiency consultancy firms to provide guidance for implementation based on turkey examples.

8 Conclusion

Turkey must go through a complete strategy to renovate its building across all sectors, and ensure energy efficiency through the process, and new policies must be set to provide support for such strategies and convincing the decision makers and investors to start as soon as possible. With new financial models being created to fund and support all the projects that are working towards energy efficiency, although efforts to improve the financial situation are not enough and must be improved to ensure the success of the energy transition. Even though the existing policies are okay in terms of energy efficient technologies, but they are incomplete with many gaps that need to be filled, filling these gaps will boost energy efficiency transformation Turkey's industrial, residential, and commercial sector. International models that implement similar policies are available worldwide, but new models should be created out of the available ones to meet Turkey market needs, not to mention the need for financing mechanisms model.

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[1] This article has been compiled and updated from the previously published articles of the author.

Better Economics for Better Energy

Ece Ozdemiroglu, Tanay Sıdkı Uyar, and Tiziana Papa

1 Introduction

In January 2022, the World Economic Forum published the latest version of its Global Risk Perception Survey (WEF 2022). Comparisons to previous years' survey results show increasing recognition and prioritisation of environmental and social risks such as extreme weather, biodiversity loss, and livelihood crises. Some of these risks are intrinsically linked. For example, the top risk of 'climate action failure' may be seen as a political failure but its repercussions will be social—adding to the risk (already ranked 4th) of 'social cohesion erosion'—as well as environmental.

Increasing recognition that environmental and social risks have economic consequences (and indeed causes) is encouraging but it is not sufficient. The action to address such risks is lagging behind. We believe economic analysis can be a powerful tool in supporting such action if it is put to good use. By good use, we mean an economic analysis that includes all factors that affect human wellbeing recognising that these are not limited to the market economy and financial returns.

In this chapter, we start with clarifying some key terms and concepts and how broadening those could encourage more action. There is still a lot of work to do

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to improve the awareness that all environmental and social risks have direct and indirect links to the economic performance of countries and businesses. Further, some of those risks pose existential threats. WEF's use of the term 'economic' to refer only to the market economy is a sign of how much work we still need to do with other economists and all decision makers to show that economics is not just about the movement of money.

How nature and human societies function; and how various risks interact with each other are complex. Different research disciplines and policy portfolios are developed to make such complexity manageable. But the risks we are now facing, like climate change, are too big for a single discipline or policy to deal with. We need to work across disciplines, ministries and businesses. We believe using a broader economic framing can help by pooling different types of data to understand best actions. As well as conceptual discussions about economic analysis, we share examples of renewable policy from the United Kingdom and the Republic of Turkey.

2 What's in a Word?

The words 'economy', 'economic', 'economics' are used almost interchangeably even though they have specific meanings that are, perhaps, broader than most imagine.

'*Economy'* is usually used to refer to what happens in markets; the act of buying and selling goods and services. At the national level, *economy* is mostly measured by the Gross Domestic Product (GDP).[1]

We are fixated on GDP, with mass media continuously reporting its ups and downs. It is as if GDP tells us all we need to know about our economic activity and its growth is the only goal a society should aspire to. This is far from the intention of the creators of the GDP as Mazzucato tells us in her great account of the history of this measure *The Value of Everything—Making and Taking In the Global Economy* (2018).

The GDP became more popular after the Great Depression and the Second World War, when public spending increased, and it was socially and politically important to show that such spending was leading to increased economic activity. But changes in economic activity are not the only factor affecting individuals' or society's welfare or wellbeing. There are three key reasons why the GDP (or any measure of market economy) is a woefully inadequate measure of what should matter to us as decision makers and as members of society.

First, the focus on economic activity within markets is too narrow as it does not take unpaid work like housework and care into account. It also leaves out social and environmental impacts of economic activity like exhaustion of natural resources and pollution, lack of good working conditions, and fair pay.

[1] GDP is the total 'market value' of all goods and services produced in a country in a given time period (usually one year).

Second, it ignores the state of capitals on which all economic activity depends—especially on human, social, and natural capitals.[2] An increase in GDP cannot be deemed *sustainable* if the increase is the result of 'mining' these capitals (or selling the family silver to put in everyday language). If not underpinned by investment in maintaining the capital basis, GDP growth cannot be sustainable and the loss of the capitals base limits our ability to survive, let alone thrive. Moreover, the GDP considers all increases in economic activity as a good thing. For example, if we spend money on cleaning up a major industrial incident, that spending leads to an increase in GDP, instead of showing the decline in our (natural) wealth and wellbeing due to pollution.

Finally, GDP says nothing about the distribution of income from economic activity. Who are the winners or losers of a change in GDP? Where are they in a country or across the world? We cannot tell by looking at GDP alone, and not event GDP per capita.

This narrow focus is not specific to the design and interpretation of GDP. Traditional economic analysis that looks at pros and cons of decisions also tends to focus on market (financial) costs and returns, while ignoring social, health, and environmental impacts (unless money is earned or spent through them) and distribution of such costs and returns across different groups in society.

This brings us to the second key term of interest: '*economic*'. The term is often used to describe the cheapest option for doing something. What it really should mean is the option that delivers the highest net benefit, when all costs and benefits are considered. By *all* we mean both financial and other costs, including internal (to the market economy) and external.[3]

While the majority of economists are busy trying to understand and advise on what happens within markets, some of us (environmental, ecological, health, and similar branches of economics) are just as interested in what happens outside the markets. Our job is to make what is invisible to the markets, visible for decisions about policy, investment, and consumption. Investing in renewable energy, in the enhancement of nature, and in nature-based solutions[4] (NbS) is a particular case in point. It is easy to calculate the financial cost of delivering these investments, but their benefits tend to be underestimated as impacts on nature and its services, simplified as reduced risks to human health and wellbeing are at best quantified but not regularly monetised for direct comparison with financial returns.

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[2] Natural capital: The stock of renewable and non-renewable natural resources that combine to yield a flow of benefits to people. Social capital: The networks together with shared norms, values, and understanding that facilitate cooperation within and among groups. Human capital: The knowledge, skills, competencies, and attributes embodied in individuals that contribute to improved performance and wellbeing (Capitals Coalition 2022).

[3] Externality: situations when the effect of production or consumption of goods and services imposes costs or benefits on others which are not reflected in the prices charged for the goods and services being provided (OECD 2003).

[4] Nature-based solutions are actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (IUCN 2016).

And that brings us to the final, and perhaps most important, term: '*economics'*. Economics are often referred to as the art (and, by some, also the science) of allocating limited resources across unlimited wants and needs. In particular, questioning what those needs and wants are and judging their worthiness are usually outside the scope of an economist. Some concern themselves with the question of *whose* needs and wants and try to use economics to make the distribution of resources more equitable to improve everyone's chance of getting their needs and wants met.

We think there is a different, but related, way of defining economics—the art (and maybe science) of understanding what makes people happier or improves their welfare, wellbeing (or 'utility' in economics terminology) and how we can make a better (wider) economic case for such improvements. You may be forgiven to think that we are defining the work area of psychology or sociology. And indeed, there are many concepts and tools that economics borrow from these disciplines in understanding what influences wellbeing. Delivering on all such influencers requires multidisciplinary approaches to research and joined-up thinking across public policy. The contribution environmental economists can make to this effort is twofold: set up a framework that acknowledges market and non-market (external) costs and benefits; and add to the evidence on the value of clean and safe air, water, land; thriving wildlife and plants, and how these affect healthy minds and bodies as well as safe and inclusive societies.

3 Better Economics for a Better Environment

So how can better economic analysis or appraisal be a conduit for a better environment?

Every economic analysis starts with defining the **baseline**—the state of the world if we do nothing or do the minimum. We still entertain the idea that a baseline in which 'business as usual' can be maintained is at least theoretically possible. We need to remove that theoretical possibility and ensure all our baselines of 'doing nothing' reflect the impacts of climate change and nature related risks. The recommendations and guidance from TCFD[5] and TNFD are welcome and should be taken up.

The **scope** needs to include financial or market *and* non-market or external costs and benefits. Our analysis must recognise that the value of nature is far beyond what we buy and sell in the markets. It's only then that we can demonstrate how the markets depend on natural, social, and human capitals and how we need to invest in those capitals to be able to adapt to a changing future. This will include investments in renewable energy that reduces our greenhouse gas emissions and hence mitigate climate change.

We must learn to care about the **distribution** of all costs and benefits and who wins and who loses. *Pareto efficiency* rule dictates that so long as the winners win enough

[5] The Taskforce on Climate-related Financial Disclosures and The Taskforce on Nature-related Financial Disclosures.

to (theoretically) compensate the loosers, the action is worth taking. But this ignores the cumulative gains and losses, and inherent vulnerabilities in the population. For example, exposure to climate risks may be the same, say, in a particular location, but individuals, households and different businesses will have different vulnerabilities, impacted differently and have different abilities to adapt. Ignoring such differences will mean even the Pareto rule may not be possible to satisfied.

Economic analysis **discounts** the future for three key reasons. The first is that individuals are mortal so we want good things to happen as quickly as possible. But societies live longer and should be more patient and not value the future less than the present. The second reason is that if we have the resources, such as money, now, we could make investments that add to their value. So if we have to wait for the same resources, we'd want more of them to be comparable to having them sooner. Finally, future generations will be wealthier than us (partly because we invest what we have now for good returns) and therefore can deal with their issues better than us. It is better to postpone costs. This assumption is no longer tenable as we are not leaving a better world to them (when all environmental, social and economic dimensions of sustainable development are considered). They may have money (financial capital) but are likely to deal with more environmental and social issues so may still not be better off.

We need to stop discounting the future. A lot of environmental improvements involve initial spending and initial or future returns and cost-savings. While acting early to assess and manage risks makes common sense, if economics continues to discount future returns, early action does not make economic sense.

We also need to show that postponing action has costs. Staying with the climate change example, we incur damage until we take action and we may have to act in haste at some stage in the future. For example, building homes that use less energy and are resilient is cheaper than retrofitting badly built ones to be more efficient. In addition, people living in badly insulated and ventilated homes pay high energy bills throughout winters and/or suffer high temperature in hot summers (CCC 2018). COVID19 pandemic has taught us that acting in haste is very expensive. We need to learn that lesson for adapting to climate change risks.

In short, better economics is realistic about the implications of 'do nothing' baselines; uses a broad scope including market and non-market costs and benefits; takes note of the distribution of costs and benefits across the society and does not discount the future.

Better appraisal is not relevant just when we make a policy or an investment decision that needs appraising. It is also relevant when pricing market goods and services. We must create incentives to make investing in the prevention of environmental degradation and pollution worthwhile. And this, in turn, requires making pollution and polluting activities more expensive, reflecting the (welfare) cost of pollution in the price of polluting activities.

4 Better Policy for Climate Change and Renewable Energy

When it comes to making an investment case for renewable energy or nature-based solutions, better appraisal means taking into account of financial, environmental and social costs and benefits. Better pricing means prices that differentiate sources of energy depending on their environmental and other impacts.

We use money as a common metric to make these invisible non-market or external benefits visible and comparable to financial costs of delivery and forgone financial benefits. This is not because we are the 'fools' Oscar Wilde was referring to when he said, "a fool is someone who knows the price of everything but the value of nothing". We know the *Extinct Rebellion* slogan is right: "there is no money on a dead planet". But because we want to make the invisible visible when making financial decisions. We think one way of doing that is to use the same unit of measurement to express the impacts on environment and human health and wellbeing as we do to express financial returns from creating such impacts. Complete measurement and valuation of environmental and wellbeing impacts will not be possible—nature and our relationship with it is way too complex for that. But what we know for certain is that the cost of impacts or the value of services are not zero.

However, it is not just markets that fail to recognise the value of environment and human wellbeing. Policies that are short-sighted and influenced by market drivers alone also fail. For example, we know coal is a polluting source of energy and historically a key contributor to greenhouse gases since the industrial revolutions. But, around the world, there are still policies that justify using public money to subsidise extraction and use of coal. This is why the first appearance of the word 'coal' in the 26th UNFCC COP document (UNFCC 2021) is hailed as a success by some while others are applauded to learn is had not featured since COP1. Box 1 shows an example of failing to improve public policy, using the case of a power station in Turkey.

Box 1: Yatagan Power Station, Turkey

Yatagan is a coal burning fuel station in the Aegean region in Western Turkey. It was set up in 1983 to make use of the locally available low-quality lignite. Its capacity of 630 MW makes it the least productive power plant in Turkey. Over the years, courts brought in several orders of closure, various studies have been conducted to show the environmental and health damage from air pollution, accumulation of ash and impact on water and soil in the surrounding areas. The plant is yet to comply with the stronger emission standards that require it to implement a desulphurization system or upgraded dust filters.

Gümüşel and Gündüzyeli (2019) argue that the three coal-fired power plants in Muğla are responsible for

- 280 premature deaths a year

- 360 million tonnes of CO_2 emitted between 1982 and 2017
- 10 s of 100 s forest and agricultural area loss with all their benefits.

Despite the low productivity of the plant and the named environmental and human-health hazards, the plant's operating rights have been extended multiple times by temporary activity certificates. And the government's support remains in force: in August 2021, 761 million Turkish Liras were spent by the Ministry of Industry and Technology to rehabilitate this plant among others to operate for 30 more years.

Source: HEAL 2019 and Gümüşel and Gündüzyeli (2019).

A good example of breaking disciplinary silos and attempting to use broader scopes for economic appraisal and encourage full-cost pricing is legislation like the UK's Climate Change Act (2008). The Act was the first legislation of its kind, comprehensive in mentioning both mitigation[6] and adaptation.[7] That said, the Act gave more roles and powers on mitigation to the independent statutory body it set up (the Climate Change Committee—CCC) than it did on adaptation; exemplified by the fact that adaptation is still the subject of a 'sub-committee' within the CCC and that it "remains the Cinderella of climate change" (CCC 2021).

The narrowing gap between mitigation and adaptation is most clearly observed in the committee's latest *Climate Change Risk Assessment (CCRA) Advice Report* published in 2021 (CCC 2021). In their foreword, the Committee says:

> Reducing climate impacts requires both emissions reduction and adaptation. The UK will face significant further changes in climate to 2050 and beyond, even if the world is on a Paris-aligned emissions trajectory… Without action on adaptation we will struggle to deliver key Government and societal goals, including Net Zero[8] itself. We cannot rely on nature to sequester carbon unless we ensure that our peat, our trees and our wetlands are healthy, not only today but under the climatic conditions we will experience in the future.

Box 2 shows the principles of good adaptation outlined by the CCC. It states that mitigation and adaptation should be thought together in all areas of policy and business, particularly to ensure that the power system is resilient to climate change which is considered one of the top risks for the UK (CCC 2021).

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[6] A human intervention to reduce the sources or enhance the sinks of greenhouse gases (GHGs) (IPCC 2001).

[7] The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. (IPCC 2001).

[8] 'Net Zero' means either zero emissions of GHGs from human activity or balancing of emissions with sequestration and storage of carbon so that the balance at the end of a given period is zero increase in the carbon released into the atmosphere.

Box 2: The UK Climate Change Committee's Principles of Good Adaptation Policy

1. A vision for a well-adapted UK
2. Integrate adaptation into other policies
3. Adapt to 2 °C, assess the risks for 4 °C
4. Avoid lock-in (investing in technologies that will not be sustainable in different climate futures)
5. Prepare for unpredictable extremes
6. Assess interdependencies
7. Understand threshold effects
8. Address inequalities
9. Consider opportunities
10. Funding, resourcing, metrics, and research.

Integrate adaptation into policies, including for Net Zero A host of government and societal goals will be undermined by the effects of climate change, including the provision of reliable and safe supplies of food and water; infrastructure services such as transport, energy, and communications; biodiversity; public health; natural and cultural heritage; and the achievement of Net Zero. A more realistic appraisal of climate risk must be embedded in the policies, investments, and decisions that relate to these goals. In the past three years, the opportunity was missed in 11 of 15 relevant major UK Government announcements to include integrated plans to adapt to climate change alongside those for reducing emissions. Where adaptation was mentioned, it often lacked specific actions or was not viewed as necessary to meeting the goal of that particular policy. In others it was simply absent. The best way to address climate change and to avoid unintended consequences is to ensure adaptation and mitigation are considered together in those areas where there are the major interactions: especially across policies for infrastructure, buildings, and the natural environment.

Source: CCC (2021).

Policies that are designed to encourage electrification need to consider climate change impacts on electricity generation and transmission, given that electrification is an important part of the mitigation strategies of many countries, including the UK. Electricity is meant to replace fossil fuels, in particular for transport and heating, with renewable sources of energy (or at least with less polluting fuels). Thus, it's crucial that electricity generation planning integrates climate and nature risks.

In the UK, electricity provides about 15–20% of the energy used today. By 2050, it could account for around 65%, as the country transitions to the use of electricity for heat, transport, and across industries, as well as for lighting, communications, and for the delivery of other critical services such as water supply. It follows, that people and the economy will be increasingly exposed and vulnerable to electricity system failures. Different parts of the power sector can be impacted by each of the major climate hazards: flooding, water shortages, increased temperatures and wildfires, sea level rises and potential increases in storms, swells, and wave heights. Within a Net Zero power system, weather-dependent renewables like offshore wind are expected to play a dominant role. The CCC strongly recommends that the UK Government works with the regulator (Ofgem) and the industry to review the approach to the electricity system design and risk assessment in the context of the more central role of electricity in the UK's future energy system. The next 10 years will see a huge growth in investment in both electricity generation and in the expansion of the distribution grid. For example, the UK Government plans a four-fold increase to 40 GW in offshore wind by 2030, alongside significant electrification in transport, heat, and industry.

Awareness of climate change risks has also been increasing in all parts of the society in Turkey. The government of Turkey ratified the Paris Agreement of the UNFCCC in October 2021; just in time for COP26 in Glasgow in November 2021. They further introduced the "National Climate Change Strategy" that will help the international joint efforts to fight climate change, considering its own special circumstances and capacity. The strategy includes a set of objectives to be implemented in short, medium, and long-term.

A set of policies and frameworks under the so-called National Climate Change Action Plan (NCCAP) are to be worked with in many sectors starting with the energy sector. The focus of actions for this sector are: increasing the use of renewable energy; reducing the use of coal in power generation; using cleaner coal technologies until a full transition to renewable energy; and reducing losses during energy transmission. In the consumption side of the policy, actions include increasing energy efficiency in buildings and lowering energy consumption in public and industrial buildings. In the transportation sector, studies are ongoing to evaluate the potential for improvement in combined transport (rails, ships, and trucks) through the freight network, and expanding public transport especially in urban areas, also the use of alternative fuels which have lower emissions then conventional ones and increasing the public awareness on hybrid vehicle technologies in urban and populated areas, leading to lowering both carbon dioxide and nitrogen oxides emissions. Other frameworks and policies are also taking effect in waste management, natural disaster preparedness and management, and construction. Policies can be summarized as the following:

1. pushing the use of renewable energy (wind, hydro, solar, biomass) and working on improving current combined heat technologies;
2. improved energy efficiency measure across public and private buildings, and across all industries;
3. reduction in High CO_2 emissions from passenger cars and making hybrid and electrical vehicles widely available both in public and private transportation;
4. a moderate decline in current high emission manufacturing methods while new technologies emerge in the industrial sector, and
5. plans to reduce greenhouse gas emissions from landfills.

5 Better Direction for Private Investments for Climate Change and Energy

But public money is not sufficient to deliver the necessary changes: private investment and economic activity need to follow the same comprehensive analytical and planning approaches.

This section borrows from Ozdemiroglu (2019) on exploring opportunities for green finance. The UK Government's Green Finance Strategy (HM Government 2019) makes a distinction between:

- Financing Green—Accelerating finance to support the delivery of mitigation, clean growth, resilience, and environmental ambitions, as well as international objectives. This is an opportunity for those who can provide 'green' projects and technologies to attract finance.
- Greening Finance—Ensuring current and future financial risks and opportunities from climate and environmental factors is integrated into mainstream financial decision-making, and that markets for green financial products are robust in nature. This is an opportunity for environmental professionals to provide evidence on risks and opportunities that should be incorporated in finance decisions.

Green finance works like any other finance: capital is invested in projects, programmes, and companies for environmental improvements alongside financial returns. Instruments for green finance/investment can be in:

- Equity—an investor buys shares (and hence part ownership) in a company that is, for example, developing a new (low-carbon or other environmental impact) technology
- Debt—an investor lends money to a company (or government) and expects it to be paid back with interest. Green bonds are an example of such lending, the proceeds of which are used to generate specific environmental gains. Green mortgages—whereby households investing in energy or other efficiency improvements can get lower mortgages—are also a form of green debt financing
- Project finance—an investor puts money into the design and delivery of a specific project. Payments for Ecosystem Services (PES) and Nature based solutions falls into this category as one party pays the other for the delivery of a specific project.

The returns to such investments could be in the form of financial flows (e.g. sustained agricultural production), a share of the cost investment saves (e.g. investing in retrofitting buildings that will save future occupants energy bills and discomfort) or save money for the investor (e.g. investing in adaptation actions to avoid future losses). All three returns need to be acknowledged.

Private investment and the finance sector depend on a strong regulatory and policy context as well as common metrics and terms that make communication and comparison easier. The following barriers are currently keeping further private investment from being channelled towards mitigation, adaptation, and natural capital in general.

Missing markets and regulation. There are some nascent carbon markets for investments in carbon emission reductions. Consequently, trading and prices are emerging. However, the direct financial cost of burning a forest or making a species extinct is typically zero and, hence, there is a fundamental barrier to investing in prevention or reversal of such non-carbon aspects of the environment.

Complexity and mindsets. It is relatively straightforward to predict and monitor the reduction of carbon emissions through investments in energy efficiency and low-carbon technologies. It is more difficult to predict levels of carbon sequestration. There are many more models for sequestration factors compared to models for emission factors. Changes are context- and location-specific, and overly simplifying this complexity could lead to unintended negative consequences. Costs and benefits are distributed over several stakeholders and there is often a mismatch between those paying for and those benefiting from such investments. While complexity is a genuine issue, there is also a mindset that believes that an ESG focus and financial performance are mutually exclusive. A shift in the mindset of all involved in terms of risks (perception and tolerance) and return (expectations) is necessary, if green finance is to become more widespread. For example, investing in nature-based solutions could be riskier to start with, but as experience grows, so will our ability to manage complexity and risks. Developments in environmental assessment, economic valuation, and policy-making will continue to lower this barrier. The decreasing cost of renewable energy in the UK and globally is testament to this: the onshore wind and solar energy costs are now 50% lower than they were in 2013. This decrease of cost is caused by technological learning, operational experience, longer project lifetimes, and cheaper finance (Evans 2020).

Uncertain/low/nofinancial returns. Investing in, say, renewable energy and energy efficiency, is directly linked to financial returns—through income generation (sale of electricity) and cost saving (lower energy bills). Links between investing in 'green' and financial returns are more difficult to establish both in time and space. Furthermore, green investments are often associated with regulatory and environmental risks such as property rights to land and conservation; and impacts of extreme weather on habitat creation. The public sector could address this barrier by underwriting some of the risks. For example, a private sector provider of a nature-based solution would take responsibility for delivering predetermined outcomes up to a 1-in-30-year storm event and the risks due to more severe impacts would rest with the public sector. Public sector funding will still be needed to provide public goods, which, by definition, do not yield private (financial) returns, and towards technical assistance (e.g., monitoring and research) to reduce uncertainties over time.

Scale. Environmental projects tend to be relatively small and this discourages private finance to get involved in a coordinated way. The costs of, say, issuing a bond means that only bonds of several hundred millions of £ are worth issuing. Joining various environmental projects as a single investment package is likely to make them more investable.

Trends in the global economy. The influence of mainstream finance and trade policies as well as commodities trading cannot be ignored. While commodity prices (e.g. cheap virgin raw materials) continue to incentivise large-scale environmental degradation, relatively small 'green' investments will not be sufficient to tip the scales in favour of nature.

In short, the role of the public sector is to recognise and legitimise all three returns to green investments: financial returns; cost savings today and in the future for investors and other stakeholders; and improvements in human wellbeing through the reduction of environmental impacts. For this, we first need to ensure our economic analysis recognises these values.

6 Learning from the UK and Turkey Examples

6.1 Having a Shared Vision

According to Ozorhon et al. (2018) conducted a comprehensive literature review to understand the factors impacting investments in renewable energy and fed into a multicriteria analysis by a multidisciplinary panel of experienced energy experts. They conclude that considerations about economics, policies and regulations, availability of funds and investment costs outweigh the technical and environmental considerations. The authors conclude that governmental institutions should implement and maintain incentive mechanisms to satisfy the needs of investors.

Stakeholder and decision makers must assess a strategy to stimulate a larger use of the widely available renewable resources in Turkey. Turkey has set several targets for renewable energy sources which electricity is generated from. The government emphasized the key role of renewable energy in achieving its goals of reducing import dependence (Natural Gas) and others, diversifying the electricity mix and meeting rising energy demand through innovations in the renewable energy market. Accelerating the transition to renewables by means of supporting research, education, and removing any misconception on renewables in public minds will facilitate a smoother transition. There are endless, fresh, and unused resources at our fingertips. Backed by renewable energy resources, such as wind, solar, hydro, and biomass, we will be able to shift towards a sustainable and healthier world once and for all.

6.2 Creation of Regulated Markets

The UK Government has adopted the standard policy response to negative externalities with taxes, subsidies, and regulations. These help markets set full-cost pricing so that energy sources can be differentiated according to their environmental and other impacts.

Importantly, it has focused on market support which acts on the incentive structures of potential renewable energy developers. In 1989, it introduced the Non-Fossil Fuel Obligation (NFFO), the first major instrument to encourage the use of non-fossil sources including renewables. This was replaced with the Renewables Obligation (RO), which came into effect in 2002 in England, Wales, and Scotland, and in 2005 in Northern Ireland. The mechanism places an obligation on UK electricity suppliers to source an increasing proportion of the electricity they supply from renewable sources.

The Government also introduced a feed-in tariffs (FOT) scheme that paid out for energy generated by households (e.g. solar panels on roofs) and exported to the National Grid. Applications for the programme closed in April 2019, but the initiative was replaced by the Smart Export Guarantee (SEG) scheme in January 2020.

6.3 Private Sector Engagement

Government policies and legislation have also been crucial in encouraging more interest from the private sector to channel investment into the sector.

The Contracts for Difference (CfD) scheme is the Government's primary method of encouraging investment in low-carbon electricity. Contracts are allocated through a competitive auction, where the cheapest projects in each technology group are awarded contracts first. It provides project developers in the UK with high upfront costs and long lifetimes with protection from volatile wholesale prices. This in turn ensures consumers do not pay increased costs when electricity prices are high.

6.4 Supporting Technology and Learning

Technological learning, partly gained through private sector engagement and research and development, has been pivotal for the success of renewable energy. This has led to larger, more efficient manufacturing plants for solar and larger turbines for wind. Meanwhile, greater operational experience has resulted in longer project lifetimes and cheaper finance (once the technology and market are accepted).

Although further progress is still needed, development of renewable energy technologies and market is an encouraging example from the UK. The investments in the technologies reducing the cost of electricity production: Electricity generated from wind and solar is now 30–50% cheaper than previously thought—according to Evans (2020) which compares the cost reports from the UK's Business, Energy and Industrial Strategy Department published in 2016 and 2020. The 2020 report also notes that electricity from onshore wind or solar could be supplied at half the cost of gas-fired power by 2025.

In Turkey, R&D support is provided for the country's own electric vehicle TOGG in 2018. Turkey's automotive venture group (TOGG) is aiming to produce and manufacture its own line of cars by 2030, the project is estimated to cost 22 billion Turkish liras ($3.7 billion), and open employment to more than 4300 staff including 300 qualified personnel. An agreement with Farasis (a Chinese electric vehicle battery makers) will allow the development of energy storage solutions for Turkey, including the development and supply of advanced lithium-ion batteries, one of the most fundamental components of the vehicles it is developing (Ajansi 2021).

Scientific and Technological Research Council of Turkey (TÜBİTAK) supported by the National Boron Research Institute (BOREN) started a sodium borohydride fuel cell vehicle project. This integrated system which produces hydrogen from borohydride is fed to the fuel cell to power the vehicle. Within the scope of this project, the fuel storage, gas washing, hydrogen production reactor design suitable for the vehicle and the synthesis of the production catalysts were made. These are some examples of the developments in Turkey which demonstrate its vision to give green hydrogen a key role in its future energy system especially for transport (Semerci 2013).

6.5 Pressure from Stakeholders

Finally, pressure exerted by NGOs, consumers that have become more environmentally conscious, the media as well as businesses, all pushing for government action and greater accountability has contributed to keeping the UK Government on track to meet many of its ambitious goals. The same developments are also seen in Turkey.

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Leveraging Knowledge on Renewable Energy in Southern and Eastern Mediterranean Region

Sanaa Zebakh, Touria Moudakkar, Ali Rhouma, Tanay Sıdkı Uyar, and Mohammed Sadiki

1 The South Mediterranean Framework Enabling the Implementation and Adoption of Renewable Energy

1.1 Why Renewable Energy Should Be Used in the Southwestern Mediterranean Region?

In recent years, the countries of the southwestern Mediterranean region have been affected by crises of political instability. However, this should not distract them from their economic and environmental efforts to be adapted to climate change and for a more sustainable development.

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In the next few years, the region must respond to several challenges in the field of energy (UNEP 2016; Moe 2020). The first challenge is to meet the demand for electricity. The latest report from the World Bank highlights the difficulty of the region's countries to meet their future electricity demand. Despite holding the world's largest oil and gas reserves, the region risks not being able to meet the future needs of its growing population and its industrial and commercial activities. Between 2005 and 2019, electricity production in the region increased from 198 to 367 TWh, representing an increase of 85% (IEA). With urbanization and economic growth, countries in the region are expected to double their energy demand by 2040. The second issue is the reduction of oil dependence in net-exporting countries that depend on oil for at least 40% of their exports and 80% of their economic revenues. Indeed, with the Covid19 crisis, oil and gas revenues in Algeria and Libya have dropped by nearly 75–90%, putting a strain on their economies. The third challenge is for net-importing countries to reduce their dependence on oil price fluctuations that can reduce the competitiveness and the growth of their economy in the long term. Although the future trend of oil prices is uncertain, it is very probable that in the long-term the demand will lead to an increase in the price of oil and natural gas. The availability of primary sources of renewable energy in the region is an advantage that will help meet these challenges while addressing the dual economic and environmental issues (IEA). Furthermore, several studies (Tagliapietra 2016; Duygu 2019; Agency IRE 2018) at the regional level have shown a positive relationship between renewable energy use and GDP.

The following section presents first the primary sources of renewable energy production in the region as well as the most sustainable sources in order to understand the development strategies of renewable electricity production adopted by the region. The second part consists of an overview of the institutional and regulatory framework in the region for the promotion of renewable energy. The last part presents the evolution of installed renewable energy in the region, its strengths as well as the constraints and limitations of its development.

1.2 Renewable Energy Potential in the Southwestern Mediterranean Region

The southwestern Mediterranean region is endowed with natural sources that provide opportunities for the production of clean energy, particularly solar and wind energy. The geographical position of the region provides the best solar radiation in the world with a solar radiation of more than 2000 kWh/m^2/year (Tagliapietra 2016). Surrounded by the Atlantic Ocean, the Mediterranean and the Red Sea, the potential for the development of wind energy is also very significant (average wind speed is 7 m/s). In addition to the solar and wind potential, the region also has geothermal, biomass and hydraulic resources that can be sources of clean energy production. For example, Algeria and Morocco have a potentially exploitable field of geothermal energy with temperatures of 200 °C at 5000 m.

However, the evaluation of the real potential of a renewable energy source must not be limited to the saving of CO_2 emissions and the saving of primary resources. A prioritization of an energy source depends on its environmental, economic, social and technical aspects. Thus, the definition of a renewable energy strategy in a country is based on an evaluation of the performance and multidimensional reliability of each source. On the technical level, the most used criteria are the energy efficiency expressing the quantity of energy that can be obtained from the primary source, the reliability of the technology and its commercial maturity measuring the diffusion degree of the technology at the national and international markets.

On the economic front, the evaluation criteria are related to the cost, such as investment cost, cost of energy produced and payback time. The environmental criterion considers the impact on the soil, water and the surrounding environment through the production of noise and solid waste. The social criterion is based on the social benefits in terms of job creation, social welfare and revenue. This criterion is very important in the less developed countries because it allows to measure the social progress induced by the energy project. All of these criteria present indicators of the sustainability of an energy source, since they consider the needs of future generations.

In this sense, several studies have been carried out to analyze and rank the renewable electricity sources in the southwestern Mediterranean region (Et and Pratiques n.d.; Académie Hassan and des Sciences et Techniques 2019), considering environmental, economic and social criteria.

Their results place solar and wind energy in the first two positions. Solar electricity alone represents more than 68% of the renewable energy potential economically and technically exploitable in the region (Et and Pratiques n.d.) (Table 1). These results explain the strategies for renewable energy development in the region (Schaffrin and Fohr 2017), which are focused on the implementation of large solar and wind capacities by 2030. These programs are more detailed in the next section.

Table 1 Renewable energy potential that is technically and economically feasible

Country	Wind (%)	Wave and tide (%)	Geothermal (%)	Hydraulic (%)	Solar (%)
ALGERIA	1.3	0	0	0.2	98.5
EGYPT	20	0.2	0	1.3	78.5
LIBYA	31	1	0	0	68
MOROCCO	28	0.6	0	2.7	68.7
TUNISIA	27	0.6	0	0.2	72.2

1.3 Analysis of Energy Policies and the Institutional and Regulatory Framework by Country

The different energy strategies in the region include targets for the share of electricity generation from renewable energy in the energy mix.

Indeed, the development of renewable energy in the region is governed by national policy strategies (Table 2), such as the "National Renewable Energy and Energy Efficiency Plan" launched in Morocco in 2008, the "Renewable Energy and Energy Efficiency Program" launched in Algeria in 2009, and the "Solar Plan" in Tunisia launched in 2009. By 2030, these programs envisage achieving fixed targets in the electricity generation mix by setting capacities to be installed from several renewable energy technologies such as PV, CSP, and wind (SCOPUS 2016).

To ensure the promotion and achievement of these energy objectives, an institutional and regulatory framework has been established in each country of the region, as detailed in Table 3. The different laws adopted by each country provide the regulatory framework for the production of electricity from renewable energy sources. In Particular, they define the rules governing the development and implementation of projects (licensing procedures), and the commercialization of energy. As for the institutional framework, the region suffered in the past due to the lack of institutional actors committed to the promotion and development of renewable energy. Today, the institutional framework is progressing and becoming more consolidated through the reform of the main ministerial departments that have monopolized this sector in the past. This reform is based on a clear allocation of the roles and responsibilities of the different actors. The main missions of these institutes are the establishment of a fund for the development of RE, the participation in the design and realization of RE projects, and the establishment of research platforms involved in training the workforce required for these renewable projects. Financial incentives have also been introduced to encourage private investors to participate in RE development, such as capital subsidies, land ownership, tax exemption and preferential loans.

Table 2 Overall renewable energy targets in the selected country (Duygu 2019)

Country	Target	Year
Algeria	27% of electricity generation	2030
Morocco	52% of electricity generation	2030
Tunisia	30% of electricity generation	2030
Egypt	42% of installed capacity mix	2035
Libya	2219 MW of capacity installed	2025

Table 3 Regulatory and institutional framework and financial incentive mechanisms in the SWM region

Country	Legislation and regulations	Financing and subsidy	Redemption rates	Institutional actors
Algeria	• Law no. 04-09 August 2004 • Decree no. 13-218 June 2013 • Decree no. 15-69 February 2015 ⟹ Licensing procedures and incentives for diversification of power generation costs	National renewable energy and cogeneration fund (FNERC) ⟹ Funding allocated depending on the technology • Reduction of customs duties and VAT on the imported RE components	Feed-in tariffs based on installed capacity (MT, HT)	• SKTM: implementation of the national renewable energy plan • CREG: permits for RE producers • APPRUE et CDER
Morocco	• Law no. 13-09: promotion of renewable energies • Law no. 58-15 2015 ⟹ possibility of selling surplus energy • Law no. 16-08⟹ authorization of self-generation by industrials by raising the installed capacity to 50 MW instead of 10 to MW	• Capital subsidy (10–15%) of credit • Tax exemption • Preferential loans ($300 K–-$5 M) • No public subsidies • SIG energy investment company: fund for the development of RE	Tariffs defined for high and medium voltage (possibility to sell the surplus but not exceeding 10% on the total annual production)	• CDER • MASEN: development of solar, wind and hydraulic energy • RESEN: R&D in renewable energy • AMEE: domestic use of RE
Tunisia	• Law no. 2009-7 autonomous production of electricity from RE • Decree no. 2009-2773 conditions for the sale of surplus to STEG • Law no. 2015-12 May 2015: national plan for renewable energy • Decree no. 2016-1123 August 24, 2016 conditions of the modalities and implementation	• 30–40% of investment (< 20,000 DT) depending on the project (RoofTop PV, solar water heater, solar pumping) • Tax exemption • Preferential loans • No public subsidies	Well-defined tariffs for LT, MT, and HT that depend on the time shift at STEG (possibility to sell the surplus of the electricity produced but not exceeding 30% of the total annual production	• STEG: design, implementation and operation of renewable energy facilities • ANME

(continued)

Table 3 (continued)

Country	Legislation and regulations	Financing and subsidy	Redemption rates	Institutional actors
Egypt	• Law no. 203 December 2014 ⟹ Authorizing private investors to provide renewable electricity to their customers • Decree no. 1947 2014 ⟹ feed-in tariffs • Law no. 87 2015: > establishing a competitive electricity market	• Incentive investment measures • Tax exemption • Tax reduction for renewable equipment	Feed-in tariffs defined for electricity received from wind and PV	• EEHC (6 generation companies, one transmission company, and 9 distribution companies) • NREA: implementation of the national renewable energy plan • EgyptERA: regulation of electricity services
Libya	• No specific law is currently in operation	No subsidies or incentives for private investment	No tariffs have been defined to date	REAOL: promotion of renewable energies

Abbreviation SKTM (Sharikat Kahraba wa Taket Moutajadida); CREG (Commission algérienne de régulation de l'électricité et du gaz); CDER (Centre de développement des énergies renouvelables); APPRUE (Agence pour la promotion et la rationalisation de l'utilisation de l'énergie); MASEN (Agence marocaine pour le développement durable); IRESEN (Institut de recherche en énergie solaire et énergies nouvelles); AMEE (Agence marocaine pour l'efficacité énergétique); STEG (Société tunisienne d'électricité et du gaz); ANME (Agence nationale pour la conservation de l'énergie); EEHC (Egyptian Electricity holding Company); EgyptERA (Egyptian electric utility and consumer protection regulatory agency)

1.4 Evolution of the Electricity Generation by Source for the Southwestern Mediterranean Countries (2005–2019)

To analyse the development strategy of renewable electricity production in the south-western Mediterranean countries, we have chosen as an indicator the amount of renewable electricity produced by the International Energy Agency (IEA) and then comparing it with the trend of the different energy sources that are used in each country of the region (Fig. 1).

Although, the renewable energy potential in the region is one of the largest in the world, the increase in primary fossil fuel power generation has been greater than the growth in renewable power generation. As illustrated in Fig. 1, the energy mix of the different countries is predominantly based on gas. Except for Morocco, which has a very diversified energy mix. Morocco has indeed reduced its fuel consumption by 63% annually during the last decade to ensure its energy security with regard to

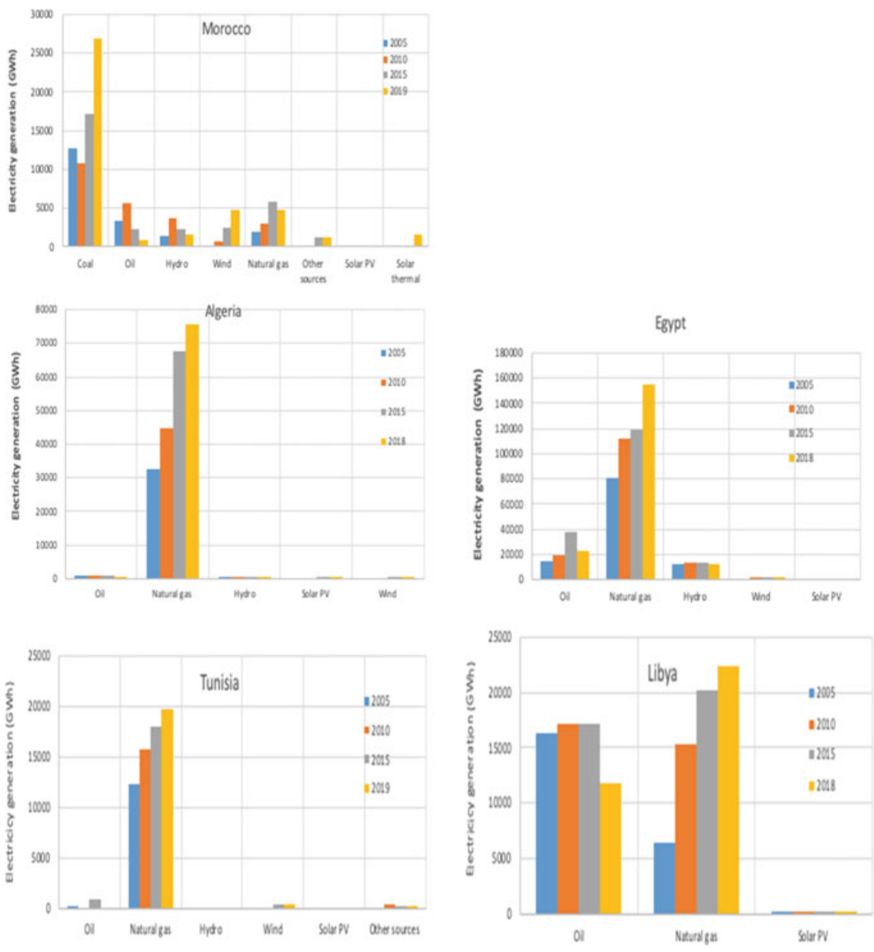
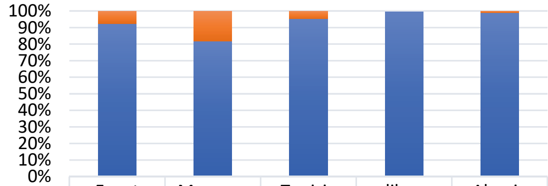


Fig. 1 Evolution of the renewable electricity generation in the region between 2005 and 2019

abroad while also increasing the share of renewable energy in the energy mix. In addition, an annual growth of 57% of coal has been noticed in the national energy transition. This is accompanied by the integration of new technologies at the power plant allowing the reduction of pollutant emissions (clean coal) while benefiting from the very low cost of this fossil energy source. Compared to other energy sources, the natural gas continues to predominate in the other countries of the region with an average annual increase of 17%. The two most widely used renewable energy sources in the southwestern Mediterranean region are solar photovoltaics and wind power, since their cost is continuously decreasing (Agency IRE 2018; Ciriminna et al. 2019). The average contribution of cleaner sources in the production of electricity in this region is thus 7%, with the maximum value of 22% reached in Morocco (Fig. 2). It should be noted, however, that the increase of renewable electricity in



	Egypt	Morocco	Tunisia	libya	Algeria
Renewable electricity generataion	15.802	9.236	1.023	0.008	0.783
Electrecity generataion (TWh)	194.069	41.65	20.737	34.171	76.663

Fig. 2 Share of renewable energy in the energy mix

the total production has not been observed in all countries. Morocco has indeed shown a very significant increase between 2010 and 2019 from 18 to 22%, while this evolution remains very low in Algeria and Tunisia from 0.4 to 1.02% and from 4 to 5% respectively, and even negative in Egypt (from 10% in 2010 to 8% in 2019).

Until 2010, hydropower dominated renewable electricity generation throughout the region. However, the hydropower potential is relatively limited compared to solar and wind potential because the available hydropower resources are already exploited to their maximum capacity.

Solar photovoltaics is currently the clean energy source with the highest annual growth rate in the region of 167%. This is explained by its world record low cost reaching one cent for one kWh. In 2019, solar photovoltaic is the second source of energy in Algeria after natural gas. In contrary to Libya, which registered the lowest ratio of clean energy in its energy mix (< 0.02%). This is explained by the war and political instability in the country since 2011.

This rapid increase of the renewable energy share in the region reflects the commitment of most countries to reach their targets in terms of installed renewable capacity by 2020–2030, as shown in Fig. 3 (Et and Pratiques n.d.).

National targets in North Africa are for 84 GW of non-hydropower renewable electricity capacity. Morocco, Tunisia and Egypt are currently the only countries that are on the right track to achieve the renewable energy targets by 2030, considering the development trends achieved between 2015 and 2019. In the next decade, Morocco, Tunisia and Egypt are led, indeed, to continue their deployment of renewable energy capacity with an annual growth rate of 52%, 108% and 211% respectively. For Algeria, it must however double the effort in its energy strategy by ensuring an annual growth rate of 420% in the years ahead compared to its current value of 207%.

Despite this remarkable presence of renewable energy in the southwestern Mediterranean region, ensuring an energy production of more than 26.8 TWh in

Targets	20 GW wind 22.9 GW PV 4.1 GW CSP	5 GW SOLAR 5 GW WIND	1.8 GW WIND 460 MW CSP 1.5 GW PV	1 GW WIND 844 MW PV 375 MW CSP	5 GW WIND 13 GW PV 2 GW CSP 1 GW BIOMASS
Horizon	2030	2030	2030	2025	2030

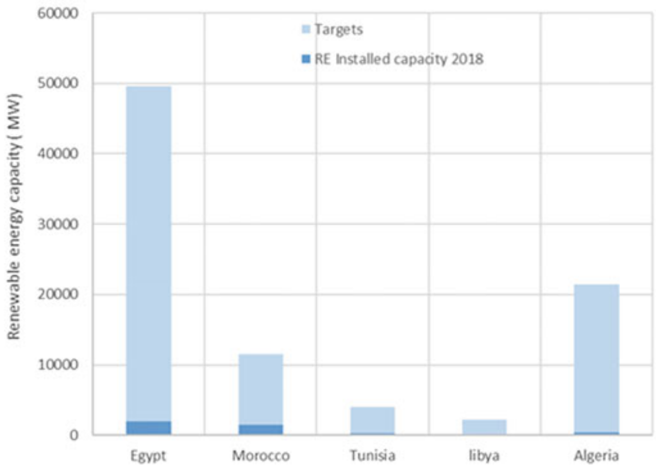


Fig. 3 Energy forecast of each country for 2020–2030 in terms of RE installed capacity (Et and Pratiques n.d.)

2019, this contribution represents only 17% of the overall renewable energy production of the southern Mediterranean region. The constraints and limitations that have hindered this development will be further detailed in the following section.

1.5 Modest Evolution of RE in the Region: Constraints and Limitations

The southwestern Mediterranean region is an excellent potential candidate to have one of the world's largest renewable energy capacities in the future due to the availability of resources and the numerous projects under development. These flagship projects have provided precious feedback at the regional level, in terms of both technical and financial aspects. Nevertheless, the pace of program implementation has been slow in the majority of the region's countries. Several reasons can be advanced to explain this situation (Tagliapietra 2016).

Table 4 Levelized cost of electricity produced by fossil energy 2020 in the Southwestern Mediterranean region

Country	Algeria	Morocco	Tunisia	Egypt	Libya
Lcoe ($/kWh)	0.03	0.09	0.031	0.045	0.0044

- Lower oil and natural gas prices due to government subsidies result in a cheaper and more competitive fossil fuel electricity production than that received by renewable energies (Tables 4 and 5).
- The majority of the region's energy plans have been restricted to public funding, as the use of private funding will require proof of economic viability for these RE projects to be funded.
- Many projects are still in the research and development stage, especially those to be installed in the desert area of the region. Although this zone has the best solar radiation in the whole region, the reliability and cost-effectiveness of solar technologies may be limited by the deposition of dust on the panels resulting from a high concentration of desert aerosols.
- Despite efforts to increase the electricity produced by renewable energies, its share in the final energy consumption will remain low. This is explained by the strong rising trend of other energy intensive sectors such as industry where 70% of energy needs are in heat.
- Geopolitical instability combined with slowing economic growth and low fossil fuel costs have led some countries to revise their targets downwards, such as Egypt and Libya.
- Unavailability of infrastructure and smart grid to receive the excess energy produced by renewable technologies has limited its value by regulation (between 10 and 30% on annual energy production). This has a negative impact on the profitability of the project.
- The cost of renewable electricity in the region is a key barrier to renewable energy deployment, as its average value in North Africa is higher than that obtained globally. This makes it more difficult for investors to engage in the development of these projects. The development of a local industry for renewable equipment is a condition for success, but a balance must be struck to avoid creating higher costs by clearly recognizing where a country can have the best competitive advantage and how to support it through R&D activities.

Table 5 Levelized cost of electricity produced by renewable energy 2020 (Ben and Ramadan 2017)

	Wind	PV	Hydro	Geothermic	Biomass
Lcoe in the Southwestern Mediterranean region ($/kWh)	0.067	0.068	0.055	0.073	0.066
Average Lcoh ($/kWh)	0.039	0.057	0.044	0.071	0.076

Given these obstacles, a few recommendations could be outlined to promote and accelerate the deployment of renewable energy:

- Establish clear and equitable rules to ensure market access for independent power producers while providing a long-term guarantee to private operators on the sale price.
- Phase out subsidies to fossil fuels, considering local socio-economic constraints.
- Accompany the increase of the renewable energy share by investments in the reinforcement and flexibility of the network by adopting, for example, smart grids, energy storage systems and new transmission methods
- Encourage research and development in industrial process electrification to enable the integration of renewable energy in industry.
- Finally, facilitate access to financing with concessional loans for industrials, SMEs and individuals by involving national commercial banks.

2 Research and Innovation Capacities Supporting the Renewable Energy Transition in South Mediterranean Countries

Southern Mediterranean countries have made important strides in structuring and strengthening their national research and innovation systems since the 2000's. The share of the budget allocated to scientific research has increased significantly between 2001 and 2016, passing from 0.19 to 0.72 for Egypt and from 0.55 to 0.75 for Morocco as an example (SCOPUS 2016; Académie Hassan and des Sciences et Techniques 2019).

Impact of research and innovation on the economic development of countries has no longer to be demonstrates. In the renewable energy sector, there is no successful global and local energy transition without innovation. Indeed, (Schaffrin and Fohr 2017) have demonstrated that local energy transition needs to consider the innovation, social, and political perspectives. This chapter section analyses the evolution of science and innovation capacities in the Southern Mediterranean countries which could be a driver toward the renewable energy adoption.

The considered countries in this study are Morocco, Algeria, Tunisia, Libya and Egypt. For some sections data related to Libya are not available or there is are no records in the extracted corpus. The scientific production of the five countries is analysed through a bibliometric approach for the 2000–2020 period relaying on SCOPUS database. We have explored as well the patenting activities through a search of filled patents from native inventors of the five countries during the same period. The data was retrieved from the Espacenet database.

In addition, we have analysed the role of EU-MED cooperation in science and technology through the participation of South Mediterranean countries to the European research programs (FP's and H2020) and join EU-MED programs such: ERANETMED and PRIMA (Zebakh and Finance 2017).

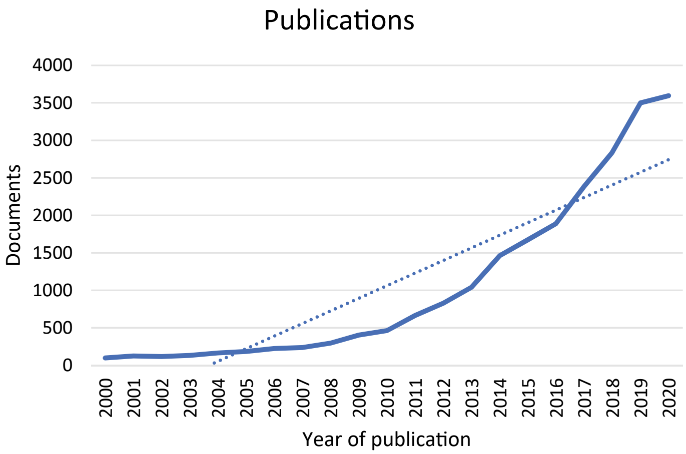


Fig. 4 Evolution of the number of renewable energy publications in South Mediterranean countries based on SCOPUS database (2000–2020)

2.1 Scientific Production in South Mediterranean Countries

- ***Impressive portfolio of publications***

In order to assess the scientific production of the Mediterranean countries, we conducted a bibliometric study based[1] on Scopus database relying on the wide coverage of SCOPUS for the region (SCOPUS 2016). Our research was based on keywords representing the main interest and potential of the south Mediterranean countries as renewable energy, solar energy, wind energy, biomass energy, clean energy, photovoltaic, etc. Our query in Scopus was limited to 2000–2020 period and focused on organizations with affiliations from Morocco, Algeria, Tunisia, Libya and Egypt. The extracted corpus was refined through combined filters. A total record of ***22,326*** contributions is registered for the last 20 years. The documents represent 70% of articles and 30% of conference papers.

The evolution of south Mediterranean countries is presented in Fig. 4. We observe a progressive growth in the number of articles with a significant rise from 2016 for the five countries. Egypt leads the ranking with a total of 8 336 publications, then Algeria with 6417. Tunisia and Morocco generate approximately the same share of outputs close to 3800 documents. Libya is ranked at the 18th position.

- ***Important international collaboration networks***

International collaborations are diversified and established through the co-authorship of publications with the authors from countries such as France, Saudi Arabia, Spain and Japan as presented in Fig. 5. Surprisingly, collaborations are noticed with non-

[1] The search was carried out on the 25.10.21.

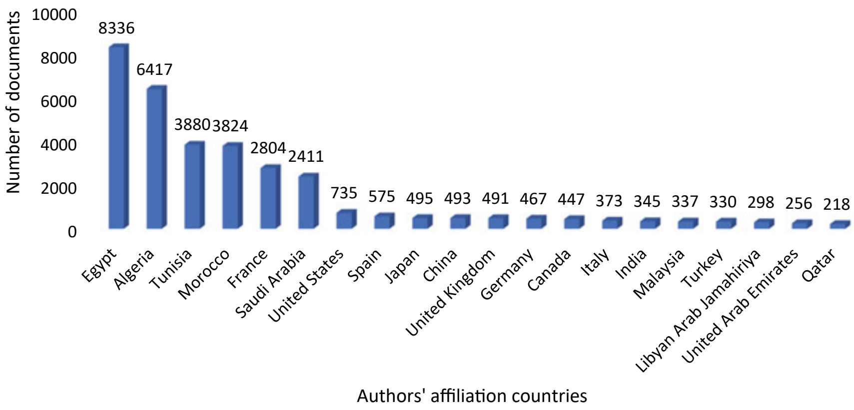


Fig. 5 Renewable energy co-authorship countries' affiliation

traditional partners of the Southern Mediterranean countries such India and Malaysia. Collaboration with EU countries except partners from France, Spain and Italy needs more support considering the availability of EU funding programs involving northern and eastern UE countries.

- ***Reliable research structures***

The main productive institutions are the Algerian Center of Renewable Energy Development, with publications accounting for approximately 5% of total documents, the Egyptians Cairo and Ain Sham universities (8.4%) and Mohammed V University in Morocco that hosts the Mohammedia School of Engineering (7.6%).

Table 6 shows that the top 15 performing institutions are mostly from Egypt. It is worth mentioning the establishment by Southern countries of specific research agencies and research infrastructures in the field of renewable energies. For instance, created in 2011, the Moroccan Research Institute for Solar Energy and New Energies (IRESEN), has stimulated the academia- industry links by offering technological support for the industrialization and marketing of entrepreneurs' innovations. IRESEN is also participating to European programs such LEAP-RE1 (COFUND) program carried by 83 European and African countries.

- ***Need to support papers quality through Journals choice***

A preliminary impression of the quality of the documents can be made through the impact factor of the newspapers. We note here that 46.7% of publications are published in 123 journals. Table 7 presents the list of journals with highest number of publications involving authors from Morocco, Tunisia, Algeria, Egypt and Libya. The 15 first journals in terms of total publications indicate that journals impact factor SJR for 2020 is variable. The Journal "Renewable and sustainable energy reviews,

Table 6 List of the top 15 main productive institutions

Affiliation	Country	Number of papers	% of total
Centre de Développement des Energies Renouvelables	Algeria	1108	5.0
Ain Shams University	Egypt	1015	4.5
Cairo University	Egypt	877	3.9
Mohammed V University in Rabat (435 Ecole Mohammedia des Ingénieurs, 510 Faculté des Sciences)	Morocco	1703	7.6
National Research Centre	Egypt	700	3.1
Université des Sciences et de la Technologie Houari Boumediene	Algeria	681	3.1
Université de Tunis El Manar (543 Ecole Nationale d'ingénieurs de Tunis)	Tunisia	1170	5.2
Tanta university	Egypt	606	2.7
Minia University	Egypt	511	2.3
Alexandria University	Egypt	494	2.2
Mansoura University	Egypt	493	2.2
University of Sfax	Tunisia	489	2.2
Ecole Nationale d'ingénieurs de Sfax	Tunisia	488	2.2
Assiut University	Egypt	484	2.2
Hassan II University of Casablanca	Morocco	484	2.2

with the highest SJR" corresponding to 3.52 records only 1.2 of total publications. 2.5 of the papers are published in Energy Procedia with a lower impact (0.47). More effort is required to motivate and support Southern Mediterranean researchers in the selection of high impact journals in view of enhancing the visibility of their research. A specific study could be useful to evaluate their publication citation in the future.

- ***Confirmed scientists with high expertise***

Table 8 highlights the high expertise of some researchers from Egypt, Algeria, Tunisia and Morocco, with high number of publications in indexed journals. Pr. Kabeel from Tanta University has reached 192 papers and Pr. TRARI from the Algerian university of Houari Boumediane counts 184. The four countries are equitably represented in the top 10 most productive authors. Incentives need to be implemented to award these scientists and encourage young and less productive researchers.

Table 7 Journals classified by number of papers, % of total publication and journal impact

Source title	Number of publications	% of publications	SJR (2020)
Energy Procedia	547	2.5	0.47
Solar Energy	445	2.0	1.34
Renewable Energy	426	1.9	1.83
Energy Conversion and Management	384	1.7	2.74
Renewable and Sustainable Energy Reviews	261	1.2	3.52
International Journal of Hydrogen Energy	260	1.2	1.21
Energy	241	1.1	1.96
International Journal of Renewable Energy Research	228	1.0	0.31
Journal of Materials Science Materials in Electronics	208	0.9	0.49
Desalination	197	0.9	1.79
Optik	197	0.9	0.48
Journal of Alloys and Compounds	191	0.9	1.11
Energies	176	0.8	0.6
AIP Conference Proceedings	162	0.7	0.18
Desalination and Water Treatment	161	0.7	0.25

Table 8 List of the top 10 main prolific authors by institution and country of origin

Author name	Number of papers	Institution	Country
Kabeel A. E.	192	Tanta University	Egypt
Trari M.	184	University of Science and Technology Houari Boumediene	Algeria
Ezzaouia H.	134	Center of Researchs and Technologies Energy	Tunisia
Mellit A.	128	Jijel University	Algeria
Maaroufi M.	112	Mohamed V University	Morocco
Ouassaid M.	107	Mohamed V University	Morocco
Allam N. K.	104	American University in Cairo	Egypt
Yahia I. S.	99	Ain Shams University	Egypt
Amlouk M.	93	University of Tunis El Manar	Tunisia
Kanzari M.	89	Université de Tunis El Manar	Tunisia

- ***Diversified funding organisations***

From 2000 to 2020, 4959 papers representing 60% of total recorded publications, have declared the research sponsorship origin. About 9.4% of the publications cited the King Saud University (Saudi Arabia) as a donor for their research work followed the European programs such the 7th Framework program and Horizon 2020. We note as well the contribution of local Funds and agencies supporting national researchers such the Egyptian Science and Technology Development Fund and the Algerian Ministry of Higher Education and Scientific Research. This support reflects a strong policy commitment to renewable energies research.

The most important financial backers are Saudi Arabia and Qatar as far as the Arab countries are concerned. Other donors such as the Chinese Research Fund also contribute to 3.4% of the projects and the Spanish Ministry of competitiveness to 1.5%. The total list of funding agencies shows the variance of donors: the Chinese cooperation support 308 research ranking China after the EU. The Japanese, Malaysian and Canadian cooperation are listed as well (Table 9).

Table 9 List of the top 15 main funding organizations

Funding agencies	Number of papers	%
King Saud University (Saudi Arabia)	470	9.4
European Commission (66 for the FP7, 64 H2020)	329	6.6
Ministry of Higher Education and Scientific Research (Algeria)	189	3.8
Science and Technology Development Fund (Egypt)	189	3.8
National Natural Science Foundation of China (China)	171	3.4
Centre National Pour la Recherche Scientifique et Technique (Morocco)	145	2.9
Ministry of Higher Education (Egypt)	169	3.4
European Regional Development Fund	108	2.2
King Abdulaziz University (Saudi Arabia)	103	2.1
Qatar National Research Fund (Qatar)	90	1.8
Deanship of Scientific Research King Faisal University (Saudi Arabia)	88	1.8
Direction Générale de la Recherche Scientifique et du Développement Technologique (Algeria)	88	1.8
Ministry of Higher Education and Scientific Research (Algeria)	82	1.6
(Morocco)	82	1.6
Ministerio de Economía y Competitividad (Spain)	75	1.5

2.2 *Innovation in the South Mediterranean Countries*

The Global Innovation index (GII) classification is considered as a valuable indicator to assess the ability of countries to innovate. The promotion of innovation in the southern Mediterranean countries has known important advances during last decade, through policy implementation, attraction of direct foreign investment, creation of technology parks, etc. However, the Maghreb countries (Tunisia, Algeria and Morocco), the innovation system is still suffering from a lack of connections between the academic world and the production world (Ben and Ramadan 2017).

The ranking of the four national innovation system capacities (Table 10) rank Tunisia in first position, then Morocco, Egypt, and Algeria, considering the Global innovation index for 2020. The data about Libya are not available. The progression of countries between 2012 and 2020 is variable. Morocco notes a constant positioning increase moving from position 88 in 2012 to 75 in 2020. The Tunisian situation is more fluctuating, with a significant loss of positions between 2012 and 2013 and a rebound between 2017 and 2018. The "Knowledge and technology outputs" indicator (Table 10) provides data on the generation of knowledge, which includes scientific articles and patents, as well as knowledge impacts and dissemination. The four countries record a positive trend from 2012 to 2020 as regards to knowledge and technology creation and diffusion. Morocco generates more innovation outputs in comparison to its level of innovation investments in 2020 data (University C Insead WIPO 2020a) and the QS university ranking (48) reveals a strength Human capital and research in Egypt (University C, INSEAD WIPO 2020b).

Looking more closely at the number of patent publications, we conducted an analysis of patents filed by Morocco, Tunisia, Algeria, and Egypt for the period 2000–2020. The Espacenet database has been interrogated with the same keywords used for the bibliometric search (presented in Sect. 2.1). The total results show a of 595 filed patents for the 2000–2020 period, considering the origin of inventors from

Table 10 GII indicators for Tunisia, Algeria, Egypt and Morocco

Global innovation index					Knowledge and technology outputs			
Year	Morocco	Algeria	Tunisia	Egypt	Morocco	Algeria	Tunisia	Egypt
2012	88	124	59	103	80	108	69	92
2013	92	138	70	108	119	115	103	113
2014	84	133	78	99	78	114	106	80
2015	78	126	76	100	73	115	87	79
2016	72	113	77	107	72	100	89	94
2017	72	108	74	105	77	107	69	93
2018	76	110	66	95	78	111	63	66
2019	74	113	73	92	69	113	60	66
2020	75	121	65	96	60	125	52	69

Source GII reports retrieved from https://www.wipo.int

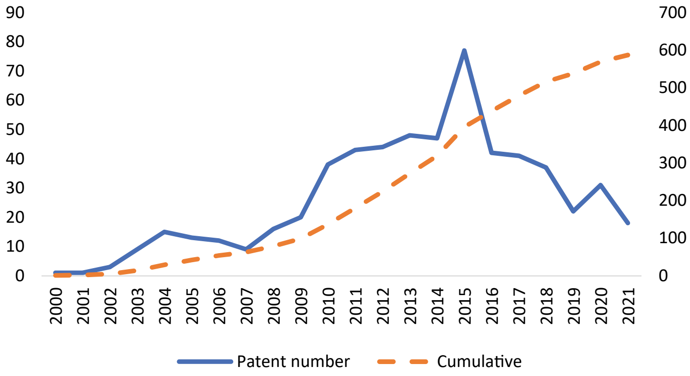


Fig. 6 Patents publication by Morocco, Tunisia, Algeria and Egypt. *Source* Extraction from ESPACENET on the 20.10.21

Morocco, Tunisia, Egypt and Algeria (Fig. 6). No records appear for Libya. Egypt is ranked first with 302 publications and Morocco 121. Tunisia and Algeria rank 89 and 83 respectively. There is an important co-patenting number of these countries with USA (115), France (91), Canada (42) and South Korea (32).

Despite the low number of Tunisian patents compared to other southern Mediterranean countries, other indicators place Tunisia at the top of the Global Innovation Index ranking since the global innovation index relies on 81 metrics that measure the multiple facets of innovation. Patents represents only one indicator for assessing the performance of the innovation system. Tunisia is ranked 7th among the 34 lower middle-income groups and performs well in 5 key areas: human capital and research; infrastructure, knowledge and technology outputs and creative outputs (University C, INSEAD WIPO 2020c).

Furthermore, the level of performance of the 4 countries is depicted in Fig. 7. The level of development of the countries is closely correlated with their levels of innovation. The countries in blue represent the most advanced in innovation. We note that Morocco and Tunisia are regarded as having a higher level of performance than their development level, unlike Egypt and Algeria. The size of the circles is related to the population size of the country.

The 2018 GII report has emphasized on the energy transition in some countries such China, Chile, Singapore, Viet Nam. The various experiences underline the role of innovation as a driving force to reach higher levels of technological and non-technological innovations (University C, INSEAD WIPO 2018). The innovation systems in the south med countries need more support to overcome development challenges.

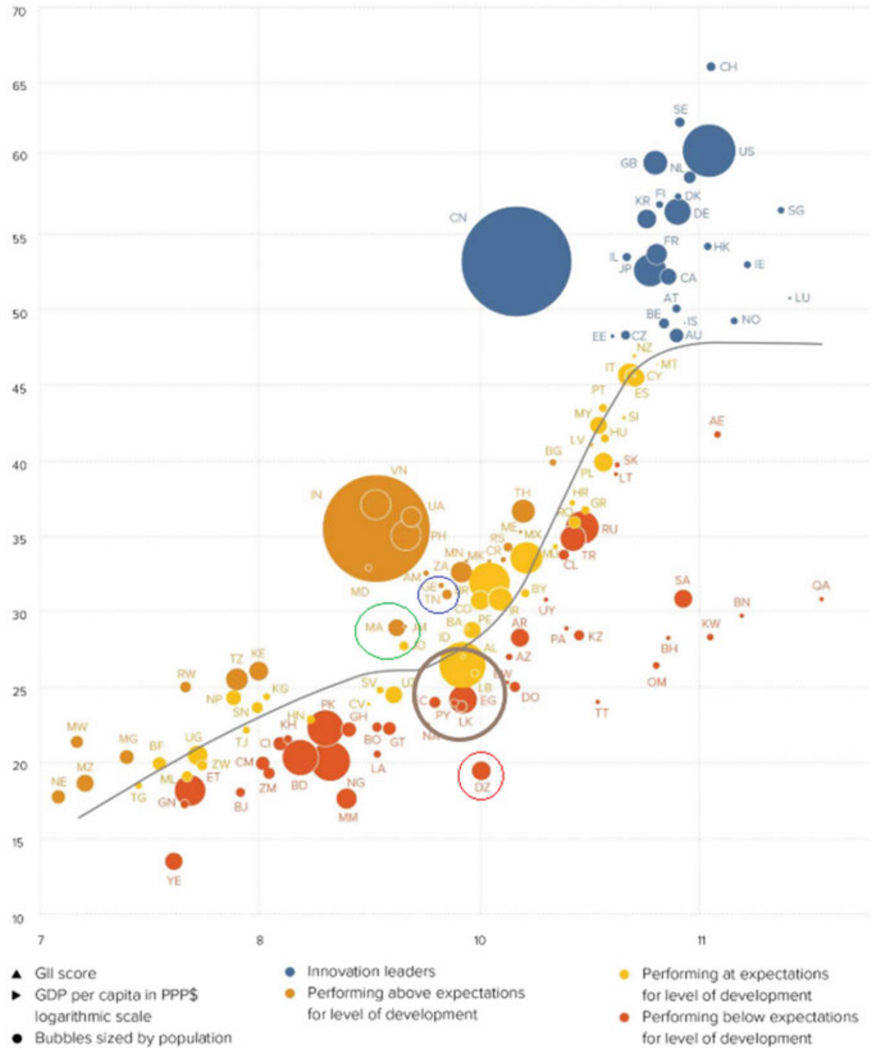


Fig. 7 Economies performance in innovation based on the global innovation index (University C, INSEAD WIPO 2020c)

2.3 Empowering Trans-Mediterranean Renewable Energy Research Cooperation: The EU-Med Research Programs

The Euro-Mediterranean partnership has known significant advances considering policy dialogue and implementation of programs to achieve the Barcelona process objectives. Research and innovation are considered as a pillar to people connection, encouraging exchange and development of human capital (European Commission

1995). The south Mediterranean countries have also taken part in the European Neighbourhood Policy, launched in 2004, which has supported national R&D in several countries such as Algeria, Tunisia and Egypt, between 2007 and 2011 (Zebakh and Finance 2017). Later on, the Union for the Mediterranean (UfM) initiative (2009) stressed on the importance to rationalize the use of natural resources to meet the global climate change. UfM has initiated the implementation of a regional platform on renewable energy and energy efficiency focusing the regulatory framework and the identification of integrated projects to develop energy markets and networks. Recently, on October, 6th 2021, a workshop was organized by the UfM inviting different stakeholders to exchange on the future of Euro-Mediterranean cooperation in Research and Innovation including renewable energy sector.

Furthermore, the last meeting of Ministers in charge of research and innovation from the Union for the Mediterranean (UfM) and the European Union (EU) was held in Malta on 4 May 2017. The resulting declaration on "Strengthening Euro-Mediterranean Cooperation through Research and Innovation, renewed the countries and the European commitment" has encouraged the development of further priorities for future research and innovation cooperation and the support of new join activities in fields such the renewable energy (Maltese Presidency of the Council of the EU 2017).

In the light of these many political engagements to strengthen the Euro-Mediterranean Partnership in Science and Technology, we were curious to examine the levels of collaboration between researchers on both sides of the Mediterranean. The analysis of the number of projects selected as well as the collaboration networks built through these projects are presented in this section. The specific projects related to renewable energy are extracted from the online databases of the European programs FP7, H2020, and the joint programs ERANETMED and PRIMA on the other.

- **Renewable energy projects in FP7**

The participation of the south Mediterranean countries has increased through the successive European Framework programs (Zebakh and Finance 2017). Since the launch of FP7, the European Commission has opened all calls to international cooperation partners. Participation of the southern Mediterranean countries is investigated for Morocco, Tunisia, Algeria, Libya and Egypt, the focus countries of our study. A reading of each of the 320 project's summary has been necessary to determine those related to renewable energies, which are not listed under the FP7 ENERGY program.

A total of 22 projects are funded under the FP7 program (2007–2014) involving 36 institutions from the four countries collaborating with 159 other partners from different EU and non-EU countries.

Morocco has participated in highest number of projects (9) involving 17 national institutions (Table 11). We expect that the Tunisian status, as an associated country to the European framework program since 2013, would distinguish it from other countries with respect to the number of selected projects. FP7 offers different funding schemes depending on the call objectives. South Mediterranean countries mostly participate to both Collaborative projects (CP) and Coordination and Support Actions

Table 11 Number of funded renewable energy projects and partners within FP7, H2020 and ERANETMED programs

	FP7		ERANETMED		H2020	
SMC	No. of energy projects	Number of participants	No. of energy projects	Number of participants	No. of energy projects	Number of participants
DZ	3	3	8	8	3	5
EG	6	11	8	9	5	6
LY	1	1	0	0	0	0
MA	9	17	9	10	9	13
TN	3	4	13	18	3	5
Other Partners	13	159	20	87	14	263
Total	35	195	58	132	34	292

(CSA). Collaborative projects are large-scale integrating projects with a budget up to 10 million Euros or small/medium-scale focused research projects. The CSA have a less limited budget around 1 million euros and aims at accompanying structuring measures such as standardization, dissemination, awareness-raising and communication, networking, coordination or support services, policy dialogues and mutual learning exercises. Examples of funded projects under the two funding schemes are presented hereafter.

- Coordination and support actions

Funded under FP7, the ETRERA 2020 project aims at Empowering Trans-Mediterranean Renewable Energy Research Alliance for Europe 2020 challenges. The project involved 11 countries including the Centre of Research for Energy Technologies (Tunisia) and the Moroccan Cadi Ayyad University. The project improved S&T and entrepreneurial relationships between European Member States and the neighbouring Mediterranean countries, with a focus on wind, photovoltaic, solar, hydrogen and fuel cells and grid connection technologies. The main project results, as presented in the EU cordis database, are:

– the catalogue of competence of the 8 Research centres: research capacity, equipment's, testing facilities, etc.
– a common R&DI strategy/roadmap with policy recommendations and a financial plan
– some tutorial/publication on market and risk assessment, finance opportunities, etc.
– the setting up of a Meta-cluster
– a Public–Private Partnership in RES technologies
– the exchange of best practices and mobility activities from Research to Enterprise
– technological/R&DI and business services

– the organisation of international brokerage events R2B
– the organisation of an international scientific conference.

- Collaborative actions

EUROSUNMED: funded with a budget of 5.2 million euros, the project has developed advanced research of new technologies in three energy field areas, namely photovoltaics (PV), concentrated solar power (CSP) and grid integration (GI), in strong collaboration with research 7 institutes, universities and SMEs from Europe and 6 partners from Morocco and 3from Egypt. The projects have published more than 9 scientific publications and conducted demonstration and testing activities. Indeed, different photovoltaic prototypes fabricated by the partners were tested under real functioning conditions. Several silicon based mini-modules were installed on the roof of three Moroccan universities, namely Rabat, Marrakech and Ifrane, which presents different conditions of altitude, temperature and solar radiation. Training and dissemination actions are also part of the projects.

- **Renewable energy projects within H2020**

The analysis of the South Mediterranean countries' participation in the FP7 (2007–2014) and H2020 (2014–2020) programs indicates a clear interest of researchers from Morocco, Algeria, Tunisia and Egypt in renewable energy projects.

The number of renewable energy projects involving southern Mediterranean countries in Horizon 2020 is about 14. In comparison to FP7, the 14 projects imply a higher number of partners from both Southern Mediterranean, European and non-European countries. Figure 8 illustrates the intensity of the connections between the countries

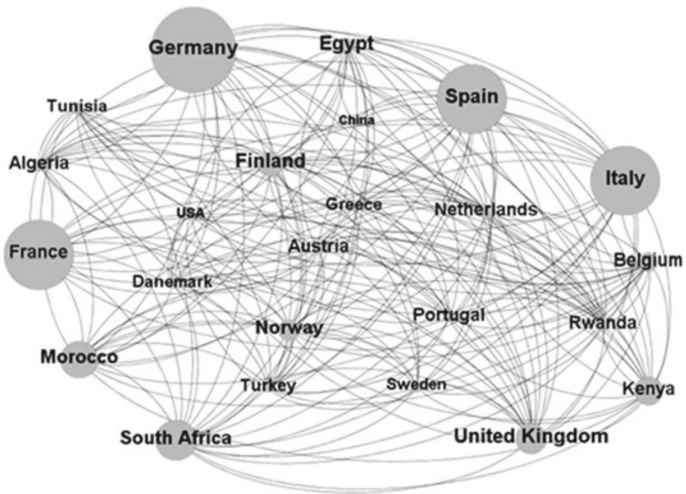


Fig. 8 Collaboration network for renewable energy H2020 projects involving Ma, TN, DZ and EG

that have worked together on the renewable energy research projects, using Gephi tool. The size of bubbles indicates the number of participants in the 14 projects.

- **ERANETMED program**

Funded under FP7, ERANETMED project aims at reducing fragmentation of programming in the Mediterranean region targeting high coordination between national research programs of European Member States, Associated Countries and Mediterranean Partner Countries. The program was launched in 2012 and enabled the funding of 67 projects in the fields of water, food and energy through 3 calls for proposals. South Mediterranean countries committed to ERANETMED co-funding with 6 million of euros. Our analysis resulted to 20 funded projects (30.5% of total projects) involving 132 institutions of which 45 belongs to Morocco, Tunisia, Egypt and Algeria (Table 11). Figure 9 illustrates the collaboration between partners from several countries in the framework of the renewable energy projects supported by the ERANETMED program. The high number of collaborations between the four southern Mediterranean countries demonstrates the development of significant subregional networks. As an example, the selected Projects have focused on design of desalination systems based on optimal usage of multiple renewable energy sources (DESIRES), Development and demonstration of a hybrid CSP-biomass gasification boiler system (BIOSOL). Other projects targeted the Water, Food and Energy nexus such the project HybridBioEnergies related to the development of an innovative hybrid renewable energy plant based on a combination of biomass and solar energy and the project EdGeWIsE dealing with Energy and Water Systems Integration and Management.

- **PRIMA**

Fig. 9 Collaboration network for renewable energy ERANETMED projects involving Ma, TN, DZ and EG

Prima represents a milestone of the Euro-Med policy dialogue in S&T. Prima program is based the article 185 of the European community treaty. PRIMA program has been launched in 2017 and a specific foundation was created in Barcelona to manage the program. This initiative enables the southern Mediterranean countries to play an active role in the design, launch, evaluation and monitoring of research projects addressing the region challenges related to water management, farming system and agri-food value chain. PRIMA calls for projects address the renewable energy topic through the Nexus Calls. However, Farming and water projects are targeting the use of renewable energy. As example, AWESOME will establish collaborations with local industry and SMEs in Egypt to establish models such as solar energy-based aquaponics and hydroponics as well as solar energy-based desalination for food production purposes.

3 Conclusion

The outcomes of this study demonstrate that several factors are in favour of the development of a rapid energy transition in the Southern Mediterranean countries: potential of renewable energy resources, policies and regulation in favour to the energy transition, developing infrastructure, programs and projects, etc.

Although, there is no transition without innovation (IRENA 2021). The implementation of changes needs in-depth research activities to reach innovative solution in products and processes. The analysis of research and innovation potentials of the South MED countries highlighted some key strengths/assets which may be listed as follow: confirmed researchers' expertise, strong sub regional and transnational networks, important portfolio of publications, co-publishing of quality papers, available research infrastructure, and diversity of research sources funding to support collaborative and coordinated actions. However, the innovation part is still weak considering the number of filled patents and the lack of initiatives to valorise the projects' results, confirming the statement of "Arab world has more problems in knowledge use than in knowledge creation" (Hanafi and Arvanitis 2016).

The renewable energy transition in the south Mediterranean countries needs to combine the policy dimensions (first section) with the scientific and innovative dimensions (second section) along with the social dimension.

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Hybrid Energy System Design Combining Solar Energy with Lignite Coal and Forest Residue

Yavuz Kirim, Hasan Sadikoglu, and Mehmet Melikoglu

1 Introduction

Forest lands in Turkey cover 27.2% of the country's total area, and Central and Eastern Black Sea Regions contain Turkey's majority of forests (Saracoglu 2015). Forest residues (FR) in these forest areas are valuable raw materials for energy production. The amount of FR that can be used annually in bioenergy production is calculated as nearly 5–7 million (M) tons (Saracoglu 2015). If this energy source is evaluated with other renewable energy sources such as solar, wind, hydro, etc., then it can be more economically and environmentally sustainable. Many governments have promoted energy production from renewable energy sources by giving financial support to feed in tariffs, promoting tax incentives and subsidies. Turkey provides government incentives for the use of renewable energy sources for electricity generation. Government incentives for solar and biomass energy sources were significantly higher until 2021, but this rate has decreased by nearly 50–70% in 2021 due to newly enacted legislation. As a result, the potential effects of changes in government incentives on hybrid energy systems (HES) design both fossil and renewable must be urgently analyzed. Turkey is increasingly benefiting from renewable energy sources, but fossil sources still have a large share in the country's energy production. In thermal power plants, lignite coal (LC) is mostly used for energy generation. Turkey's LC reserves are approximately 19.32 billion tons as of 2021 (General Directorate of Mineral Research and Exploration 2021). Using LC in HES design alongside with renewable energy sources could provide significant economic and environmental benefits.

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Nag and Sarkar designed a HES including solar, wind, hydrokinetic and bioenergy by using Hybrid Optimization Model for Multiple Energy Resources HOMER (Nag and Sarkar 2018). They considered optimization and sensitivity analysis by evaluating net present cost (NPC), cost of energy (COE), and carbon dioxide (CO_2) emissions, they found that configuration of solar-bioenergy-battery system had lower NPC value compared to other configurations and moderate COE and renewable fraction (RF) (Rahman et al. 2014). Mohammed and co-workers reviewed different biomass wastes including forest biomass in order to use in hybrid renewable energy systems (HRES) (Rahman et al. 2014). They observed that price of energy, legislative regulations and socio-political resolutions encourage expansion of HRES applications in developing countries (Rahman et al. 2014). Patil and colleagues analyzed different HRES scenarios including micro hydropower, biomass (forest and crop residues), solar and wind sources (Kanase-Patil 2010). They used HOMER and other software to evaluate technic and economic feasibility in terms of NPC and COE. Akhtar and co-workers investigated technic and economic feasibility of utilizing FR or biomass by considering their advantages and disadvantages (Islam et al. 2018). Gur and colleagues analyzed gasification of LC in Western Thrace of Turkey (Gur et al. 2017). They used dual combination of oxygen, air and steam gasification of LC to measure syngas compositions, and they found that syngas production in oxygen gasification stage had higher carbon monoxide (CO) and hydrogen content when to compared to the literature (Gur et al. 2017). Kale and others investigated gasification of LC in the presence of steam and CO_2 (Kale et al. 2014). In their study, found that exact ratio of syngas to be used in petrochemical manufacturing and fuel systems. Karimipour and co-workers studied gasification of LC in a fluidized bed gasifier. They evaluated syngas quality based on carbon conversion, hydrogen (H_2) to carbon monoxide H_2/CO and methane (CH_4) to hydrogen CH_4/H_2 ratios, gas yield, and gasification efficiency (Karimipour et al. 2013). Consequently, detailed analysis of the literature clearly showed that the information about HES design for Turkey that combines solar energy with LC and FR is scarce in published in literature.

In the current study, gasification potential of LC and FR with natural gas (NG) is analyzed, and electricity generation from combination of solar, LC and FR hybrid system is estimated in order to meet electric demand of a hazelnut processing plant (HPP) by selling or purchasing electricity to/from the national grid. A HES consisting of a biogas generator, PV panel, converter and grid is simulated. Four different scenarios including Scenario A (LC for 0.080 $/kWh), Scenario B (LC for 0.133 $/kWh), Scenario C (FR for 0.080 $/kWh) and Scenario D (FR for 0.133 $/kWh) are compared with regard to NPC, COE and greenhouse gas emissions analysis HOMER. In addition, techno-economic analysis of the proposed HES design is made based on these different scenarios.

2 Methodology

HOMER pro simulates renewable and non-renewable energy systems, displays cost-optimized system configurations, and is capable of performing sensitivity analyze. In this study, electricity generation potentials of LC and FR with NG and solar panels are estimated in a plant located in Ordu province of Turkey via using HOMER pro. A HPP is simulated using a grid-connected system to estimate the gasification potential of LC and FR. Details of this HPP is given in a recent of publication of the authors. The technical, economic and emission analysis of the proposed HPP on the basis of different subsidies for biomass and solar energy are analyzed before and after 2021 due to the renewable energy legislation that came into force after 2021. The government incentives given to biomass and solar energy before and after 2021 are 0.133 $/kWh and 0.080 $/kWh, respectively (Energy Market Regulatory Board 2021; EMRA 2021). Configuration of LC and FR in four different scenarios (Scenario A: LC for 0.080 $/kWh, Scenario B: LC for 0.133 $/kWh, Scenario C: FR for 0.080 $/kWh, and Scenario D: FR for 0.133 $/kWh) are determined depending on NPC, COE and emission values. Biogas generator, PV panel, converter and grid system are analyzed in two different HOMER configurations.

2.1 Location of the HES

The simulated HPP for HES consisting of solar and biomass sources is located in Ordu province of Turkey (Kirim et al. 2021). LC is provided from Turkish Coal Enterprise (TCE) and FR is bought from Forestry General Directorate Enterprises or local enterprises. The latitude and longitude of the plant for this study are 40° 56.6′ N and 37° 53.3′ E. Supply of LC and FR amounts are assumed as 30 tons/day.

2.2 Electricity Generation from LC and FR

Electricity generation from biomass in HOMER is performed by thermochemical or biological processes. In this study, thermochemical and gasification processes are applied to LC and FR in order to generate electricity. Biogas term in HOMER is entitled to gasified biomass (LC and FR) and product of gasification mainly constitute CO, H_2, CO_2 and considerable amounts of nitrogen when thermal gasification is applied in the presence of air. From here onwards, the term biogas is used to represent gasified LC and FR. Trace amount of CH_4 and water vapor is generated via thermal gasification. Gasified biomass or biogas possesses lower calorific value than fossil fuels provided that it consists of higher amounts of nitrogen. However, it introduces significant advantages to fossil fuels such as cleaner combustion, higher efficiency and better control (HOMER Pro User Manual 2020). In this study, gasified LC and

FR are combusted together with NG at certain rates. At each step, the output required by the generator, and accordingly the mass flow rates of biogas and fossil fuels are calculated by the Eq. (1) (HOMER Pro User Manual 2020). At the same time, fuel consumption and fuel efficiency graphs are obtained via this equation.

$$\dot{m}_0 = \rho_{fossil}\left(F_0 \cdot Y_{gen} + F_1 \cdot P_{gen}\right) \quad (1)$$

In Eq. (1) $\dot{m}_0$ is denoted as fossil fuel flow rate, which is in pure fossil mode. ρ_{fossil} is density of fossil fuel (NG). F_0 is the biomass generator fuel curve intercept coefficient. Y_{gen} is denoted as maximum output of the biomass generator, which is at minimum fossil fraction (NG). F_1 is biomass generator fuel curve slope and P_{gen} is biomass generator power out.

2.3 Solar Energy Potential of the Proposed HPP Location

Solar irradiation and clearness index of HPP location is obtained from the National Aeronautics and Space Administrations (NASA). These values can be found in monthly table forms in HOMER. The average daily irradiation and clearness index of the HPP location are 3.940 kWh/m^2/day and 0.497, respectively (Stackhouse et al. 2020). Daily radiation and clearness index of HPP are given in Table 1 (Stackhouse et al. 2020). Depending on the climate, the electrical energy provided by solar energy in the HES system is high in the period of May–September, but that values in December and January have the lowest electricity generation. To calculate the energy production from the photovoltaic (PV) array Eq. (2) is used.

Table 1 Monthly clearness index and daily radiation data (Stackhouse et al. 2020)

Month	Clearness index	Daily radiation (kWh/m^2/day)
January	0.446	1.820
February	0.461	2.530
March	0.483	3.620
April	0.460	4.390
May	0.488	5.370
June	0.543	6.300
July	0.549	6.190
August	0.559	5.630
September	0.569	4.660
October	0.516	3.130
November	0.479	2.100
December	0.416	1.520
Average	0.497	3.940

$$P_{PV} = Y_{PV} \cdot f_{PV}\left(\frac{G_T}{G_{T,STC}}\right)\left[1 + a_p\left(T_c - T_{c,STC}\right)\right] \quad (2)$$

Output of PV array is denoted as P_{PV}(kWh). Y_{PV}(kW) represents the rated capacity of the PV array, in other words the power output under standard test conditions. f_{PV} (%) is PV derating factor, and G_T (kW/m^2) represents the solar radiation incident on the PV array at the current time step. Solar radiation incident at standard test conditions represents as $G_{T,STC}$ (1 kW/m^2). Temperature effect is not considered in this study. As a result, the $a_p\left(T_c - T_{c,STC}\right)$ term is assumed as zero (negligibly small).

2.4 Load Profile of the HPP

Electricity demand of the HPP is supplied from the national grid, and energy is generated from NG. Daily load demand of this facility is about 2673 kWh and this demand mainly stems from three phase motors and rooftop air-conditioners. Electric power demand load varies based on seasonal change thus load profile of the facility arranged according to these changes. Arranged load profile of the HPP is given Table 2 (Kirim et al. 2021). The peak hours of electricity demand are between 08:00 and 16:00 (local time) and 16:00–24:00 (local time) because the HPP operates in two shifts throughout the year. Daily load profile obtained from HPP is processed by HOMER to generate hourly load data depending upon monthly average daily load profiles. Random variability option is selected to achieve more realistic load profile using daily 10% and hourly 20% random noise, respectively.

2.5 Components of the HES

In this study, electricity generation potential based on LC and FR using thermal gasification in HOMER is applied to the HPP. LC and FR HES configurations are evaluated depending on government incentives before and after 2021. Load profile of HPP, biomass generator supported by NG, flat PV panels, system convertor, which converts DC bus to AC, and grid-connected system are the main components of HES systems. Any storage device such as battery systems are not used because the system is planned to connect to national grid. HES configuration of LC and FR are shown in Fig. 1. Monthly net metering option is selected for both configurations to find purchase from national grid and sale to national grid.

Table 2 Daily load profile of HPP (Kirim et al. 2021)

Electric appliances	Number of units	Power per hour (W)	Average usage (h/day)	Total usage per day (W)	Total usage per day (kW)
Armature lamp (18 W) (all is turned on)	166	18	6	17,928	17.928
Armature lamp (18 W)	40	18	8	5,760	5.760
Armature lamp (40 W) (all is turned on)	36	40	6	8,640	8.640
Armature lamp (40 W)	9	40	8	2,880	2.880
Three-phase motor (1500 W)	18	1,500	12	324,000	324.000
Three-phase motor (3000 W)	26	3,000	12	936,000	936.000
Refrigerator (300 W)	5	300	24	36,000	36.000
Refrigerator (500 W)	1	500	24	12,000	12.000
Commercial dish washer	1	6,000	3	18,000	18.000
Deep-freezer	1	500	24	12,000	12.000
Toast machine	1	3,000	2	6,000	6.000
Tea maker	1	3,000	12	36,000	36.000
Electric water fountain	2	100	24	4,800	4.800
Black light	6	36	12	2,592	2.592
Air-conditioner	2	2,000	8	32,000	32.000
TV	1	150	4	600	0.600
Monitor system	1	800	24	19,200	19.200
Computer	7	200	8	11,200	11.200
Projector	1	400	1	400	0.400
Printer	5	300	8	12,000	12.000
Coffee machine	1	300	8	2,400	2.400
Sodium vapor lamp	2	500	8	8,000	8.000
Fire detection system	1	500	24	12,000	12.000
Conveyor	6	2,000	12	144,000	144.000

(continued)

Table 2 (continued)

Electric appliances	Number of units	Power per hour (W)	Average usage (h/day)	Total usage per day (W)	Total usage per day (kW)
Commercial Hazelnut weighing machine	10	300	12	36,000	36.000
Automatic door system	1	600	4	2,400	2.400
Roof-top fan	5	200	24	24,000	24.000
Rooftop air-conditioner	1	45,000	12	540,000	540.000
Total				2,266,800	2,266.800

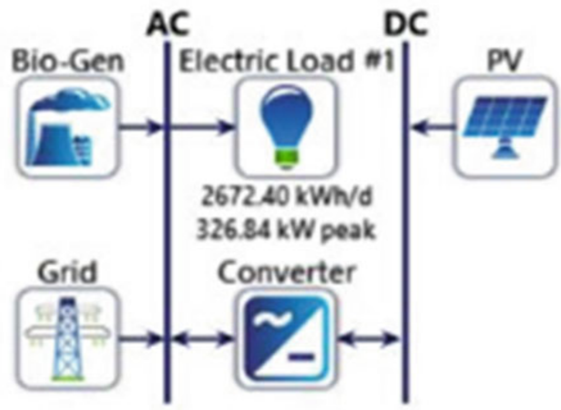

Fig. 1 HES configuration of LC and FR

2.5.1 PV Panel

Optimum PV capacity for HES configurations of LC and FR is calculated by HOMER optimizer. The PV panel's capital cost and operation and maintenance (O&M) cost are calculated using solar energy feasibility report issued by Mevlana Development Agency (2014). Capital and O&M cost of PV panel is found $3140/kW and $21/kW (Mevlana Development Agency 2014). Component, module and inverter which is part of total replacement cost, which is $15.37/kW is obtained from renewable energy feasibility report of National Renewable Energy Laboratory (NREL) (NREL 2018). Derating factor and ground reflectance of PV panel (250 kW rating capacity) are assumed to be 80% and 20%, respectively.

2.5.2 Biomass Generator

Generic biogas genset generator is used in the HES systems design. The cost of capital, O&M, and replacement cost of the biogas generator are \$3000/kW, \$1250/kW and 0.010 (\$/op.h), which are defined by HOMER. Optimum generator size is selected using search tab option. Generator capacity of 1000, 1500 and 2000 kW are chosen. Average natural gas price is \$0.28 per m^3 for commercial use and price of LC and FR are taken \$94 and \$65, respectively. Minimum load ratio and lifetime of the biogas generator are 50% and 20,000 h, respectively.

2.5.3 Converter

Capital, replacement, and O&M cost of the system converter are obtained from HOMER which is \$300 per kW, \$300 per kW and zero, respectively. In advance tab, upper and lower limit are selected 1250 kW and zero, respectively. Lifetime and efficiency of the inverter input are 15 years and 95%, respectively while relative capacity and lifetime of the rectifier input are 100% and 95%, respectively.

2.5.4 Grid

Grid connected is planned to use for the HES of the LC and FR. Scheduled rates option is selected considering grid purchase (0.088 \$/kWh) and sellback price (0.133 \$/kWh). Government incentives for solar and biomass energy that published in the "Law of the Ministry of Energy and Natural Resources on the Use of Renewable Energy Sources for Electrical Energy Production" is used to determine grid sellback price (Ministry of Energy and Natural Resources 2005). Commercial grid purchase price is obtained from Energy Market Regulatory Authority (EMRA) (EMRA 2021). Interconnection charge is not charged due to law amendment in 2017 which is determined in "Article 21 of the Electricity Market Connection and System Use Regulation" (EMRA 2017). The stand by fee which is \$9477 per year is charged by EMRA (2019).

2.6 Economic Definitions and Formulas in HOMER

Simulation, optimization, and sensitivity analysis are base elements for technical and economic analysis in HOMER. All system configurations in HOMER is applied with energy balance calculation. Then, HOMER determines whether a configuration is feasible under specified conditions and estimates the cost of capital and operating the system over the life of the project (HOMER Pro User Manual 2020). As NPC and COE are more reliable economic estimation methods these baseline metrics are generally preferred when determining project feasibility. The base definitions and formulations for technical and economic analysis are given in Table 3 (HOMER Pro User Manual 2020; Kirim et al. 2021). Central bank of Turkey data is used to find inflation and discount rate which is 12.26% (average) and 15.75% (average), respectively (Central Bank of Turkey 2020). Project life of the HES designs are selected as 25 years.

3 Results and Discussion

PV panel and gasified FR and LC backed up with NG are used in the grid-connected HES design. HOMER is used to find optimum HES configuration, which meets load demand of HPP. Change in government incentives before and after 2021 is considered when calculating feasibility of the study.

Among the scenarios (Scenario A, B, C, D), Scenario D has the lowest NPC and COE which is $1.46 M and $0.017/kWh, respectively. This is due to government incentives given before 2021 and price of FR is about 30% lower than LC. However, Scenario C has nearly threefold higher NPC, and nearly nine fold higher COE values which is $4.300 M and $0.143/kWh, respectively. In addition, Scenario A possesses the highest NPC and COE because the price of LC and usage of the high amount NG, and the government incentives after 2021 in this scenario increases the cost of the system. Government incentive before 2021 for the Scenario D provides nearly nine fold less NPC and nearly 20-fold decrease in COE than that of Scenario A. RF of Scenario B and D is 81.6% and 72.1%, respectively, while RF of Scenario A and C 62.3% and 53.9%, respectively. The rate of RF in Scenario B and D are higher than that of Scenario A and C because energy generation in Scenario B and D are mostly generated from PV panel. System configurations, NPC, COE, and RF are given in Table 4.

In Scenario A, biogas generator has the highest capital and replacement cost which is $6 M and 1.10 M, respectively, although salvage value is 1.81 M. Capital and O&M cost of the PV panel is second highest cost in Scenario A but it has no salvage value after decommissioning of the project. Component cost of the system for Scenario A is shown in Fig. 2. Electricity production mainly obtains from PV panel which is 1,752,869 kWh/year (74%) while biogas generator only accounts for 220,000 kWh/year (9.3%). The highest electricity generation from PV panel is in July, August and September. Monthly electricity production for Scenario A is shown in Fig. 3.

Electricity generation in Scenario B is generated from PV panel and grid purchase. NPC and COE in this scenario are $2.550 M and $0.026/kWh, respectively. The share of energy generation from PV panel is 81.6% and operation hours of PV panel is 4383 h per year. Component cost of the system for Scenario B is shown in Fig. 4. The share of PV panel and grid purchase to meet HPP load demand is 83.7% and 16.3%, respectively. The electricity generation from PV panel is more than fivefold compared to grid purchase. Monthly electricity production for Scenario B is shown in Fig. 5.

Table 3 The main economic definitions and formulas in HOMER (HOMER Pro User Manual 2020; Kirim et al. 2021)

Economic parameters	Definition	Formula
Initial capital cost	The initial capital cost represents total amount of component at the beginning of the project including equipment and installation cost	
Replacement cost	The replacement cost means that if a component complete economic life, the new one is replaced. It differs from initial capital cost as only some part of the component may require replacement	
Operation and maintenance cost	O&M cost is the overall scheduled cost for life time operation and maintenance of the facility. O&M cost is mainly entered as an annual amount but some component is in hourly basis such as generators	
Salvage value	This value represents remainder in a component of the power system at the end of the project lifetime. HOMER presume that the salvage value only subjects to replacement cost	$S = \frac{C_{rep} \cdot R_{rem}}{R_{comp}}$ *S: Salvage value ($)* C_{rep}: *Replacement cost of the component ($)* R_{rem}: *Remaining life of the component (year)* R_{comp}: *Lifetime of the component (year)*
Life cycle cost (LCC)	LCC is the sum of the installation and operation cost of a component along the project lifetime. It includes initial capital cost, O&M cost, fuel cost, replacement cost and salvage value	*LCC = Initial capital cost + O&M cost + fuel cost + replacement cost − salvage value* *LCC: Life cycle cost ($)*

(continued)

Table 3 (continued)

Economic parameters	Definition	Formula
Annualized cost	HOMER associates the capital, replacement, maintenance, fuel costs and other costs with the revenues and salvage values of each component in order to calculate annualized costs of the components. This annual cost is suppositional cost that if taken place every year of the project lifetime, it would give a NPC equivalent to that of all the individual costs and revenues combined with that component along the project lifetime	$C_{ann} = CRF(i, R_{proj}) \cdot C_{NPC}$ C_{ann}: *Annualized cost ($)* C_{NPC}: *Net present cost ($)* *i: Annual real discount rate (%)* R_{proj}: *Project lifetime (year)* *CRF (): A function returning the capital recovery factor*
Operating cost	The operating cost covers the annualized value of all costs and revenues expect the initial capital cost	$C_{operating} = C^{*}_{ann,tot} - C_{ann,cap}$ $C_{operating}$: *Operating cost ($/year)* $C_{ann,tot}$: *Total annualized cost ($/year)* $C_{ann,cap}$: *Total annualized capital cost ($/year)* $*C_{ann,tot} = C_{ini,tot} \times CRF()$ $C_{ini,tot}$: *Total initial cost ($)* *CRF: Capital recovery factor*
Net present cost (NPC)	NPC of a power system is the difference between the present value of the costs incurred during the life of the system and present values of the revenues	$NPC = C_{ann,tot} / CRF^{*}_{(i,Rproj)}$ *NPC: Net present cost ($)* $C_{ann,tot}$: *Total annualized cost ($)* *i: Annual real interest rate (discount rate) (%)* R_{proj}: *Project lifetime (year)* *CRF: Capital recovery factor* $*CRF(i, N) = \frac{i(1+i)^N}{[i(1+i)-1]}$ *i: Annual real interest rate (%)* *N: Number of years (year)*

(continued)

Table 3 (continued)

Economic parameters	Definition	Formula
Levelized cost of energy (COE)	COE is defined as average cost per kWh of beneficial electrical energy generated by the system. HOMER calculates COE dividing annualized cost of producing electricity by the total electric load served	$COE = \frac{C_{ann,tot}}{(E_{prim}+E_{def}+E_{grid,sales})}$ *COE: Cost of energy($/kWh)* $C_{ann,tot}$: *Total annualized cost* E_{prim}: *Total amount of primary load (kWh/year)* E_{def}: *Total amount of deferrable load (kWh/year)* $E_{grid,sales}$: *The amount of energy sold to the grid (kWh/year)*

Table 4 System configurations, NPC, COE, and RF of the proposed HPP

Scenarios	System configuration	Biogas-NG generator (kW)	PV (kW)	Converter (kW)	NPC ($)	COE ($)	Initial capital ($)	Total fuel (m^3/year)	RF (%)
A	LC for (0.080 $/kWh)	2000	1,336	625	13.60 M	0.333	10.40 M	484,000	62.30
B	LC for (0.133 $/kWh)	2000	1,671	964	2.55 M	0.026	11.50 M	0	81.60
C	FR for (0.080 $/kWh)	1500	535	417	4.30 M	0.143	4.35 M	39,112	53.90
D	FR for (0.133 $/kWh)	2000	1,311	715	1.46 M	0.017	7.73 M	68,655	72.10

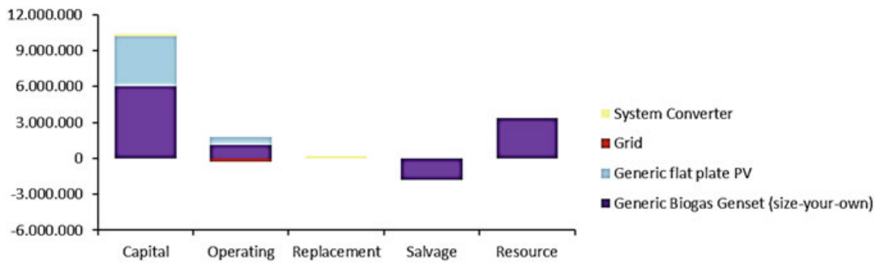

Fig. 2 Component cost of the system for scenario A

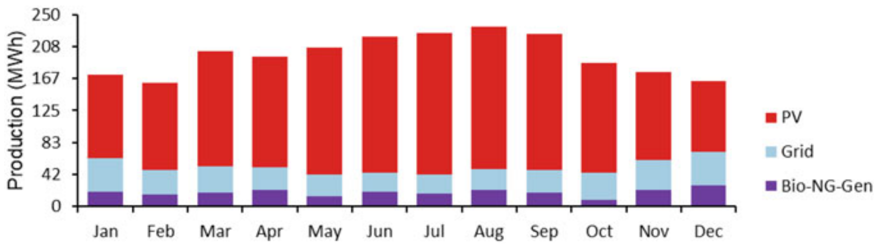

Fig. 3 Monthly electricity production for scenario A

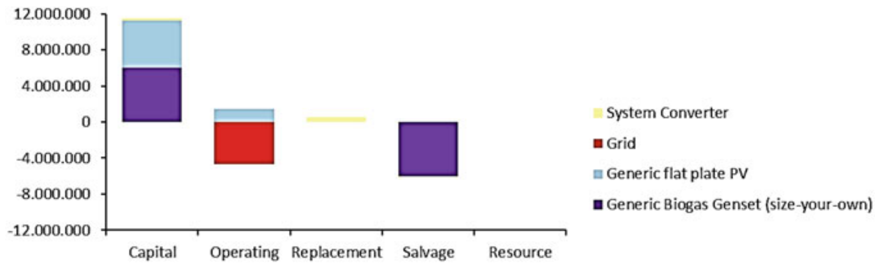

Fig. 4 Component cost of the system for scenario B

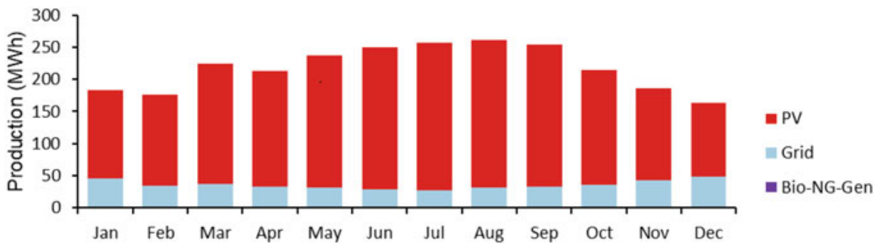

Fig. 5 Monthly electricity production for scenario B

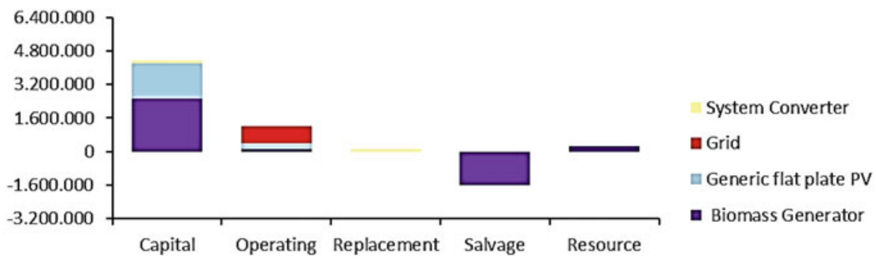

Fig. 6 Component cost of the system for scenario C

In Scenario C, contribution of PV panel cost is the higher compared to cost of the system converter. Capital and O&M costs of the biogas generator in Scenario C are $1.68 M and $280,655 M, respectively. Cost of the biogas generator in Scenario C is higher than other components but salvage value of the biogas generator affect decrease in total cost of the biogas generator at the end of the project lifetime. NPC and COE of the Scenario C are $4.30 M and $0.143/kWh, respectively and RF of the Scenario C is 53.9%. Component cost of the system for Scenario C is given Fig. 6. Purchase electricity from grid in Scenario C is 493,319 kWh/year (39.2%), electricity production from PV panel is 701,148 kWh/year (55.8%), and electricity production from biogas generator is 62,973 kWh/year (5.1%). The share of grid purchase in this scenario is much higher than other scenarios. Monthly electricity production for Scenario C is shown in Fig. 7.

Scenario D is the most optimum scenario in terms of NPC and COE, which is more reliable indicator when determine the feasibility of a system. The value of the NPC and COE are $1.46 M and $0.017/kWh, respectively. The usage of total fuel in Scenario D 68,655 m^3/year and RF of that scenario is 72.1%. The share of grid purchase is 17.5% and energy sold to the grid is 82.5%. Component cost of the system for Scenario D is given Fig. 8. Electricity generation from biogas generation Scenario D is nearly 2% higher than Scenario C. Electricity generation from PV panel in Scenario D is also about 20% higher than Scenario C. Thus, renewable energy generation share in Scenario D increases when government incentives is applied before 2021.

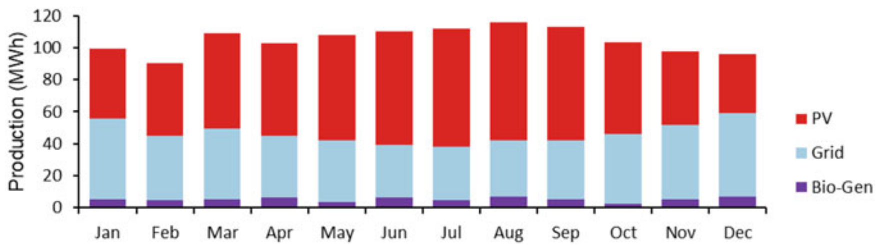

Fig. 7 Monthly electricity production for scenario C

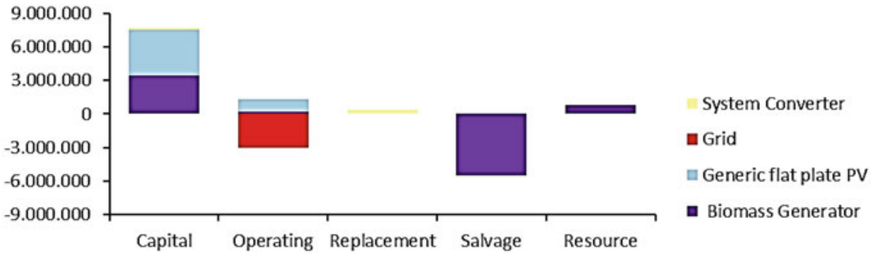

Fig. 8 Component cost of the system for scenario D

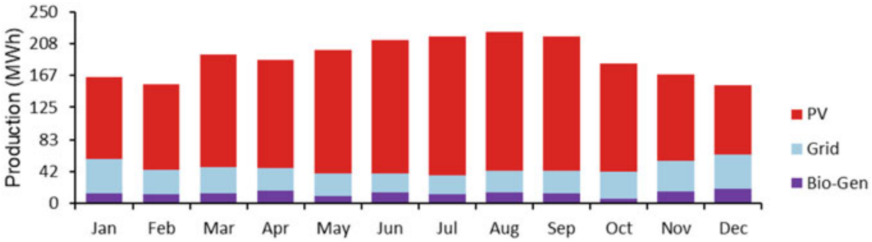

Fig. 9 Monthly electricity production for Scenario D

Monthly electricity production for Scenario D is shown in Fig. 9.

Comparison of renewable and non-renewable sources environmental impacts are also investigated in this study based on greenhouse gas (GHG) emissions. Emissions of CO_2 and CO in Scenario A, which are 1,188,043 kg/year and 968 kg/year, respectively are considerably higher than the other scenarios. The amounts of particulate matter (PM) in Scenario A and B are much higher than those values in Scenario C and D. This is due to combustion of FR leads to more emissions of PM and sulfur dioxide (SO_2) and nitrogen oxides (NO_x). Emissions of PM in Scenario A and B are zero while those values in Scenario C and D are 7.08 kg/year and 12.50 kg/year, respectively. There is no CO_2 or other GHG emissions originated from LC in Scenario B because electricity generation is provided from PV panel and national grid. Emission of CO_2, which is 270,562 kg/year is originated from national grid sources. Emission of CO_2 and SO_2 are seen in Scenario D but it has the highest PM. Unburned hydrocarbon is zero in all scenarios and the amount of NO_x, which is 1462 kg/year is highest in Scenario D. Hybrid system consisting of solar and FR sources has the lowest CO_2 emission compared to non-renewable sources (LC) and the amount of emitted CO_2 in Scenario D is three times less than that of in Scenario A. Amount of emissions of four different scenarios consisting of CO_2, CO, unburned hydrocarbons, PMs, SO_2 and NO_x are given in Table 5.

Table 5 Amount of emissions of four different scenarios consisting of CO_2, CO, unburned hydrocarbons, PMs, SO_2 and NO_x

Emission values of four scenarios	Carbon dioxide (kg/year)	Carbon monoxide (kg/year)	Unburned hydrocarbon (kg/year)	Particulate matter (kg/year)	Sulfur dioxide (kg/year)	Nitrogen oxides (kg/year)
Scenario A	1,188,043	968	0	0	1085	1136
Scenario B	270,562	0	0	0	1173	574
Scenario C	387,290	251	0	7.08	1352	1188
Scenario D	384,800	443	0	12.50	1091	1462

4 Conclusions

In this study, configuration of solar and biomass HES configuration composed of PV panel, converter and biogas generator is examined. Change in government incentives for solar and biomass energy before and after 2021 are used to estimate optimum NPC and COE values in the four different scenarios. It is found that Scenario D has NPC and COE values of $1.46 M and $0.017/kWh, respectively. The NPC and COE, which is estimated as $13.60 M and $0.333/kWh, respectively in Scenario A is much higher than Scenario B, C and D. Price of LC and lower feed in tariff ($0.08/kW) are the main reason of the highest NPC and COE values in Scenario. RF of Scenario B is about 35% higher than Scenario A and Scenario C because electricity generation is mostly supplied from PV panel in Scenario B. The highest CO_2 emission, which is 1,188,043 kg/year is calculated in Scenario A due to higher usage of LC and NG but the emission of CO_2 in Scenario D is about one-third of Scenario A. SO_2 emission in Scenario C is about 20% higher than Scenario D however emission of NO_x in Scenario D is 1462 kg/year (18% higher than Scenario C). Therefore, it is thought that results and findings of this study could help investors using FR and LC in hybrid systems to scrutinize advantages of biomass and coal gasification and solar energy, and promote academics and researchers to analyze gasification capabilities of different renewable and non-renewable sources in HES configurations.

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Integration of Renewable Energy to Trigeneration Systems for Rural Sustainability in Developing Countries

Nuraini Sunusi Ma'aji, Victor Adebayo, Ali Shefik, and Tanay Sıdkı Uyar

1 Introduction

Energy is a significant contributor to sustaining life on Earth. Modern energy transformation techniques have enhanced life quality by providing better services such as lighting, refrigeration, cooking, transportation, and all kinds of electrical equipment. This, however, has led to an increased reliance on fossil fuels for growth. Population growth and increased living standards, because of dependence on fossil fuels have significantly contributed to climate change Bagade et al. (2019) and even now more than 60% of the world's electricity is still generated by fossil fuels Liu (2020). On the other hand, it is interesting to note that many countries are currently modifying their

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fossil-fuel-fired power plants so that waste heat can be utilized to provide heating and cooling. Recovering heat from flue gases and exhaust steam released in power plants and using this hear to generate electricity via organic Rankine cycles (ORC) is an efficient way to reduce fossil fuel use and greenhouse gas emissions Liu (2020).

A wide range of alternative fuels and energy conversion technologies have been proposed for the industrial, commercial, and electric utility industries. Trigeneration is one of the most promising among such commercially available technologies. A trigeneration system can be defined as a system that combines power generation with cooling or heating through the use of a single primary source of energy Lai and Hui (2009). Trigeneration is a green and resilient solution for simultaneously addressing the three vital needs of electric power, freshwater, and air conditioning Anand and Murugavelh (2019). Electric power produced by a trigeneration system can be used on-site and distributed via the utility grid, or both Leonzio (2018).

In the past ten decades, global carbon emissions have increased by over two billion tons International Energy Agency (2020), mainly because the three vital needs of human societies, namely, electric power, freshwater, and heating are generated in inefficient and unsustainable ways. More recently, however, solar energy utilization as an alternative way to produce electricity, heating, and freshwater has led to a reduction in energy expenses by up to 70% and a reduction in carbon footprint by up to 90% Kalogirou, (2014).

Life without fundamental resources can be a challenge and that is why it is important to design a green trigeneration system that improves energy efficiency and reduces the cost of energy use. It is really hard to imagine a day without air-conditioning, electricity, and clean water. They become our backbone which keeps our homes comfortable and hospitals running. Electric power, freshwater production, and heating needs are everyday necessities. As a result, trigeneration systems are promising alternatives to compete with cogeneration systems, electric resistance, and conventional thermal energy technologies since they are fairly affordable and can be used with higher efficiencies. Moreover, they can be employed in places where there are large thermal energy requirements and/or there is a need to satisfy on-site energy requirements for producing substantial amounts of power to the distribution network.

Many rural communities are disregarded in rural electrification projects due to their remote location or low demand potentials. Yet such communities are often rural agricultural villages that farm crops the residue of which might be used as solid biomass fuel for power generation if appropriate techniques are applied Arranz-Piera et al. (2016). In their efforts to deliver contemporary and clean energy to semi-urban and rural regions, several governments and international aid groups have tended to rely on distributed energy resources such as photovoltaics, solar water heating and cooling, biogas digesters, and wind turbines Situmbeko (2017).

In addition to the lack of adequate means to meet energy needs, freshwater scarcity also limits the population settlement and development in remote and rural locations. In such isolated places, new methods, such as saline water desalination procedures, are needed to help enable access to freshwater for home and industrial use. In this regard, the main difficulty is to provide the required energy for desalination systems since there is limited availability of fossil fuels. Moreover, fossil fuel prices are not stable and tend to increase in general and fossil fuel-based energy conversion technologies have severe effects on the environment. These issues can be extenuated by using renewable energy integrated systems which depend on renewable resources like solar, geothermal, and biomass energy to power desalination plants. The principal benefit of renewable-based trigeneration systems is their ability to cut out the transmission costs, improving system efficiencies, economic viabilities, carbon emissions reduction, and energy surety. However, the present practices of trigeneration systems include data centres, food processing units, resorts, airports, refrigeration warehouses, manufacturing units, etc., and these systems can be adapted for use in rural areas to help those that do not have access to electricity.

While solar-based trigeneration systems are gaining popularity, Al-Sulaiman et al. (2011), Anand and Murugavelh (2019), and several other researchers have summarized what has been done in this field Kumar et al. (2021). Most of these researchers have studied the practicality of using solar in trigeneration plants. Wang et al. (2009) proposed a new solar-based combined trigeneration system to limit the need for fossil fuel; this system is powered by solar energy and it combines the ejector refrigeration and Rankine cycle for heating, power production, and cooling. Another study published by Jinget al. (2012) proposed a thermal system design for buildings heating, cooling, and power system that is powered by solar and natural gas sources. Wang et al. (2009) conducted an exergy modelling study to evaluate the exergetic performance of the novel trigeneration plant that uses an organic Rankine power cycle, and parabolic trough solar collectors. Another study carried out by Arranz-Piera et al. (2016) presented a feasibility study of trigeneration (heat, power, and refrigeration) for small farm typologies in Ghana with sufficiently clustered crop leftovers. In addition to the feasibility study, they also studied a way of determining the optimal power generation technologies. A sample of 11 Ghana districts was investigated to estimate the quantities of agricultural waste produced in small farm holdings and the clustering that would lead to the delivery of these waste in a hypothetical centralized trigeneration system. The results obtained in terms of plant capacity, biomass waste production, energy yield flows, and economic analysis point to an encouraging prospective for trigeneration deployment as a solution in Sub-Saharan African rural communities.

Wegener et al. (2019) presented various renewable energy solutions for a hotel resort in Neil Island, India, where they investigated locally accessible biomass and solar energy as an alternative solutions for needed energy. Four cases are simulated with the modelling software HOMER and their economic, energy, and ecological (3E) performances are assessed based on local demand statistics, commercial information, and scientific literature. With sensitivity analysis, the effectiveness of each case configuration is also examined. The results reveal an economic saving potential of more than US$500,000 over 20 years for a biomass-based solar-aided trigeneration system which could cut CO_2 emissions by 365 t per year. If the trigeneration concept is not applied, system performance will considerably deteriorate. Implementing a biomass-based trigeneration system might reduce the island's ecological footprint, save money for the hotel owner, and provide a new source of revenue for local farmers through biomass sales.

Combining power, cooling, and heating or freshwater production plant with renewable-based trigeneration systems would be a turning point for the sustainability of most rural areas without direct access to basic amenities. Based on this relationship, geothermal, solar, and biomass are suggested as feasible renewable energy sources Kumar et al. (2021). In various parts of the world the solar-powered trigeneration system is by far the most available and reliable heat source known among all renewable sources Anand and Murugavelh (2019). Renewable energy-based trigeneration technologies have been reviewed and presented in this study.

2 Biomass Powered Trigeneration System

Biomass-powered trigeneration systems have increased in popularity, and numerous studies have been published in this area. In this section, based on a survey of the available literature such technologies are grouped and discussed. After going through the related literature, it is noted that most of the trigeneration systems that are integrated with ORC units that are based on various low/medium-temperature heat sources. Flammable agricultural wastes, crop residue, wood and woody wastes from forestry and manufacturing industries, biowastes (municipal solid wastes—MSW) from cities/towns, and vegetable oil can provide the most reliable energy solutions if managed properly to secure and diversify the supply of energy biomass and/or biofuels Wang et al. (2010), Heinimö and Junginger (2009).

It is also worth noting that the majority of the publications on biomass-powered trigeneration systems that we came across in our literature survey were focused on modelling data rather than experimental and/or practical installation data. Puig-Arnavat et al. (2014) presents a novel design approach of trigeneration system modelling based on the biomass gasification process and compares different configurations. The proposed model offers five alternative configurations for the simultaneous production of heating, cooling, and electricity. The modelled components include an internal combustion engine, absorption chillers, and gasifiers. The findings indicate that it is a viable tool for evaluating the performance of trigeneration systems that use various forms of biomass and that it allows making a sound comparison across various configurations for real-world applications. Huang et al. (2017) proposes small-scale biomass or biodiesel-fuelled trigeneration system that can provide power, hot water, and space heating and/or cooling for dwellings in remote places in developing countries.

Bamisile et al. (2019) developed and analysed a unique trigeneration system that is driven by biogas produced from maize silage and chicken manure. The proposed system employs two steam ranking cycles, a gas cycle, a hot water chamber, and an absorption cycle to generate power, hot water, and cooling. The system's overall energy and exergetic efficiencies are 64% and 34.51%, respectively. Moreover, the highest exergy destruction was found to occur during the combustion process inside the system. Safari and Dincer (2019) have analysed new biomass-powered combined model for power generation, heating, hydrogen synthesis, and desalination all together. All systems units, including the digester, Brayton, ORC cycle, multi-effect desalination (MED), and electrolyser, are subjected to exergy, and energy evaluations. The overall system's exergy and energy efficiencies are 63%, and 40%, respectively, while the performance ratio (PR) of the MED system is calculated to be 4.25.

Trigeneration is a cost-effective system that generates electricity, heat, and refrigeration/cooling from a biomass gasifier with a built-in gas cleaning mechanism. The biofuel can be used to power a generator that produces electricity for the buildings. An investigation of a trigeneration plant based on an engine Genset, which produces electricity from producer gas generated in a biomass gasifier while also providing heating and cooling via waste heat is studied by Rentizelas et al. (2009). Their main aim was to investigate a method to replace conventional energy systems with biomass-powered trigeneration systems which will be cost effective. Another internal combustion system was studied by Huang et al. (2011) and they proposed a trigeneration system combining an internal combustion (IC) engine with biomass gasification which provides a clean and cost-effective way to deliver heat, power, and cooling. Their system is intended to address the power requirements of a limited number of community buildings and district heating and cooling applications.

3 Geothermal Powered Trigeneration System

The efficient use of geothermal heat has spawned a new field of study in trigeneration systems. Trigeneration plant technologies based on geothermal heat sources are presented in this section based on available literature. Geothermal energy, among other renewable energies, is offered as a prime mover for power plants and provides a more dependable and sustainable alternative with a guaranteed supply. Geothermal energy is mostly stored as heat in the earth's subsurface fluids and rocks. Because of their promising attributes, trigeneration systems powered by geothermal heat sources are emerging as a key component of the next generation of renewable energy plants.

An analysis on the thermo-economic and exergy consideration for the small-scale novel trigeneration plant for the optimum utilization of the low-grade geothermal temperature heat sources is conducted by Behnam et al. (2017). This study also looked at the impact of decision variables on the system's thermodynamic and thermo-economic performances. Using a single-phase absorption heat exchanger, this system raises the heat supply source temperature, allowing it to be used in a single-stage evaporation desalination process while also heating the water and producing electricity from an ORC. The proposed model is validated using existing data and the influence of decision variables such as geothermal source, condenser temperatures, and absorber on overall system energy and exergy performances, electricity to freshwater ratio, and cost of energy are examined.

In their study, Takleh and Zare (2021) design a novel trigeneration plant for power, cooling, and heating. They come up with a cost-effective thermal system design by employing a realistically simple approach. The organic Rankine Cycle system's heat exchanger cools the superheated steam refrigerant at the turbine outlet which transfers that waste heat to the liquid phase refrigerant at the pump outlet in the secondary rig. As a result, the heat exchanger of the system leads to a significant reduction in the evaporator volume that indicates enhanced thermal efficiency over simple ORC systems. Another study conducted by Gholizadeh et al. (2020) introduces a creative trigeneration system that uses a geothermal flash binary heat source at 170 °C temperature for electricity generation, cooling, and freshwater production. Two unique multi-generation plants powered by medium-temperature geothermal heat sources are considered. The potential of the suggested systems to operate in full heating, cooling, and power or combined power and cooling modes is an intriguing feature. Switching between summer and winter modes is straightforward and practical, and depending on the user's energy needs. The systems may also run in combined power, heating, cooling mode simultaneously.

Canbolat et al. (2019) studied the performance of the ORC cycle which produces electrical energy, using a 145 °C temperature geothermal resource. The system's fluids were determined to be dry-type fluids, with R142b, R227ea, R245fa, R600, and R600a being the ideal working fluids. An energy and exergy analysis of the system was carried out as part of this research. The performance of the cycle components was assessed as part of their analysis, and the first and second law efficiencies of the system were compared for various refrigerants. The first and second law efficiencies of the cycle were found to have increased by a maximum of 4.86% and 19.78%, respectively, while the refrigerant and evaporator pressures were kept constant at values chosen within the scope of other similar studies.

4 Solar Powered Trigeneration System

Solar energy has been presented as a viable source of trigeneration. Solar-powered trigeneration systems can only use solar energy to satisfy every energy requirement of buildings for heating, cooling, and power. These technologies have the potential to improve thermal energy utilization and therefore, in particular, allow access to the benefits achieved by on-site electricity generation.

The technological and economic choices for rural electrification in Africa are explored in Orosz et al. (2013). This study presents the justification for trigeneration for applications in the fields of healthcare and education (electricity, heating, and cooling capacity). A rural health clinic load profile (25 kWhe·day − 1 and 118–139 kWht) is outlined and regional analysis for sub-Saharan Africa is carried out by utilizing the correlations with latitude, aggregating meteorological data from NASA (insolation, temperature, and cooling degree days). Traditional electrification approaches, such as photovoltaic (PV) systems and diesel generators, are quantified as a baseline for their comparison. Moreover, alternatives to provide heating and cooling loads (e.g., gas-fired heaters, absorption chillers, or solar water heaters) are evaluated alongside emerging micro-concentrating solar power (CSP) technologies. Energy demand comprises a mix of electrical and thermal loads, such as in typical health and education locations. Non-carbon emitting CSP trigeneration techniques can be cost-effective, according to a comparative review of existing technologies Orosz et al. 2013.

Ghasemkhani et al. (2018) suggests a trigeneration system with three subsystems: solar, Kalina cycle, and lithium bromide-water absorption chiller. Solar energy is used to generate electricity, cooling, and hot water in their proposed system. The system under consideration is constructed and analysed in consideration of the climate of Zahedan, Iran. Cioccolanti et al. (2017) investigated the potential of a small-scale concentrated solar Organic Rankine Cycle plant coupled with an absorber by simulating a 50 m^2 CPC solar field, a 3.5 kWe ORC, and a 17.6 kW absorption chiller to meet the heating, electricity, and cooling needs of residential users. The ultimate purpose of the work is certainly to analyse the performance of the integrated small-scale system and to evaluate its viability for residential applications.

Gnaifaid and Ozcan (2020) propose a freshwater, power, and cooling trigeneration plant. The use of parabolic trough collectors with thermal energy storage is explored. Solar heat is used to generate electricity using an ORC cycle and to cool the building using an absorption chiller. A portion of the power generated is used to run a desalination plant that employs reverse osmosis. The solar radiation measurements are gathered from a Turkish southern city. Exergetic efficiency and system costs range between 9 and 14% and 287–335 $/h, respectively. According to a multi-objective optimization study, at a plant cost rate of 328 $/h, ideal exergy efficiency of 12.5% can be achieved.

Abbasi and Pourrahmani (2020) offer three different potential modes of the proposed integrated system to provide power, cooling, and freshwater. The study was conducted by integrating high-temperature Thermal Energy Storage (TES). The reverse osmosis (RO) unit is used to produce freshwater and the absorption cooling cycle (ARC) provides cooling. The system uses a high-temperature PCM material (Phase Change Material), to keep the system functioning even during the night. The Organic Rankine Cycle is also used to recover the heat from the gas turbines.

5 Environmental Concerns

Fossil fuels are the main source of conventional energy generation systems which result in enormous emissions of greenhouse gases (GHG). Therefore, it is urgent to investigate renewable energy sources or to utilize low-grade waste heat from the power generation process for heating and/or cooling. The latter is one of the methods to save energy and trigeneration technologies are thus highly relevant from this viewpoint. Different environmental studies have demonstrated that CO_2 emissions have been reduced significantly while using the trigeneration system compared to a single power generating.

The severe energy supply challenges, as well as the depletion of natural resources and environmental concerns about global warming and climate change, have prompted a total shift in energy supply, and/or production and consumption patterns Jradi and Riffat (2014). As a result, a shift to renewable energy resources, as well as the development of energy-efficient innovations are vital components in achieving a safe and secure energy sector and alleviating global warming and climate change. Scientists have begun to investigate a transition to renewable energy resources in response to growing concerns about the negative environmental effects of fossil fuels and rising energy demand and environmental implications of fossil fuels Raghulnath et al. (2020). A notable and potentially viable system with an environmental benefit, technical, and commercial, has been recorded with simultaneous production of electricity, heating, and cooling application with a trigeneration plant. Geothermal energy, like other renewable energy sources, is a promising and dependable source for power production, heating and cooling, distillation, industrial drying, and desalination Jradi and Riffat (2014).

Based on the environmental concern regarding climate change and global warming, a serious and outright restructuring of energy generation, supply, and consumer habits is required. In Espirito Santo (2012) two different geothermal-powered trigeneration designs are proposed. The main distinctions in the aforementioned systems are the relative deployments of the organic Rankine cycle and Kalina cycle for power generating units.

6 Concluding Remarks

This paper has reviewed examples of renewable energy-based trigeneration systems for electricity production, air conditioning, and freshwater that utilizes solar, biomass, and geothermal energy. Figure 1 presents a flow chart that outlines the main processes of the renewable energy sources discussed in the preceding parts and their uses in other thermal systems. The rural trigeneration system shows promising opportunity for rural areas of undeveloped or developing countries.

In the initial part of this study, the biomass-powered trigeneration system is reviewed based on findings from available research. A biomass trigeneration system is an efficient and cost-effective option for the usage of most of the rural communities. The geothermal-powered trigeneration plant is considered in the second phase of this study. The system efficiency of the combined Kalina power system is higher than that of the organic Rankine-based system. The combined solar-powered trigeneration system is inspected in the last phase of this research. This system is based on linear Fresnel reflector, solar towers, and parabolic trough collector. The installation of an Organic Rankine bottoming cycle or Kalina cycle results in the generation of additional electricity from the solar heat provided to the system as well as a higher conversion efficiency of the power block.

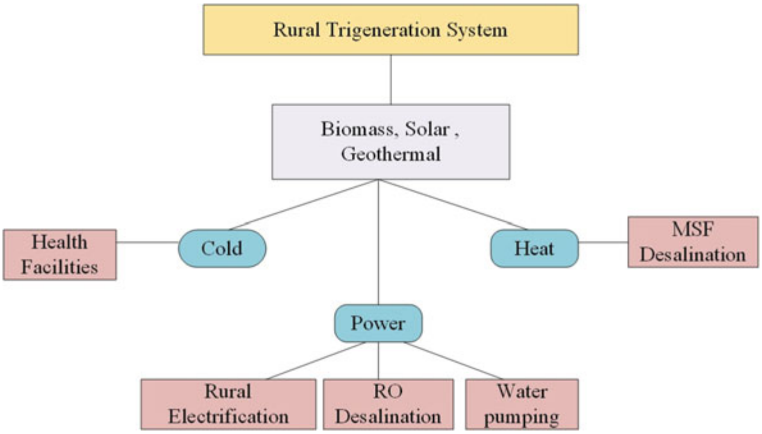

Fig. 1 Renewable energy integration for various sources for different types of necessity

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Wave Energy Conversion Technologies

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1 Introduction

The energy crisis experienced in the 1970s showed that meeting the energy requirements mostly from fossil fuels could adversely affect our lives. While the energy requirements are mostly met from fossil fuels, their harmful effects on the environment are also becoming more evident by each day. As a result, different energy sources were started to be researched to diversify the supply of energy and to prevent the pollution of the environment. Waves are a promising and abundant source of renewable energy that was started to be studied during the days of the energy crisis. Many different types of wave energy converters have been designed so far, which are at different levels of development. Designing a wave energy converter that will satisfy many requirements in a very harsh environment is a complex process. Many factors should be analyzed, such as the geometry and the size of the float, the type of the power take-off system and its dynamics, the mooring system, and the environmental conditions. Thus, the wave energy converters will be briefly introduced in the following sections and the analyses that are carried out during the design process will be explained.

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2 Types of Wave Energy Converters

The research studies that have been carried out for many years resulted in different types of wave energy converters. These devices have different shapes and methods of extracting the power of waves and are deployed in different locations at sea. The wave energy converters that are developed so far are generally classified as the following, depending on their geometries and the method of extracting the power of the waves.

- Oscillating body wave energy converters
- Overtopping
- Oscillating water column (OWC).

The oscillating body wave energy converters possess one or more bodies that move in different degrees of freedom and convert the motion of waves into electricity. The floats of this type of wave energy converter oscillate in the surge, heave or pitch modes of motion and drive a power take-off system that generates electricity.

A point absorber type wave energy converter generally has a floating buoy that interacts with the waves and converts the motion of waves into linear motion. Then, the linear motion of the float activates a power take-off mechanism that converts the mechanical power into electrical energy. The dimensions of this type of wave energy converters are generally smaller than the wavelengths and they have axisymmetric geometries that enable them to capture the power of waves coming from all directions. The point absorber wave energy converters can have either a single body or a two-body design. While the power take-off system of a single-body wave energy converter is activated by the motion of the float, the relative motion between the bodies of a two-body wave energy converter drives the power take-off system. Currently, there are 83 point absorber wave energy converter developers according to European Marine Energy Centre ("European Wave Energy Centre (EMEC) Wave Developers". 2021). Some examples of point absorber-type wave energy converters are presented in Table 1 and Figs. 1, 2, 3, 4 and 5 (Eriksson et al. 2007; Muliawan et al. 2011; Falcao et al. 2012; Wacher and Neilsen 2010; Prado et al. 2006).

Another type of wave energy converter is called an attenuator that floats parallel to the direction of wave propagation. The bodies of this type of wave energy converters generally oscillate in the pitch direction. The relative motion between two or more bodies or the oscillations of the entire body of the wave energy converter drives a power take-off system that generates electricity. Pelamis, Oceantec, Searev, and McCabe Wave Pump wave energy converters are examples of this type of wave energy converters and are presented in Figs. 6, 7, 8 and 9 (Henderson 2006; Ruellan et al. 2007; Salcedo et al. 2009; Cordonnier et al. 2015).

The wave energy converters that possess a surging body are called oscillating wave surge converters. These wave energy converters capture the energy of the waves via a surging flap-type structure and the motion of the flap activates a power take-off system. Oyster and WaveRoller that are shown in Fig. 10 are examples of this type of wave energy converter (Cameron et al. 2010; Folley et al. 2007).

Table 1 Point absorber type wave energy converters

Device name	Type	Installation	Power take-off	Power (kW)
Lysekil project	Single-body	Bottom mounted	Linear generator	10
PB3 powerbuoy	Single-body	Floating	Direct drive generator	3/7.5
Wavebob	Two-body	Floating	Hydraulic system	220
L10	Single-body	Floating	Linear generator	10
IPS buoy	Single-body	Floating	Hydraulic piston/turbine	–
AquaBuoy	Single-body	Floating	Hose pump/ hydraulic turbine	–
Archimedes wave swing (AWS)	Single-body	Fully submerged/bottom mounted	Linear generator	2000

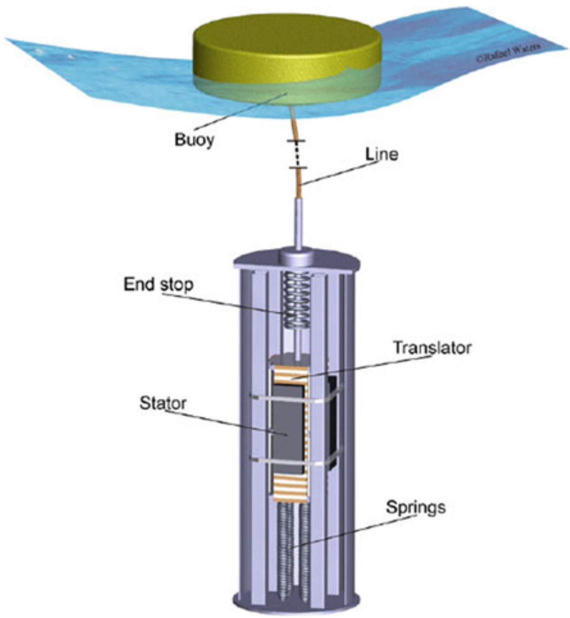

Fig. 1 Lysekil project point absorber WEC

Oscillating Water Column (OWC) wave energy converters capture the energy of waves by an air turbine that drives an electric generator. An oscillating water column wave energy converter comprises a chamber where the waves enter and force the air inside to flow through an opening. The up-and-down motion of the water surface inside the chamber generates a bi-directional airflow, thus an air turbine coupled to a generator is driven. Although the airflow caused by the vertical oscillations of the water surface inside the chamber is bi-directional, these wave energy converters

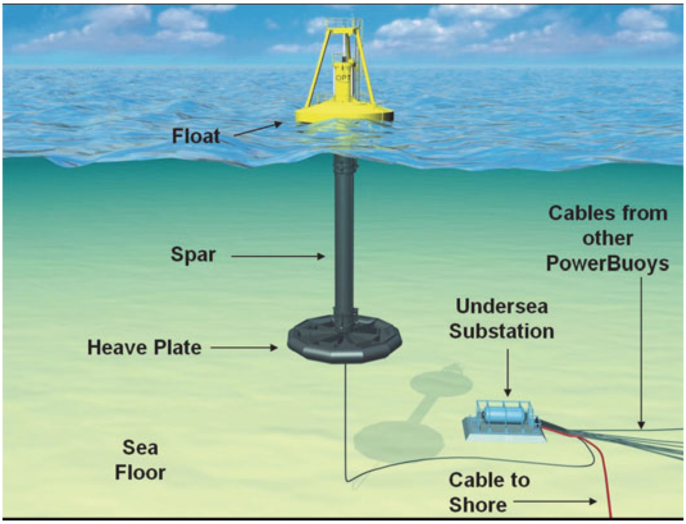

Fig. 2 OPT powerbuoy

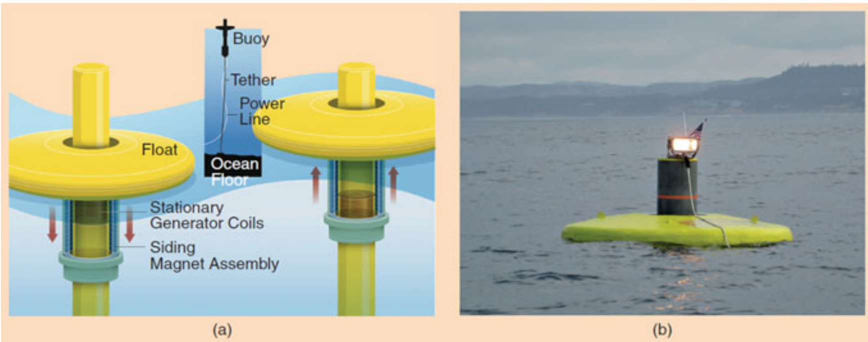

Fig. 3 L10 wave energy converter

are equipped with air turbines that are capable of rotating in one direction. Wells turbine is the most common type of air turbine employed in this type of wave energy converter. Oscillating Water Column wave energy converters can be shore-based or floating. Some examples of OWC wave energy converters are presented in Table 2 (European wave energy pilot plant on the island of Pico, Azores 2015; Torre-Enciso et al. 2009; Q. U. of Belfast 2002; Thorpe 1999; Washio et al. 2000).

Overtopping devices are another kind of wave energy converter. These wave energy convertors collect the waves in a reservoir that is above the mean water level by directing the waves towards a ramp. Then, the waves break over the ramp and the water is accumulated. The water collected in the reservoir is then allowed to flow back to the sea through a hydro turbine and the electricity is generated by

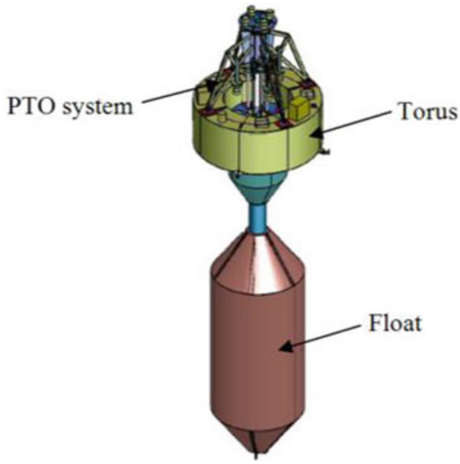

Fig. 4 Wavebob two-body point absorber WEC

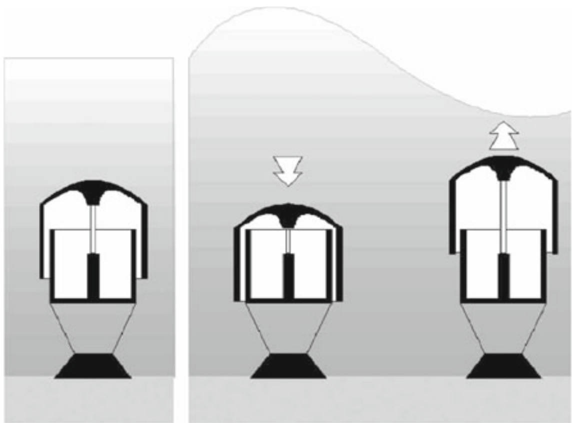

Fig. 5 Archimedes wave swing

a generator coupled to the turbine. These wave energy converters have both shore-based and floating examples. TAPCHAN (Tapered Channel), whose schematic is shown in Fig. 11, is a shore-based overtopping wave energy converter (Mehlum 1985). Wave Dragon is a floating device (Figs. 12 and 13) in which the waves are concentrated by reflectors and then break over a ramp, filling a reservoir (Kofoed et al. 2004). Finally, Seawave Slot-Cone Generator (SSG) (Fig. 14) is an overtopping device built onshore which collects water in three reservoirs that are at different levels and generates electricity by a multi-stage water turbine (Margheritini et al. 2009).

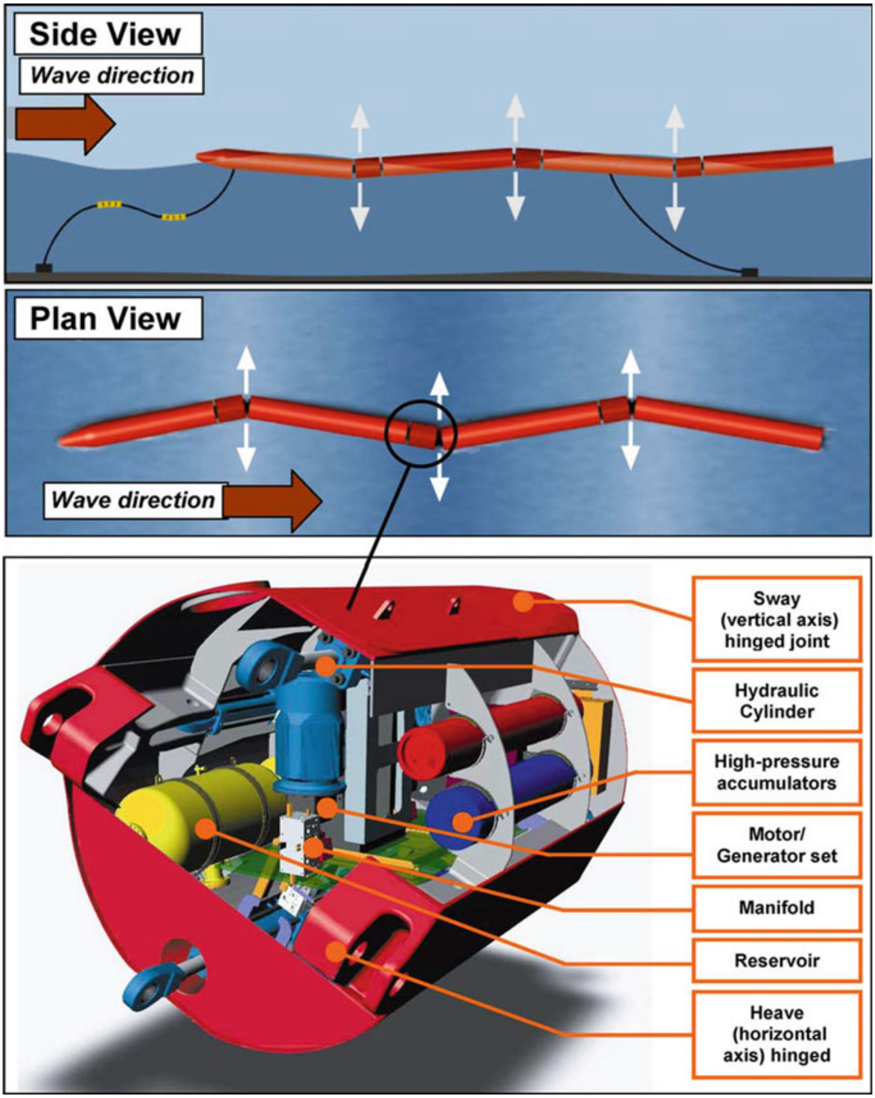

Fig. 6 The layout of pelamis WEC and its power take-off system

3 Power Take-off (PTO) Systems

The part of a wave energy converter that converts the mechanical energy into electrical energy is called a power take-off system. Currently, four types of power take-off systems are employed in wave energy converters (Erselcan and Kükner 2014). These systems are;

Fig. 7 Pelamis WEC deployed at sea

Fig. 8 OCEANTEC wave energy converter

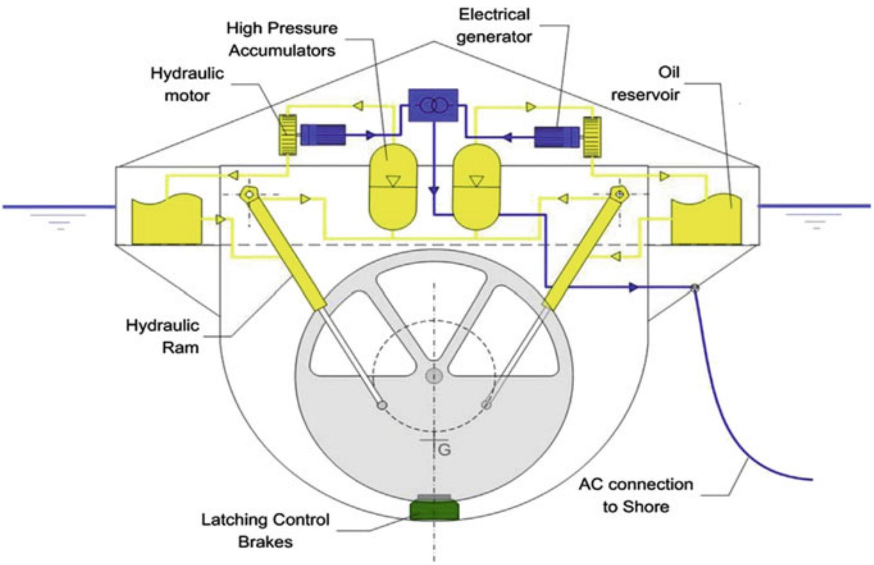

Fig. 9 SEAREV wave energy converter

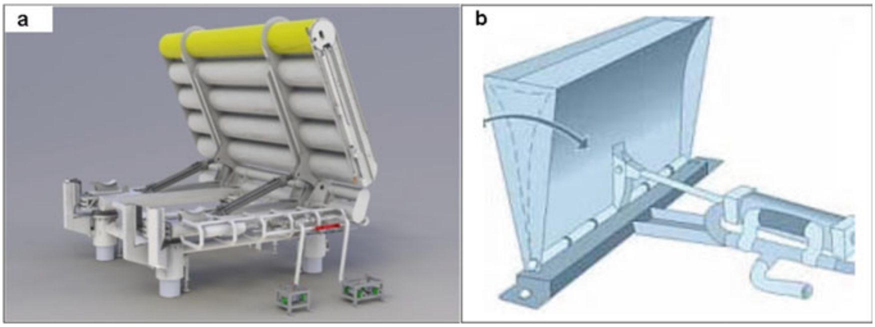

Fig. 10 **a** OYSTER and **b** WaveRoller surging WECs

Table 2 OWC wave energy converters

Device name	Installation	Turbine	Power (kW)
Pico	Shoreline	Wells	700
Mutriku	Shoreline	Wells	296
LIMPET	Shoreline	Wells	500
OSPREY	Floating	Wells	500
Mighty whale	Floating	Wells	110

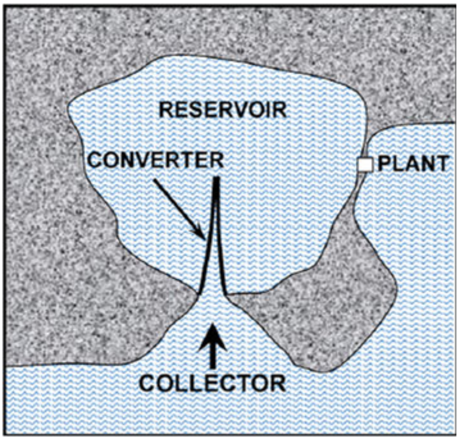

Fig. 11 A schematic of TAPCHAN overtopping WEC

Fig. 12 Wave dragon overtopping WEC

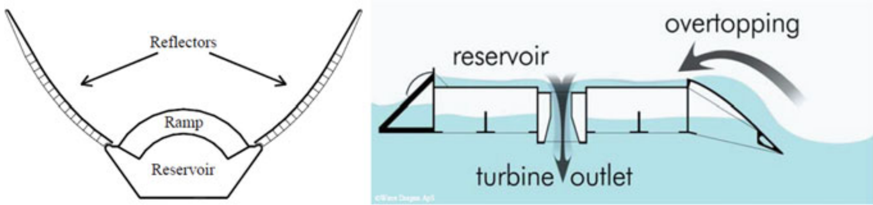

Fig. 13 Working principle of wave dragon

Fig. 14 Seawave slot cone generator (SSG)

- Hydraulic power take-off systems,
- Air turbines,
- Low head water turbines,
- Linear generators.

Hydraulic power take-off systems generally comprise a hydraulic actuator, check valves, hydraulic accumulators, and a hydraulic motor that drives an electric generator. The hydraulic actuator is activated by the motions of the float or the body of the wave energy converter which interacts with waves. The hydraulic actuator pumps the hydraulic fluid into the system at high pressures. The motions of the wave energy converters are oscillatory due to the nature of the waves, thus the flow generated by the hydraulic actuator becomes bi-directional. As a result, a group of check valves is employed in the system as a rectifier to generate a one-directional fluid flow. The motions of the wave energy converters are irregular since the real waves are irregular. As a result, the flow rate and the pressure of the hydraulic fluid fluctuate. The fluctuating flow causes the hydraulic motor to run irregularly which results in an irregular electrical output. The fluctuations in the fluid flow can be regulated by employing hydraulic accumulators in the system. If the fluid is first charged in a hydraulic accumulator, the fluctuations in the flow will be suppressed. Then, the fluid can be discharged at the desired flow rate which will enable the hydraulic motor to run at the desired speed, thus generating electricity at a certain frequency. A schematic of a hydraulic power take-off system is given in Fig. 15 (Erselcan and Kükner 2017, 2020).

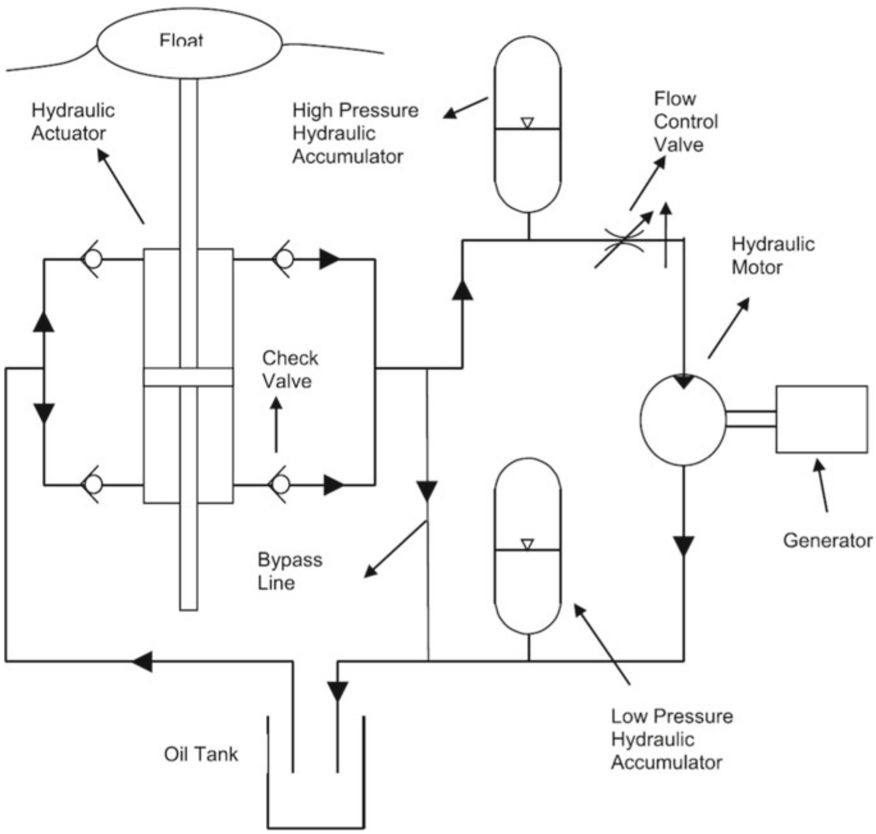

Fig. 15 Hydraulic power take-off (PTO) system of a point absorber WEC

Air turbines coupled with electric generators are used as a power take-off system in the oscillating water column (OWC) wave energy converters. The disadvantages of bi-directional airflow caused by the oscillatory motion of the water surface inside the chamber are overcome by using self rectifying turbines. Wells turbines are the most common air turbines employed in OWC wave energy converters. These turbines comprise guide vanes that direct the airflow such that the turbine always rotates in one direction. In addition to using guide vanes to control the direction of airflow and the rotation of the turbine, turbines that have rotors with self-pitching blades have also been developed and implemented in OWC wave energy converters (Fig. 16) (F. A.F.O. 2010; Lopez et al. 2013; Takao and Setoguchi 2012).

Driving electric generators by hydraulic turbines is another method of converting the mechanical force into electricity. Hydraulic turbines can be classified as impulse turbines and reaction turbines. Impulse turbines convert the kinetic energy of the water flow into mechanical energy. The speed of the water increases significantly when it flows through the nozzles. Then, the water is directed to the bucket-shaped

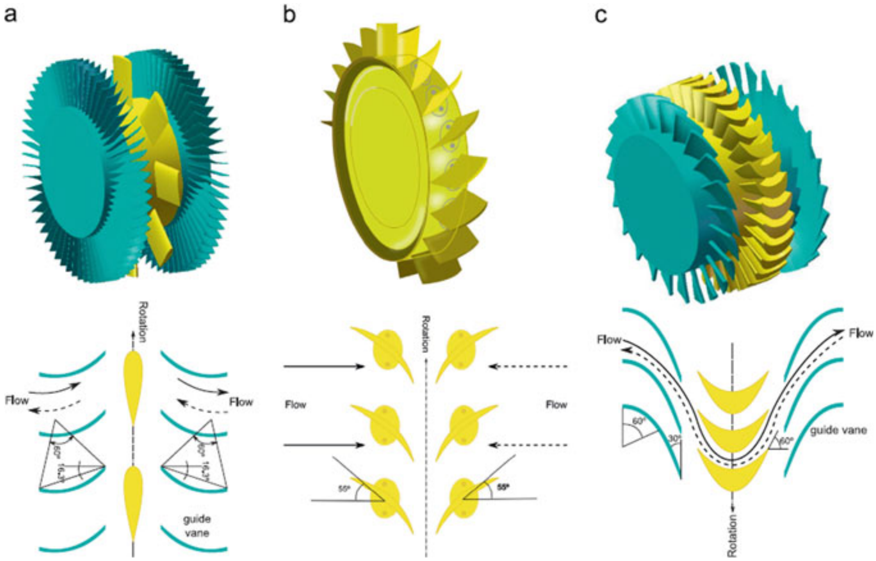

Fig. 16 Air turbines, **a** wells turbine, **b** self-pitching turbine, **c**, impulse turbine

blades of the turbine and the turbine is rotated by the transfer of kinetic energy from the water to the turbine. Pelton turbine is the most common type of impulse turbine and it is employed in Oyster and AquaBuoy wave energy converter (Wacher and Neilsen 2010; Cameron et al. 2010).

The change of the pressure of the flow in the rotors of reaction turbines generates the mechanical power to drive an electric generator. Francis and Kaplan turbines are widely used in engineering applications. Kaplan turbines convert the energy of water at low heads which makes them more suitable for wave energy conversion, while Francis turbines are more suitable for high head applications. Low head turbines that are shown in Fig. 17 (Lopez et al. 2013) are used in the overtopping wave energy converters such as Wave Dragon and Sea Wave Slot-Cone Generator to generate electricity (Kofoed et al. 2004; Margheritini et al. 2009).

The linear motion of the wave energy converters allows the use of a permanent magnet linear generator as a power take-off system. This system comprises powerful permanent magnets that create the necessary magnetic field to generate electricity. These magnets are placed in the rotor of the generator that is driven by the float of the wave energy converter. When the magnets move, they induce electricity on the coils that are placed on the stator of the generator. Although the linear generator has a simple structure, the number of permanent magnets required to generate the desired electrical power may make the generator heavy since the velocity of the float's oscillations is considerably lower than that of a rotary generator. The structure of a linear generator is given in Fig. 18 (Lopez et al. 2013).

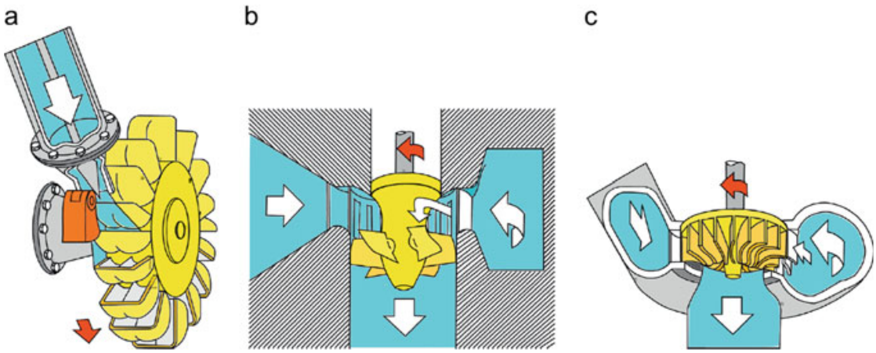

Fig. 17 Water turbines, **a** Pelton wheel, **b** Kaplan turbine, **c** Francis turbine

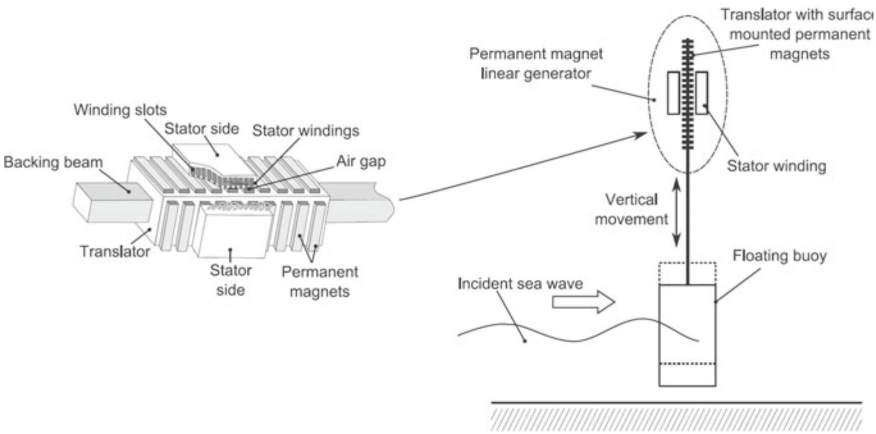

Fig. 18 A schematic of a permanent magnet linear generator

4 Moorings

The mooring system of a floating wave energy converter satisfies two requirements. First, the mooring system holds the wave energy converter in its deployed position and acts as a reference point. In addition to holding a WEC in position, the mooring system also plays another role by reacting to the motions of the wave energy converter. The resulting motions of the wave energy converter determine the energy generated by the system.

The size of a wave energy converter, the water depth, and the design of the wave energy converter affect the design and the type of the mooring system. The suitable types of moorings for wave energy converters and their design are discussed in Harris and Johanning (2006) and (Xu et al. 2019). The effects of the moorings on the energy generated by single wave energy converters and an array of point absorbers are studied in Fitzgerald and Bergdahl (2008); Elwood et al. (2011), Vicente et al. (2009).

5 Numerical Analysis Methods

The bodies or the floats of the wave energy converters undergo oscillatory motions due to the forces exerted by the waves. Calculating the displacement, velocity, and acceleration of the oscillations is the key to evaluating the energy that can be generated by a wave energy converter in a targeted area. The linearized first-order solution of the free surface problem is the most common method to analyze the motions of a wave energy converter. Assuming that a Cartesian coordinate system that the *xoy* plane coincides with the undisturbed free surface of the sea, and the positive z-axis points upwards, the governing equation and the boundary conditions of the linearized free surface problem is given as the following (Newman 1989).

- Continuity Equation:

$$\nabla^2 \emptyset = 0 \tag{1}$$

- Linearized free surface boundary condition:

$$\frac{\partial^2 \emptyset}{\partial t^2} + g\frac{\partial \emptyset}{\partial z} = 0, z = 0 \tag{2}$$

- Bottom boundary condition:

$$\begin{cases} \frac{\partial \emptyset}{\partial z} = 0, z = -h, \text{Finite water depth} \\ \lim\limits_{z \to -\infty} \frac{\partial \emptyset}{\partial z} \to 0, \text{Infinitely deep water} \end{cases} \tag{3}$$

The velocity potential of plane progressive waves can be evaluated by employing the method of separation of variables. As a result, the potential function corresponding to incident waves can be written as the following.

$$\begin{cases} \emptyset_I = \frac{gA}{\omega}\frac{\cosh[k(z+h)]}{\cosh(kh)}\sin(kx - \omega t), \text{Finite water depth} \\ \emptyset_I = \frac{gA}{\omega}e^{kz}\sin(kx - \omega t), \text{Infinitely deep water} \end{cases} \tag{4}$$

The velocity potential of the diffraction waves can be evaluated by satisfying the body boundary condition on the surface of a floating body as the following.

$$\frac{\partial \emptyset_D}{\partial n} = -\frac{\partial \emptyset_I}{\partial n} \tag{5}$$

Finally, the radiation forces acting on a floating body due to its oscillations in calm water can be written as the following,

$$F_{ij} = \iint_{S_B} \left(-\rho \frac{\partial \emptyset_j}{\partial t}\right) m_i dS \tag{6}$$

where ϕ_j is the velocity potential of body motions in 6 degrees of freedom, and m_i is the generalized unit normal vector. The wave forces and moments acting on the bodies by incident and diffraction waves can be calculated by using the potential functions given in Eqs. (4) and (5), and the added mass and hydrodynamic damping of a body oscillating with unit amplitude can be calculated by evaluating Eq. (6).

The motions of the float or the body of a wave energy converter can be calculated once the wave forces and hydrodynamic parameters of a floating body are evaluated. The 6 degree-of-freedom motions of a floating body can be calculated either in the frequency domain or in the time domain. The equation of motion in the frequency domain can be written as the following,

$$\begin{aligned}&\sum_{j=1}^{6} \left[\left(M_{ij} + A_{ij}(\omega)\right)\ddot{x}_j + B_{ij}(\omega)\dot{x}_j + C_{ij}x\right] \\ &= F_i^{FK}(\omega) + F_i^{D}(\omega),\ i = 1,\ 2, \ldots, 6\end{aligned} \tag{7}$$

and the time domain representation of the equation of motion can be given as in Eq. (8) (Cummins 1962; Bruzzone and Grasso 2007)

$$\begin{aligned}&\sum_{j=1}^{6} \left[\left(M_{ij} + A_{ij}^{\infty}\right)\ddot{x}_j(t) + B_{ij}^{\infty}\dot{x}_j(t) + \int_0^t k_{ij}(\tau)\dot{x}_j(t-\tau)d\tau + C_{ij}x(t)\right] \\ &= F_i^{FK}(t) + F_i^{D}(t), i = 1, 2, \ldots, 6\end{aligned} \tag{8}$$

The evaluation of the motions of the wave energy converters by solving either Eqs. (7) or (8) can be used to evaluate the energy that can be generated both in regular waves and in irregular waves. Generally, the performance of a wave energy converter deployed in an area is evaluated by its annual energy production. The annual energy production can be calculated as the sum of energy that is generated at each sea state observed in the deployment site. Thus, evaluating the annual energy production of a wave energy converter requires both the knowledge of the sea states observed in the targeted area and their durations of occurrence throughout a year.

6 Cost Analysis

The cost of the energy generated by a wave energy converter is perhaps the most important factor that determines the performance of that system. The cost of energy should also be evaluated during the design of a wave energy converter to determine whether or not that system is a feasible solution to generate electricity in an emission-free and environmentally friendly way. The cost analysis of the energy generated by a wave energy converter is generally carried out by taking the costs of the float or the structure of the WEC, the power take-off system, the moorings, repair and maintenance, and decommissioning into account. While these parameters are the most basic factors that are considered in cost analysis, the costs of the connection to the grid, installation of the WEC, subsea cables, the permits, the use of land and sea areas, research and development studies, and the project management are other cost factors that should also be considered. Consequently, the Levelized Cost of Energy (LCOE) in a wave energy project can be calculated as the following (Ocean 2013).

$$\mathrm{LCOE} = \frac{\mathrm{SCI} + \mathrm{SLD}}{87.6 \cdot \mathrm{LF}} \cdot \frac{r \cdot (1+r)^n}{(1+r)^n - 1} + \frac{\mathrm{OM}}{87.6 \cdot \mathrm{LF}} \tag{9}$$

The capitals costs (SCI), the decommissioning costs (SLD), the load factor (LF), the discount rate (r), the lifetime of the energy facility (n), and the annual operating and maintenance costs of the facility (OM) are taken into account to calculate the LCOE of a wave energy farm in Eq. (9). Calculating the LCOE of a wave energy system will require determining the initial cost of each component of the WEC, the costs of operating, repairing, and maintaining the system throughout its life along with and these costs will vary from one design to another and from one array configuration to another.

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Towards More Geothermal Energy in Turkey

Wietze Lise and Tanay Sıdkı Uyar

1 Introduction

The energy policy of the Turkish government has two main priorities, namely (a) maximizing exploitation of domestic primary energy resources, and (b) securing sufficient, reliable, and affordable energy to a growing economy in an environmentally sustainable manner.

In this context, the government of Turkey has put in place a supportive legal framework to facilitate geothermal development. A critical milestone was the Geothermal Law of 2007. This set out the rules and principles for effective exploration, development, production, and protection of geothermal and natural mineral water resources. In 2010 an amendment to the Renewable Energy Law established a feed-in tariff (FIT) of 105 USD/MWh for geothermal power, for a 10-year period from the commissioning date, with an addition of up to 27 USD/MWh, for a 5-year period from the commissioning date, to reward the use of locally produced equipment. This is guaranteed for geothermal power plants being commissioned until 30/06/2021.

This FIT has changed to 540 (+80) TL/MWh; valid for geothermal power plants being commissioned until 31/12/2025. The value is updated every 3 months based on CPI and PPI (both 26%), € and $ exchange rates (both 24%) with ceiling of 86 $/MWh for the base part of 540 TL/MWh, there is no USD-ceiling for local addition of 80 TL/MWh.

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Geothermal resources in Turkey are used for power production, as well as for space heating and tourism-related applications. The installed capacity of geothermal power plants in Turkey has grown rapidly in recent years. From some 15 MWe in 2006 to 1613 MWe produced by 60 power plants by end 2020. Moreover, power plants with a total installed capacity of 167 MWe are under construction and another 477 MWe have obtained a pre-license, as of SEP 2020. This rapid growth has led the government to increase the target of developing 1000 MWe geothermal electric generation capacity by 2023 to a target of 2000 MWe (JD 2021). However, this growth has been restricted to Western Turkey; most of the capacity development has taken place in the Menderes and Gediz Grabens.

The key research question of this chapter is: how can Turkey attract new investments and further accelerate the installed capacity in geothermal for power generation and direct use?

The outline of the chapter is as follows. Section 2 gives an overview of energy transitions to zero carbon economy with a special focus on the role of geothermal energy in that process. Section 3 assesses the current situation of geothermal in Turkey and point out the potential and the geographical hotspots, which should be focused upon to further develop geothermal power. The literature on investments in geothermal power is assessed in Sect. 4, leading to an estimate of the reasonable installed capacity per drilled production well. A simple business model needed for profitable investments is discussed in Sect. 5. Financial support in the form of a risk-sharing mechanism (RSM),[1] which has recently been launched in Turkey will be crucially important. Section 6 draws the main conclusions.

2 Transition to Zero Carbon Economy

Driven by global warming, a transition to zero carbon economy has been on the agenda for a long time (e.g. Kraan et al. 2019; Kakoulaki et al. 2021, among others). This transition cannot be accomplished by focusing on one single renewable energy technology, such as solar, wind, biomass, hydro, geothermal, etc., but all these options should be developed in the best possible manner. In addition, energy efficiency measures to reduce energy consumption will also play a key role in this transition. Among the renewable energy resources, geothermal is probably the least developed. However, geothermal can provide a good source of meeting a baseload energy need both for electricity generation and heat supply (see for instance Yale School of Environment 2021; JRC 2021; Climate Reality Project 2021; NREL 2021a, b).

Figure 1 presents an overview of geothermal technologies. This can be divided into three categories, namely geothermal heat pump (GHP), hydrothermal and enhanced geothermal systems (EHS). Firstly, GHP resources use the heat storage in relatively shallow depths, which can be used for heating and cooling of buildings via heat

[1] More information about the RSM project and the application procedure is available via http://rsmgeoturkey.com.

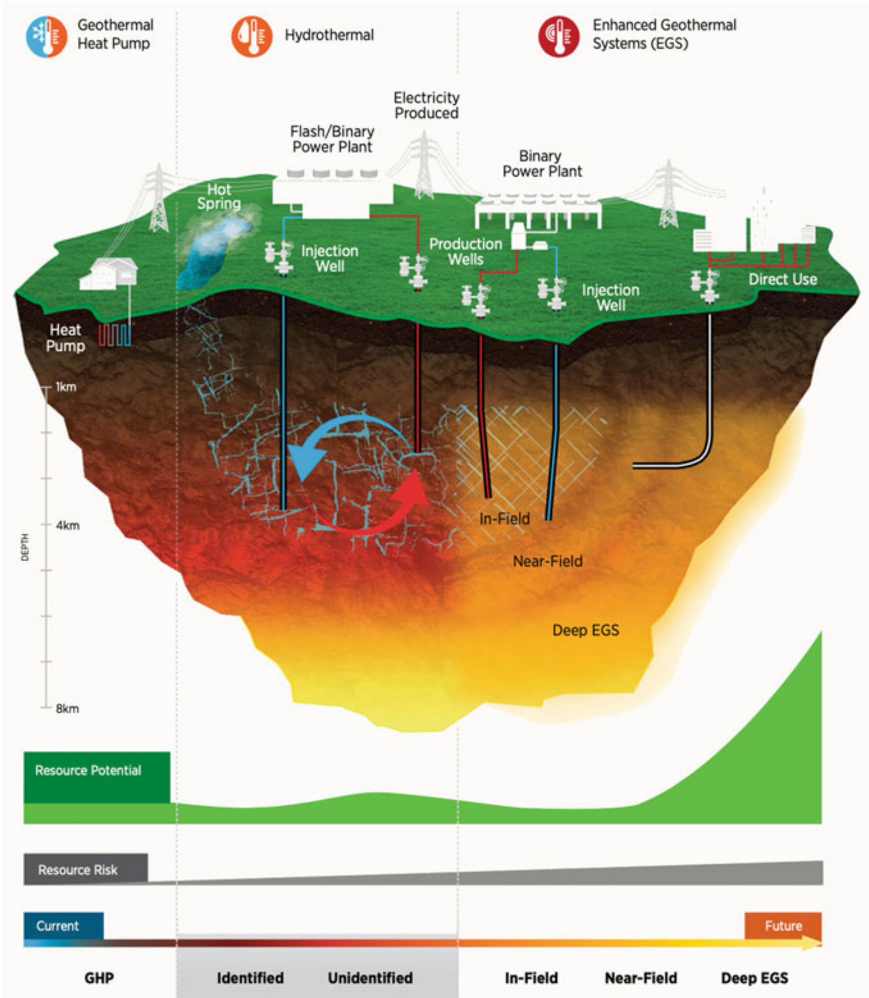

Fig. 1 An illustration of geothermal technologies with an increasing level of complexity *Source* Geo Vision (2021)

exchangers. Secondly, hydrothermal resources can be found in two ways, namely either as geothermal direct use applications for hot springs, district heating, greenhouse heating, SPAs and hotels, or by feeding a flash/binary power plant for electricity generation, especially in combination with reinjection wells. Hydrothermal geothermal resources are the main focus of this chapter. Finally, the most advanced geothermal technologies are found under unconventional EHS resources. These technologies are still under development and not yet proven; but have the potential for increasing the utilization of geothermal energy even further. Here the temperature found at deep levels are exploited using advanced technologies, such as hot-rock

Table 1 Distribution of installed capacity of geothermal power in Turkey as of end 2020

Province	Number of power plants	Total installed capacity in MWE
Aydın	30	812
Manisa	15	380
Denizli	10	379
Çanakkale	3	27
İzmir	1	12
Afyonkarahisar	1	3
TOTAL	60	1,613

Source EA (2020)

extraction with water injection. According to JD (2021) the power generation technical potential of Turkey in case EHS resources would be tapped into would be 400 GWe. With a dedicated FIT of 150 USD/MWh for 15 years a potential of 20 GWe could be developed.

3 Assessment of Current Situation of Geothermal in Turkey

As of the end of 2020, there is about 1613 MWe of installed capacity in geothermal power in Turkey (TEIAS 2020). Table 1 shows the breakdown of the installed capacity of geothermal by province. We can see from Table 1 that the highest installed capacity is in Aydın followed by Denizli and Manisa. These provinces are the hot spots for geothermal development in Turkey. In addition, some geothermal power plants are also found in Çanakkale, İzmir and Afyonkarahisar.

A map with key geothermal locations is presented in Fig. 2. Hence, the hotspots for geothermal can be found in the Menderes and Gediz grabens in the provinces of Aydın, Denizli and Manisa.

Karamanderesi (2013) presents the key geographical characteristics of geothermal reservoirs in Turkey. Well-known geothermal fields are Kızıldere, Germencik, Salavatlı, Alaşehir-Alkan, Salihli-Caferbeyli, MDO-1 well, Sandıklı AFS wells, Afyonkarahisar geothermal area, and Çanakkale Tuzla. However, geothermal resources can also be found in central and eastern Anatolia.

Based on data from the Turkish Geothermal Association (JD 2021), current geothermal district heating capacity of Turkey is as follows (Table 2).

A projection for geothermal direct use is presented in Table 3.

The following graph shows the key geothermal areas in Turkey, both the hot spots for power generation and for geothermal direct use (Fig. 3).

Mertoglu, Simsek and Basarir (2015) report on the geothermal potential in Turkey. These are reported as 4500 MWe for power generation[2] with well depths up to

[2] Melikoglu (2017) also uses the number of 4500 MWe of geothermal power potential in Turkey.

Fig. 2 Distribution of locations with geothermal resources suitable for electricity generation and power plants in Turkey. *Sources* Aksoy (2014), Kilic (2016)

Table 2 Direct use installed capacity in Turkey

SPAs	1400 MWth (520 SPAs)
House heating in cities	1120 MWth (126,000 R.E.)
Greenhouse heating	855 MWth (450 ha)
Thermal hotels/time sharing	435 MWth (48,600 R.E.)
Ground source heat pump	8.5 MWth
Fruit, vegetable drying	9.5 MWth
District cooling	0.3 MWth
Total installed power	3828 MWth (373,000 R.E.)

Source JD (2021)

Table 3 Conservative projection for potential of thermal capacity of Turkey

				Current status-2020	Short term (10 years)	Intermediate term (20 years)	Long term (30 years)
Total thermal capacity of Turkey (60,000 MW_{th})	Total electric power capacity (with 10% conversion efficiency to MW_{th})			16,130	25,000	32,500	40,000
	Total direct use capacity of Turkey MW_{th}	Direct use area (% share of direct use area in 2020)					
		Residential (+thermal hotel facility + cooling) heating (41%)	MW_{th}	1564	4000	6500	9000
		Greenhouse heating (22%)	MW_{th}	855	2000	3500	4500
		Thermal tourism (37%)	MW_{th}	1400	3000	4500	6250
		Drying (0.2%)	MW_{th}	9	80	150	250
	TOTAL		MW_{th}	19,958	34,080	47,150	60,000

Source Baba (undated)

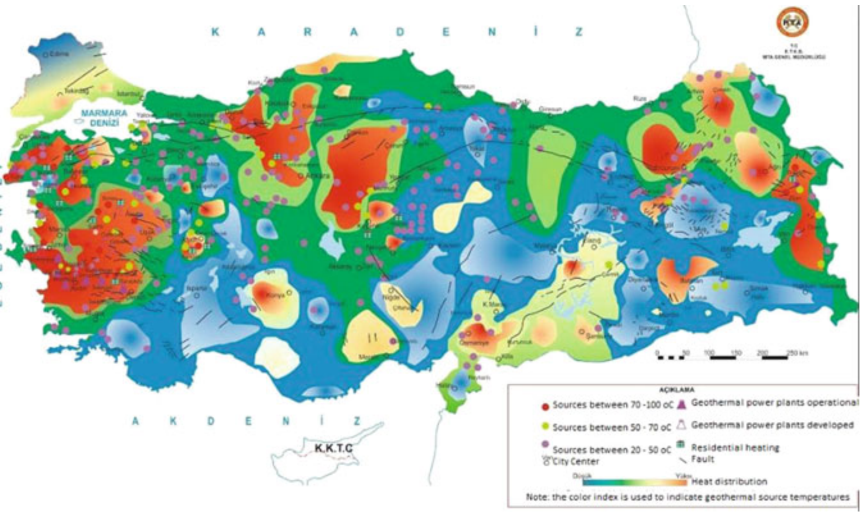

Fig. 3 Distribution of key geothermal areas in Turkey. *Sources* MENR (2021)

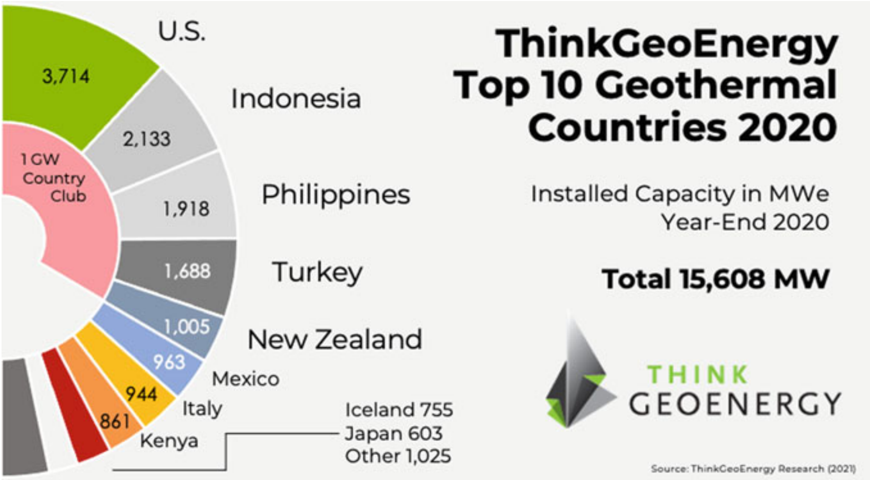

Fig. 4 Installed geothermal power capacity around the globe. *Sources* TGE (2021)

3 km, whereas the potential of direct use has been increased from 31,500 to 60,000 MWth (JD 2021). An important step for accelerating geothermal development has been the geothermal law No 5686 of 2007. Together with the FIT for geothermal power production, the installed capacity has increased substantially. The geothermal potential in Turkey is also studied in detail by Korkmaz, Serpen and Satman (2014). They arrived at a lower estimate for geothermal power potential, namely 2263 MWe. In 2017, Turkey entered the so-called 1 GWe country club with respect to geothermal power installed capacity, where Turkey is ranked fourth in the world after the USA (3714 MWe), Indonesia (2133 MWe), Philippines (1918 MWe) and New Zealand (1005 MWe) (TGE 2021) (see Fig. 4).

Ates and Serpen (2016) focus on which technology to choose to optimally fit the characteristics of the geothermal reservoirs. Based on a model simulation analysis the authors conclude that a model using a single flash and binary cycle processes together to be an optimal choice for many reservoirs in Turkey.

4 Investments in Geothermal Power

ESMAP (2012) provides a handbook into the planning process and financing geothermal power projects. Figure 5 shows how risks develop over time in the project cycle, where the need for financial support, such as RSM is particularly important during the exploration phase.

Figure 5 shows that the risk to the investor is typically the highest during the exploration phase until test results have been obtained. After establishing the presence

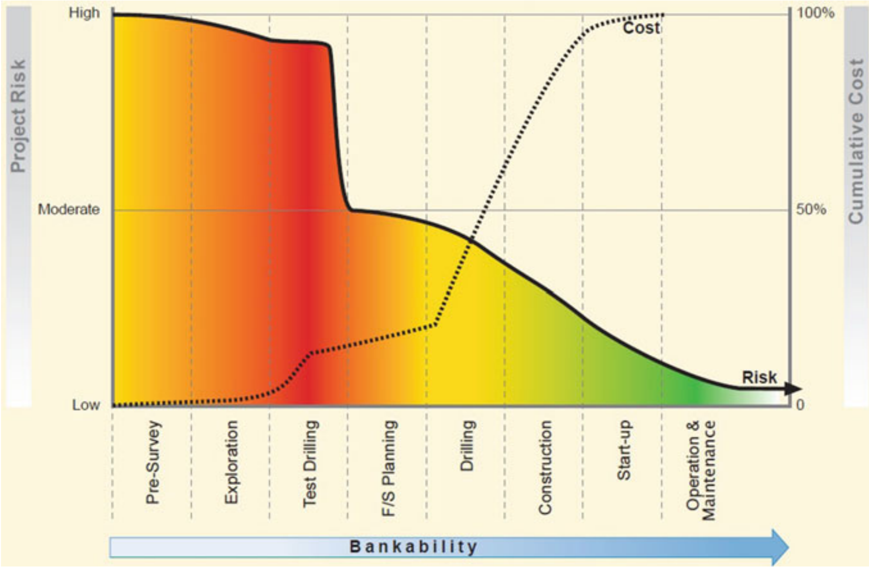

Fig. 5 Project cost and risk profile at various stages of development. *Source* ESMAP (2012)

of a geothermal resource, the risk lowers considerably, and it should be relatively easy for the investor to secure finance for the next steps.

Salmon et al. (2011) provide a guidebook into recent trends in geothermal power finance, which is based on experiences in the USA. Figure 6 summarizes the main results.

Figure 6 shows a similar pattern as in Fig. 5, namely that the risk level drops after identifying a geothermal resource. The reduction in risk is expressed in easier financing terms as the geothermal power plant comes closer to operation.

IFC (2013) focuses on success criteria for geothermal wells, developing a database of wells from all around the world, covering 2613 wells. The main conclusion is that 78% of the drilled wells were considered successful. However, the success for the first well is determined at only 50%, whereas the success rate for consecutive wells after one successful well is going up quickly. The average capacity per well is 7.3 MWe in that study, but averages vary significantly between different geothermal areas and resource types. The total dataset is skewed with a few very large wells. It is better to consider the modal average capacity which is 3 MWe. That geothermal fields are generally small is also confirmed by WEC (2016).

Olivier and Stadelmann (2015) present a very detailed case study of one power plant in Turkey: Gumuskoy, which is the first geothermal power plant where the exploration costs and risks has been borne by the investor. In the end, the risk-taking appetite of the investor paid off and this project led to a profitable enterprise.

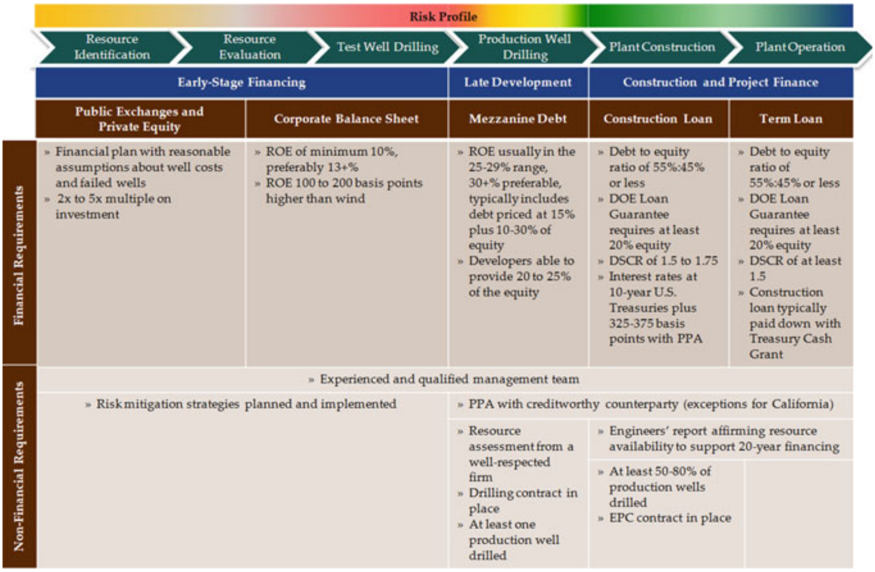

Fig. 6 Key information for financing the development of geothermal power plants. *Source* Pater Salmon et al. (2011)

5 A Simple Business Model for Profitable Investments

Financial modeling of geothermal power plants has been undertaken by various authors. Gunnlaugsson (2012) presents the financial detail of a large geothermal power plant in Iceland. Ngugi (2014) has built a financial model for geothermal power projects in Kenia. Chatenay and Johannesson (2014) compare the economics of geothermal power plants to other power generation technologies. Table 4 shows the typical costs of two types of geothermal power plants.

Table 4 Typical costs of geothermal power plant

Cost item	Steam plant	Brine plant
Preparation	2%	2%
Exploration	8%	5%
Geothermal well field development	50%	44%
Power plant	30%	39%
Indirect cost	10%	10%
Total installation cost, $/kW Gross	3650	5300
Temperature °C	250	150
Installed capacity, MW	50	10

Source Chatenay and Johannesson (2014)

In order to build a simple financial model relevant to Turkey, the following bullet summarise the key assumptions:

- Key drivers of profitability are the CAPEX and OPEX. These are taken as 4000 USD/kWe net installed capacity for CAPEX and 100,000 USD/MWe net installed capacity for OPEX.
- The net installed capacity is taken as 5 MWe.
- From year 7 onwards a new well will have to be added every five years to maintain the flow to the power plant, where the well cost is assumed as 2 million USD.
- A flat 80% availability is assumed, which is equal to 7008 running hours.
- Prices are 90 $/MWh for the first ten years and 75 $/MWh for the next 15 years, all assumed to be in nominal USD.
- Depreciation and amortization are assumed to be 10%.
- The loan is dispatched in 2 years and paid back in 11 years in equal instalments.
- Interest payments for the first two years are added to the CAPEX as financing costs.
- The projections are made in nominal USD.

The result of the financial model with these assumptions is as follows: the profitability in terms of project internal rate of return or project IRR is 7.9%. This is a sufficiently high rate of return. However, the key driver of this result is the ability to benefit from the going FIT, which means that the project needs to be commissioned until end 2025 and should maximally benefit from the incentive for local equipment. Also, if some of the drilled wells are not successful, this may add to the cost of the investment and lower the overall profitability considerably. To have an insurance against this risk, there is a need for a RSM, which is currently available in Turkey.

6 Conclusions

Turkey has entered the so-called 1 GW country club with respect to geothermal power installed capacity. Moreover, Turkey is ranked fourth in the world after the USA, Indonesia and the Philippines. The development of geothermal installed power capacity in Turkey, has gone quicker than expected, driven by a favorable regime with feed-in tariffs (FIT), namely 105 $/MWh for ten years, which may be increased with another 27 $/MWh for five years for including local equipment in the investment. However, these projects need to be completed by the end of June 2021. Initially the official target was to reach 1 GW until 2023; this has been revised to 2 GW until 2023, in line with recent developments. Turkey has an extensive potential for geothermal power, estimated to around 4.5 GW. To reach this potential, the current FIT regime has been extended until end 2025, which may be expected to average around 90 $/MWh if incentives for local equipment are included.

Also new areas need exploration, which may be suitable for geothermal power development. Here the literature shows that the largest risk of the investor is during exploration. Moreover, the likelihood of drilling a successful well increases as more wells are drilled in the same location. Also, according to IFC (2013), across all resource types, the average size of a successful production well has been estimated to be around 3 MWe globally and Turkey is no exception to this. Here, to facilitate exploration drilling in new areas, there is a need for a Risk Sharing Mechanism (RSM), which is currently an ongoing project in Turkey funded by the Clean Technology Fund through the World Bank.

Future research will need to focus on the sustainability aspect of geothermal energy. New geothermal wells need to be drilled following worldwide best practices. An important aspect is to minimize the impact on the environment and the settlements in the vicinity of the geothermal facility. Ideally, geothermal facilities will have reinjection wells as well to circulate the geothermal fluids in such a way to reach full sustainability. Moreover, the benefits from geothermal should also be partially shared with the local communities. This could be done by setting up geothermal direct use systems that provide district heat or cooling to residences or industries, providing heat to greenhouses or to hotels for health tourism, among others. In this manner geothermal may be fully embraced by local communities.

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Transition Period to Renewable Energy Usage: Turkey Case

İsmet Turan and Tanay Sıdkı Uyar

1 Introduction

Turkey is a country with all kinds of renewable resources due to its geography and the adventure of generating electricity from these resources has the potential to be a case study.

The first period of power generation applications, which started with the coal-fired "Silahtarağa Thermal Power Plant" that was opened in 1914 to meet Istanbul's electricity needs, continued with small sized water and coal fired power plants.

With the commissioning of Keban Dam and HEPP in 1975, the period of building major projects began. The construction of Afşin-Elbistan A thermal power plant, which will be the largest coal fired power plant in the country by using domestic lignite reserves, was started (1975), and the first large-scale natural gas fired power plant was commissioned with natural gas from the present Republic of Russia (1987). The sole purpose for that period is to solve the problem of electricity supply and to increase the production of economic goods and services.

Although political powers, which felt that the Public was inadequate in the production of electrical energy, initiated a "third term" in the 1990s, which encouraged the participation of the private sector in the production of electrical energy using various legal and financial models, sustainability was not achieved.

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The "fourth term" was built during the negotiations for membership in the European Union (EU). In this context, within the framework of EU acquis compliance efforts, the Electricity Market Law was enacted in 2001, and in 2002 the Electricity Market Regulatory Authority (EMRA) was established. In order to establish "Renewable Energy Sources" (RES) intensively, the law on supporting RES had to be passed into law in 2005.

Turkey has been a country with ever-increasing demand for electrical energy and supply security problems, both geographically and in terms of population size. Turkey, which does not hesitate to implement the same support mechanisms of the EU, has done RES licensing, supporting and installing in a very lucky period regarding both wind and solar PV investment costs and partly financing costs (loan interest). Thanks to the US Dollar-based incentives, a balance has been established in security of supply.

However, all these regulations, especially expropriation have created serious problems in the fields of environment, nature, forest, water and human rights. Problems with the legitimacy have led to poor experiences, especially small hydro projects. Within the scope of this chapter, Turkey's experiences between 2000 and 2020 will be examined.

2 Europe's Renewable Adventure

It can be said that Europe's adventure for unity began with energy: "Treaty establishing the European Coal and Steel Community" (1951). Just six years after this signature, an energy-based organization was established again: the European Atomic Energy Community (1957). After the 1960s, when states addressed the energy issue internally, the European Council had to take a series of decisions on the 1973–74 oil crisis that would remain in force until 1985:

- Close cooperation to combat energy problems,
- Adapting guidelines for energy supply (Promoting nuclear, hydrocarbon and solid fuels: diversification),
- Adapting guidelines on energy demand (effective use).

However, the new topic that stood out in Europe in the following years was "environmental protection". As a result of the long negotiations that continued within the community, first the "*Directive for the internal market in electricity*" (1996) and then the "*Directive for the internal market in natural gas*" (1998) came into force. These two directives were followed by the "*Directive on the promotion of electricity produced from renewable energy sources in the internal electricity market*" which entered into force in 2001. This trio will be the determinant of Turkey's renewable energy policies in the coming years.

At the same period, in 1990, the "Intergovernmental Panel on Climate Change" (IPCC) report was published, the "Earth Summit" was held in Rio in 1992, the "Kyoto Protocol" was organized in 1997, climate change and energy issues were brought to the top of the world's agenda by developed countries, and the EU became the leader in the fight against climate change.

The targets which were named "20/20/20" and were prepared by the EU, were outlined in 2007 and adopted in 2009. According to this plan, by 2020, emissions will be reduced by 20%, 20% of energy consumption will be provided from renewable energy sources and the use of primary energy sources will be reduced by 20%, taking into account security of supply, the domestic energy market and energy technologies. Apart from these, the interconnection of energy grids will be another topic that is encouraged.

It can be said that the common feature of the countries that have implemented the transition to renewable energy most successfully is that they make short-medium-long-term plans and stick to them. In the last days of 2011, the European Commission announced the "Energy Roadmap 2050" plan, outlined the tasks to be completed between 2020 and 2050, and set a typical example of this success by setting the target to be achieved in 2050.

When the dates showed 11.12.2019, The European Commission took another historic step by publishing the document titled "The European Green Deal". European Commission President Ursula von der Leyen said at the European Commission "This is Europe's man on the moon moment".[1] According to this document; climate policy will be the EU's new development strategy.

"Energy, Climate Change and Environment" is one of the 12 titles on the EU's website. The scope of this title is continuously on the agenda of both the community and the commission and is updated when necessary. The last decision taken in this context is as of 2030; 32% of energy is derived from renewable energy and energy efficiency targets are at least 32.5% (Fig. 1).

As can be seen from this brief summary, the European Community and the European Union, respectively, are carrying out a successful plan to prepare future generations for a clean life by establishing a very successful transition process without compromising economic development.

3 European Union Effect

At the center of the economic and social relations of the young Republic of Turkey has been mostly the European Continent. After the establishment of the European Economic Community (EEC), there was no hesitation in applying for membership, an association agreement with the EEC was signed in 1963 and a "Full Membership Agreement" was signed in 1987. Although the intention to join the EU is positive for all periods and for every government, the effort was not sufficient and the point of full membership has not been reached. However, the issues stipulated by the EU were studied on the basis of "chapter" and the necessary legal regulations were put into effect, especially in the "chapters" related to the economy.

One of these "chapters" was "Energy Chapter". The Electricity Market Law (EML), which was drafted in accordance with the EU directive, was enacted in

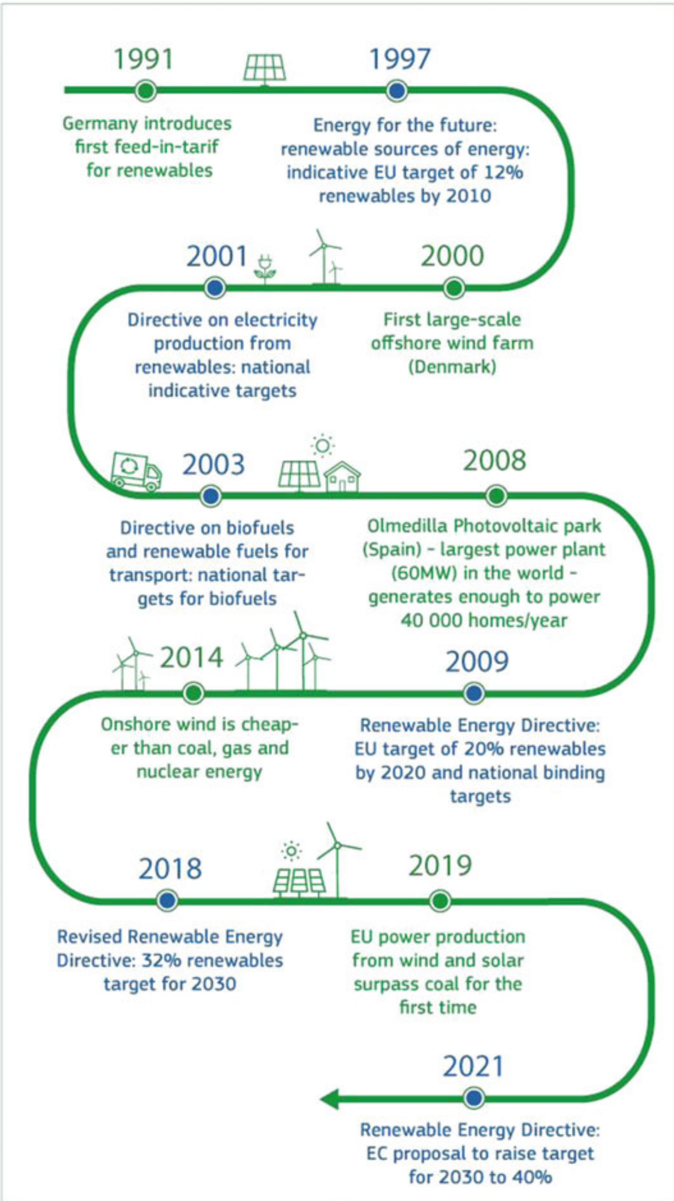

Fig. 1 Timeline for renewable energy in the EU[2]

2001 and the EMRA, the independent regulatory body that should be established under this law, was established in 2002. Turkey's real RES adventure started after this.

The purpose of the EML is as follows: "The purpose of this Law; is the establishment of a financially strong, stable and transparent electricity energy market that can operate in accordance with the provisions of private law in a competitive environment, and to ensure an independent regulation and supervision in this market, in order to provide sufficient, quality, continuous, low-cost and environmentally compatible electricity to consumers.". Within the scope of this article, there is no direct provision regarding RES. However, although EMRA, as its duty, has issued production licenses to private sector companies, the desired level of progress/construction has not been achieved, especially in licenses under RES.

While the bureaucracy is in these works, non-governmental organizations are trying to bring renewable energy to the national agenda by organizing workshop-like meetings by bringing together various parties. The most comprehensive of these were "Sarıgerme Workshops". At the 2nd meeting of this workshop series held in 2001, the "National Solar Cells Strategy" was studied, and "Power Generation from Solar" was discussed at the 3rd meeting held in 2002.[3] In the meetings, it is seen that besides the examples from the world, solution proposals for Turkey are also presented. It will be seen that such workshops will make a great contribution to the RES support law, which will be put on the agenda in the near future.

At a time when it was seen that licensing was not the only solution, the remedy has been EU experience and legislation. For RES's, the most popular incentive mechanism at the time, the "Feed-in-Tariff" mechanism, was selected, and in 2005 the "Law on Use of Renewable Energy Sources for The Production of Electrical Energy" came into force. This was assessed as part of the EU's "Turkey 2006 Progress Report" published in 2006: "*Some progress has been made on renewable energy sources. However, Turkey has not set itself an ambitious target yet for their increase.*"

With the introduction of the RES support law, banks at home and financial institutions abroad have been able to obtain the guarantees they expect. With the resolution of the financial problem, an installed power of approximately 30 thousand MW was commissioned over a 15-year period, including hydro, wind, solar, geothermal and biomass.

The EU's interest in the use of RES in the "Energy Chapter" and especially in the generation of electricity during Turkey's accession process has yielded a positive result. The energy section of the EU's "Turkey 2021 Report" published in October 2021, states: "*Turkey is moderately prepared in this chapter.*" "*Following a strategy of maximizing the use of domestic and renewable energy sources, in 2020, the share of the country's renewable energy in the electricity generation reached 44%, most of which came from hydropower (29% percent). The ratio of renewable energy installations in the total installed power generation capacity increased from 45% last year to 51% in 2020.*"

4 Common Issues

Turkey is a country with a geographical structure where four seasons can be experienced at the same time. This geographical structure enables the generation of electricity originating from mini hydro in the north, wind in the west, solar in the whole country, geothermal in regions with fault lines, and biomass in regions with forest and agriculture density.

On the other hand, 49.1% of the consumption of electrical energy is in the west of the country.[4] This situation requires the transfer of electricity generated from water sources in the east to the west, for which, network investments are required.

In the licensing process for the generation of electricity initiated by EMRA in 2003, the first demands have been to the regions where there are projects that have been included in the public inventory in the past years. We will refer to this situation, in short, as "clustering".

Just as the advantages and disadvantages of "clustering" can be mentioned, "clustering" of energy generation licenses based on RES in certain regions also has various pros and cons. It can be said that the most important cause of "clustering" is "uncertainty" and another is "risk". Investors have preferred known and tried "resources, sites and applications" in order to be careful about these two issues.

EMRA's licensing mechanism implemented between 2003 and 2007 was "first in—first out", and the first company to apply for a resource and field became the owner of the production license in case there were no other applications. In case there is more than one application for the same source, the tender system has been used. It can be said that Turkey has been very generous with the RES support, given the high RES capacity factor and the low land prices.

The widespread use of RES is not a situation that can be realized only with financial means. Before finance, a solid legal infrastructure is required. Apart from the law, the fact that other sub-force regulations have been established affects the speed at which projects progress, its projection and supply chain security.

One of the criteria that measures the success of the regulatory authority in a country is the number of cases. If one of the issues that slows down the RES installation is incomplete regulation, the other is the lawsuits. As of the end of 2020, the number of cases EMRA is a party to is 8028.[5]

For the development of RESs, it is as essential as providing incentives and financial provision, establishing a sense of justice in the public opinion. The duty to enlighten the community about disputes arising in the face of processes to be carried out on the basis of transparency belongs to the public. However, in Turkey, there is no central and autonomous platform for this issue yet. For now, this need can be addressed through some platforms supported by the EU (Fig. 2).

The stakeholders in the energy system, public/private, were surprised for a short time in the face of increasing renewable energy installed power, and it was unclear what approach to take. However, the increased RES-based facility installation has pushed the relevant institutions to take precautions, organize trainings, prepare EU projects (TAIEX and TWINNING), and share information.

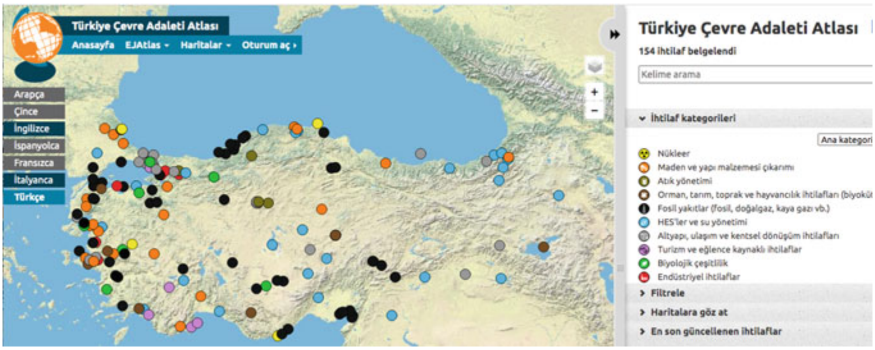

Fig. 2 Turkey environmental justice atlas[6]

KONDA's 2018 study found that 72% of citizens of the Republic of Turkey prefer solar energy use, 54% prefer wind energy use, 25% use natural gas and 8% prefer geothermal resource use.[7] Based on this survey, it is evaluated that social consensus can be established in the establishment of new RES, but it is also necessary to determine how the cost of RES will be distributed to all segments of society.

In this chapter, which examines Turkey's experiences of the RES adventure, the topics that make the difference between projections and realizations can be listed under the following general headings:

- The absence of planned and long-term integrated strategic planning of the new system, "Energy, Climate Change and the Environment", created under the name of liberalization
- "Environmental Impact Assessment (EIA) is Not Required" application
- Lack of "Cumulative Impact Analysis"
- Lack of "Basin Planning"
- Urgent Expropriation application
- Non-mandatory Carbon Certification
- Mistakes in the use of farmland and pastures
- Extending the incentive model for another 5 years, not ending in 2015
- Licensing according to investor demand, not according to technical and economic capacity program
- Delays in establishing technical rules to be followed in the installation of facilities based on renewable energy sources
- Lack of strategies to reduce greenhouse gas emissions
- Public/University/Industry cooperation is not sufficient.

5 Feed-In-Tariff Mechanism (YEKDEM)

The Mechanism for Supporting Renewable Energy Sources, i.e. YEKDEM, is the name of the "Feed-in-Tariff "system implemented by Turkey between 2005 and 2020.

Accordingly, the right of purchase guarantee in $ basis is granted for 10 years at different base prices for different sources. In addition, in case of using domestic equipment, it is possible to receive an additional payment for the first 5 years of operation, depending on the equipment used.

The use of this right is on a yearly basis. If the investor makes an application, he/she can be included in the system for the period between 1 January and 31 December. Alternatively, he/she can exit the system for the same period and sell its energy to the free market (Fig. 3).

The following base prices are applied for the facilities that entered operation between 2005 and 2020 under the RES support law (Table 1).

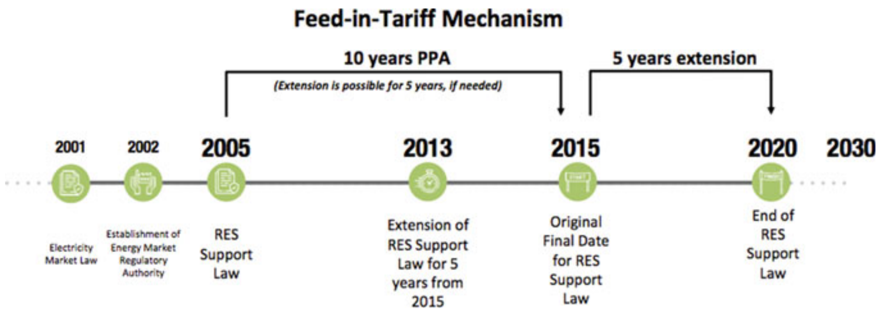

Fig. 3 Timeline of Feed-in-Tariff mechanism in Turkey[8]

Table 1 Feed-in-Tariff prices between 2005–2020[9]

SCHEDULE I (Provision of the law dated 29/12/2010 and numbered 6094)	
Type of Production Facility Based on Renewable Energy Resources	Feed-in-tariff Prices Applicable (US Dollar cent/kWh)
a. Hydroelectric production facility	7.3
b. Wind power-based production facility	7.3
c. Geothermal power-based production facility	10.5
d. Biomass-based production facility (including landfill gas)	13.3
e. Solar power based production facility	13.3

In addition to these basic incentives, the following incentives are given for the first 5 years of the period in operation if the equipment specified in the following table is manufactured within the borders of Turkey (Table 2).

6 Alternative System—RE-ZONE (YEKA)

The RE-ZONE (YEKA) application is defined by the Presidential Investment Office as follows: "*The main purposes of the Regulation have been identified as follows: to commission renewable energy resources much more efficiently and effectively through identification of renewable energy zones on the public, treasury, or private-owned territories; to realize the renewable energy investments much more rapidly; to manufacture renewable energy equipment in Turkey; to use locally-manufactured equipment/ components; and to contribute to research and development activities through technology transfer.*"[9]

We see that after the Renewable Energy Resource Zones (RE-ZONE/YEKA) model, the clustering continued until the second model was put into practice, and after YEKA, the control passed to the public administration and the determination of the source and region began to be determined by the public administration. Although this has solved some problems, some continue to have problems, especially environmental and social issues.

It is difficult to say that the second model, RE-ZONE/YEKA, has achieved the desired success. It can be said that the most important reason for this is the fluctuating course of the Turkish Lira against the USD (Table 3).

7 Hydro Case

In Turkey, the first type of river that comes to mind when it comes to power plants or renewable power plants is hydroelectric power plant (HEPP). On this subject, many technical, economic, social and legal reports have been prepared. There has been an experience in the country that can be the subject of a book on its own.

On average, 60% of Turkey is mountainous.[10] As for precipitation, long-term measurements are available. Construction is one of the locomotive elements of the country's economy. The combination of this trio has created investor interest in all water resources, small and large, even when there is no guarantee of purchase. However, since the detailed arrangements did not happen as quickly as investor interest, there were serious problems between the local people and the investor and public officials, especially regarding the water resources in the north of the country. At the root of these problems, it can be stated that the application of "EIA is Not Required" leads the way, and secondly, the implementation of "Basin Planning" is passed too late and this application does not have a sanction on licensed projects.

Table 2 Local content contributions[9]

SCHEDULE II (Provision of the law dated 29/12/2010 and numbered 6094)		
Type of Facility	Local Production	Local Content Contribution (US Dollar cent/kWh)
A-Hydroelectric production facility	1- Turbine	1.3
	2- Generator and power electronics	1.0
B- Wind power based production facility	1- Blade	0.8
	2- Generator and power electronics	1.0
	3- Turbine tower	0.6
	4- All of the mechanical equipment in rotor and nacelle groups (excluding payments made for the blade group and the generator and power electronics).	1.3
C- Photovoltaic solar power based production facility	1- PV panel integration and solar structural mechanics production	0.8
	2- PV modules	1.3
	3- Cells forming the PV module	3.5
	4- Invertor	0.6
	5- Material focusing the solar rays onto the PV module	0.5
D- Intensified solar power based production facility	1- Radiation collection tube	2.4
	2- Reflective surface plate	0.6
	3- Sun tracking system	0.6
	4-Mechanical accessories of the heat energy storage system	1.3
	5-Mechanical accessories of steam production system that collects the sun rays on the tower	2.4
	6- Stirling engine	1.3
	7- Panel integration and solar panel structural mechanics	0.6
E- Biomass power based production facility	1- Fluid bed steam tank	0.8
	2- Liquid or gas fuel steam tank	0.4
	3- Gasification and gas cleaning group	0.6
	4- Steam or gas turbine	2.0
	5- Internal combustion engine or stirling engine	0.9
	6- Generator and power electronics	0.5
	7-Cogeneration system	0.4
F- Geothermal power based production facility	1- Steam or gas turbine	1.3
	2- Generator and power electronics	0.7
	3- Steam injector or vacuum compressor	0.7

Table 3 RE-ZONE/YEKA tenders

Türkiye - RE-ZONE - YEKA - Tenders										
resource	**date**	**city/region**	**capacity (MW)**	**ceiling price**	**price unit**	**PPA period (year)**	**Licence duration (year)**	**tender result**	***parity: USD/TL***	***Türkiye CDS Premium***
solar PV	2021-03-08	list of regions	1,000	35	*kuruş / kWh*	15	30	21.8	*7.5939*	*329.23*
	2021-01-19		1,000	30	*kuruş / kWh*	15	30	posponned	*7.4485*	*326.14*
	2020-10-19		1,000	30	*kuruş / kWh*	15	30	posponned	*7.8778*	*529.09*
wind	2019-05-30	Balıkesir	250	5.5	*$cent / kWh*	15	49	3.53	*5.9253*	*395.04*
		Muğla	250					4.00		
		Çanakkale	250					3.67		
		Aydın	250					4.56		
solar PV	2019-01-31	Şanlıurfa	500	6.5	*$cent / kWh*	15	30	cancelled	*5.2109*	*299.26*
		Hatay	200							
		Niğde	300							
off-shore wind	2018-10-23	Trakya	1,200	8.0	*$cent / kWh*	-	-	cancelled	*5.7710*	*377.45*
wind	2017-12-25	list of regions	2,110	7.3	*$cent / kWh*	10	49	min (-2.78) max (+7.29)	*3.8087*	*167.34*
wind	2017-08-03	Kırklareli	405	7.0	*$cent / kWh*	15	49	3.48	*3.5375*	*164.48*
		Edirne	295							
		Sivas	250							
		Eskişehir	50							
wind	2017-06-22	list of regions	710	7.3	*$cent / kWh*	10	49	min(-1.61) max(+4.78) mean(+0.76)	*3.5180*	*194.45*
solar PV	2017-03-20	Konya	1,000	8.0	*$cent / kWh*	15	30	6.99	*3.6261*	*235.47*

Whether the expected goal has been achieved, especially regarding river type HEPP, is another matter of debate. There are doubts that the production of electricity/benefit worth the destruction in nature cannot be achieved. With the mini HEPP application in Turkey, it is also possible to interpret that the benefits of small HEPPs to nature and humanity have been greatly reduced, and a significant part of the benefit has been transferred to electricity production and licensed companies.

8 Wind Case

Turkey's most surprising development within the scope of RES has been in the wind energy power plant (WEPP) field. The society, which is familiar with water sources due to large dam HEPPs, geothermal resources due to hot spring use, and solar for water heating purposes, initially welcomed the installation of wind turbines, found them sympathetic and called RES; "wind rose".

On the other hand, the first serious studies in the public sphere were carried out by the General Directorate of Electrical Works Survey Administration (EWSA). With the 1984 research titled "Turkish Wind Energy Natural Potential" prepared by EWSA, the country's wind energy potential was announced to the public.[11] Again, "Wind Atlas Statistics" prepared by TUBITAK Marmara Research Center and calculated for 20 regions were shared with the public in 1988.[12]

After the decision was made to liberalize the generation of electricity, applications for generation licenses started to be received in 2003. The first day's license applications were for WEPP. The focus of these applications was the projects developed within the scope of the build-operate-transfer (BOT) model that was tried to be implemented in the late 1990s, and there was a "clustering" around the projects developed before liberalization.

The concentration of applications to certain regions, which we call clustering, brings with it the problem of grid connectivity. This causes a delay in projections. Applications of a variety of multi-part, small and large capacities have low economic value. The reason is that the "economy of scale" has a direct impact on energy investments. After these problems manifested themselves over time, the public administration decided to move to a new model: Renewable Energy Resource Zone (RE-ZONE, in Turkish YEKA).

RE-ZONE application has been a new beacon of hope for RES applications that have reached the point of congestion. However, starting the application with 1000 MW within the scope of a single tender raised the problems experienced in the past and this first RE-ZONE tender did not enter operation on the projected date. According to this experience, the model was changed, and the new RE-ZONE tenders were allocated to small and medium-sized capacities.

Another issue has been the social problems created by the unbalanced distribution of capacity throughout the country. Izmir Province, Cesme district, Karaburun town is the most typical example of this.[13]

The fact that some wind projects are being built close to the settlements, rather than being built in mountainous areas, has also been a planning and implementation error for Turkey. There are lawsuits filed by citizens in this regard.

The technical realizations were similar to those in the EU countries. Wind, a source of intermittent electrical power, has caused technical problems in the grid. The fact that some of the WEPPs are connected to the grid from distribution transformers has also created similar problems. In order to increase the installation of WEPPs, the transmission level areas should be preferred as well as mountainous areas away from settlements.

In order to solve these problems, additional investment to the grid was required. At this point, technical consultancy services have been received and continue to be received in cooperation with the EU and The World Bank.

9 Solar PV Case

One of the energy sources that Turkey is familiar with is solar energy. For the use of solar energy, which is used for water heating purposes in almost all of the country, for electricity generation, the RES Support law had to be enacted first.

However, although the relevant law was introduced in 2005, applications for licenses for solar PV electric power generation (SEPP) had to be waited until 2014. Meanwhile, no official reports have been reached regarding the justification of the past years.

On the other hand, during the same period, unlicensed electricity generation was also encouraged, and according to the relevant regulation, applications were accepted for facilities under 1000 kW. In this context, 6907.8 MW SEPP has been commissioned by the end of 2021. Although the financial dimension of this practice is high for the community, it can be considered to have a positive effect in terms of the spread of "Community Energy" throughout the country. The licensed SEPP commissioned during the same period was 907.9 MW.[14] Failure to strike a balance between licensed and unlicensed projects will put pressure on the price of selling electrical energy to the public if the Turkish Lira suddenly loses significant value against the USD.

With the introduction of the new application called RE-ZONE, control has been restored to the public administration in the licensing process. Accordingly, applications for 1000 kW were closed and capacity allocation method was started over capacities of 10–15–20 MW.

In parallel, by switching to the "prosumer model", the offset system was put into effect, especially in roof solar pv applications. This is predicted to be a good practice for the future of solar pv. In this context, it is evaluated that the evaluation of the roofs of the houses, especially in the south of the country, within the scope of community energy should be a priority project.

An advanced infrastructure of solar PV has also been established. Panel assembly plants have been commissioned in various cities of the country and an important step has been taken in terms of supply chain. On the other hand, there are still steps to be taken within the scope of the circular economy.

10 Geothermal Case

The existence of hot water sources in Anatolian geography dates back to the Hittites period. In the western regions, there are spa ruins from the Roman and Byzantine periods.[15] The first application in which these resources are used for the production of electrical energy is the Kizildere geothermal energy power plant (GEPP) in Denizli province, which was commissioned in 1984. However, in order for geothermal application to become widespread, the EPK and then the RES support law had to be passed into law.

We see two types of applications in GEPP licensing applications. The first is the privatization and transfer of publicly developed sites to the private sector and thus licensing them, and the second is that the private sector obtains licenses for the fields developed within the scope of its own exploration activities.

While the clustering situation we see in wind development can be stated for geothermal, it is seen that the intensity of application, license and installation is in western Anatolia. The most important reason for this can be said to be the aforementioned Kizildere GEPP. Likewise, the cost of developing GEPP is the highest among RESs. This creates a great risk for investment. The clustering of investors who want to minimize this risk in a certain region has brought environmental and social problems.

While various grants are given by the EU for the development of GEPPs in Turkey, problems such as unruly/lawless operation are frequently reflected in the media. Video news by BBC Turkish is one of them.[16]

Intense public complaints, similarly, have placed geothermal regions within the monitoring area of political parties. A comprehensive report on geothermal activities has been prepared by the Republican People's Party (CHP). In the recommendations section of this report, it is emphasized that the main problem is in the implementation and management processes, and that the ecological destruction caused by the mistakes made here does not meet the purpose of "clean" energy.[17]

Geothermal source may be a chance for Turkey since the imbalance of wind energy on the grid is a problem of Turkey, like all countries. Geothermal resources can be used as an alternative to coal in solving this problem, provided that the operating and audit rules are complied with.

11 Biomass and LFG Case

It is a RES whose definition and scope may vary from country to country. In Turkey, according to law no. 5346, biomass refers to the resources obtained from urban wastes as well as agricultural and forest products, including vegetable oil waste, agricultural harvest waste, and by-products resulting from the processing of these products and waste tires, as well as industrial waste sludge and treatment sludge.

Ministry of Energy and Natural Resources website lists the biomass sources listed as follows.

I. Biomass Sources of Organic Waste, City and Industrial Waste
II. Biomass Resources Derived from Forest and Forest Products
III. Animal Biomass Resources
IV. Herbal Biomass Resources

- Oil seed plants
- Sugar and starch plants
- Fiber plants
- Protein plants
- Vegetable and agricultural residue.

As you can see, the variety of resources is high. With this, the relatively high price in the incentive system has also increased the demand for investment. However, the lack of "basin planning" and "cumulative impact analysis" that we have seen in other resources has also manifested itself as a significant problem here, and in some cities the application for multiple and close-knot plant installations has led to legal problems.

Another major problem is the use of spring water in such facilities. Water is a vital product that is increasing in importance not only for Turkey, but also for the whole world. The use of water for cooling in electricity generation facilities should be stopped and dry type systems should be used. Unfortunately, Turkey has advanced with conventional techniques in the way of producing electricity using RES, which it started late, and has not been able to follow the trends of developed countries.

Similarly, there is concern that combustion-based biomass plants will replace coal plants. In this regard, energy and environmental authorities should cooperate.

Considering the agricultural potential of the country, it is considered to be beneficial for the society to increase biomass investments in a coordinated manner and with the participation of the local people.

12 Today's Numbers and Future

In Turkey, according to the report published in 1999 by the State Planning Organization, solar and biomass capacity was zero, while geothermal and wind installed power totaled 23.7 MW. On the other hand, according to December 2021 data published by Transmission System Operator, number of power plants and installed capacity of renewables in Turkey are as follows (Table 4).

On the consumption side, according to the "Turkish Electric Power Demand Projection Report" prepared by MENR and published in 2020, the low-demand scenario for the coming years is as follows (Table 5).

Accordingly, Turkey will grow at a lower rate in the coming years than in previous years. According to the scenario of shifting total energy demand from oil and coal to electrical energy, the above demand scenario is also subject to change. However, given that this can be done with a political decision and a medium-long-term plan, it is not clear which way Turkey's electricity needs will go.

This directly affects the installation of new RESs. In fact, the dates of the RE-ZONE tenders planned to be carried out by MENR are being postponed. According to Turkey's commitment to the UNFCC under the INDC; "increasing capacity of

Table 4 Renewable energy based power plants

Source	Number of power plants	Installed capacity of renewables (MW)
Hydro hydro	604	8212.2
Wind	355	10,607.0
Solar	8,389	7815.6
Geothermal	63	1676.2
Biomass	380	1644.5

Table 5 Electricity demand projections for 2021–2030

Years	Senario (TWh)	Change (%)
2021	340.5	4.0
2022	353.2	3.7
2023	366.8	3.8
2024	380.4	3.7
2025	392.6	3.2
2026	404.6	3.1
2027	416.6	3.0
2028	428.8	2.9
2029	441.0	2.9
2030	453.0	2.7

production of electricity from solar power to 10 GW until 2030 and wind power to 16 GW until 2030" (Table 6).

Table shows the total installed capacity of the power plants that will benefit from YEKDEM in 2022, according to their sales price and source type.

13 IRENA Innovation Toolbox

International Renewable Energy Agency (IRENA) is an intergovernmental organization that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international cooperation, a center of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy.[19]

Rapidly integrating solar and wind power to cut emissions and meet key climate goals poses technical and economic challenges. IRENA, "Innovation Toolbox" offers 30 innovations emerging across four key dimensions: enabling technologies, business models, market design and system operation. The Toolbox outlines 11 solutions as examples of how to achieve system-wide synergies.[20]

By referring these resolutions, a solution proposal for Turkey has been prepared and presented in Table 7.

14 Conclusions

It can be assumed that Turkey has managed to reduce its dependence on natural gas and imported coal in part through the RES support process. It is evaluated that the most important shareholder in this is RES support law and Renewable Energy Resources Support Mechanism (YEKDEM). On the other hand, it is foreseen that

Table 6 Feed-in-Tariff application, i.e. YEKDEM, in Turkey—2022[18]

Feed-in-Tariff application, i.e. YEKDEM, in Türkiye - 2022		
$cent/kWh	type of power plant	MW
16.130	bepp	12.81
15.720	bepp	2.30
15.650	bepp	5.37
15.300	bepp	7.78
14.600	bepp	113.95
14.455	sepp	118.00
14.100	bepp	54.25
13.900	bepp	25.56
13.800	bepp	45.60
13.740	sepp	318.91
13.300	sepp	31.90
13.300	*sepp**	6,907.80
13.300	bepp	1,982.78
12.500	gepp	182.29
12.290	gepp	30.81
12.095	gepp	10.20
11.800	gepp	538.18
11.200	gepp	165.00
10.500	gepp	783.36
9.600	hepp	431.20
9.400	wepp	2,845.15
9.390	wepp	20.00
9.370	wepp	30.00
9.300	hepp	19.57
9.280	wepp	15.00
9.200	wepp	20.00
8.845	hepp	1.00
8.800	wepp	59.00
8.700	wepp	1,204.90
8.600	hepp	635.26
8.600	wepp	92.00
8.590	wepp	10.00
8.470	hepp	3.40
8.145	hepp	510.09
7.900	wepp	370.00
7.780	wepp	46.00
7.300	hepp	10,186.13
7.300	wepp	4,362.25
7.300	*wepp**	73.10
6.880	wepp	32.00
6.290	wepp	40.00
	TOTAL	32,342.89
	bepp:	*biomass*
	sepp:	*solar PV*
	hepp:	*hydro*
	gepp:	*geothermal*
	wepp:	*wind*
	*:	*unlicensed*

Table 7 IRENA innovation toolbox proposal for Turkey

No	KEY DIMENSIONS	INNOVATIONS	FLEXIBILITY SOLUTIONS											Solution Offers for Türkiye
			Supply-Side		Grid			Demand Side				System-Wide Storage		
			I	II	III	IV	V	VI	VII	VIII	IX	X	XI	
1	Enabling Technologies	Utility-scale batteries					■					■		Türkiye, needs "Utility-Scale Batteries" by taking into account its geography, population, distribution, transmission system infrastructure and power capacity.
2		Behind-the-meter batteries						■	■	■	■			It may be compulsory for consumers with good economic status who live in places far from the natural gas pipeline network.
3		Electric-vehicle smart charging						■	■	■	■			First of all, additional taxes on EVs should be removed and domestic "smart charging" should be encouraged. Depending on the number of vehicle passes, its installation may be required at gasoline stations on certain routes.
4		Renewable power-to-heat					■	■	■	■			■	According to geographical location, incentive practices should be introduced on the basis of resources. For example, in western provinces of Türkiye, heating from geothermal sources can be promoted by using price mechanism.
5		Renewable power-to-hydrogen					■						■	Plans can be made within the scope of the national hydrogen energy roadmap prepared by the Ministry of Energy of Türkiye.
6		Internet of things	■	■	■	■	■	■	■	■	■	■		It should be seen as the most important and priority topic, and the internet infrastructure should be strengthened throughout the country as the first move. Afterwards, all kinds of energy consumption and production points must be connected to the internet.
7		Artificial intelligence and big data	■	■	■	■	■	■	■	■	■	■	■	Considering its geographical structure and population distribution, Turkey is a country that should have a strong on-site management capacity. To ensure this situation, "Energy Provincial Directorates" can be established. By using Consumption and Production data on a provincial basis, a database can be created in cooperation with a university in that province. These data can be turned into "big data" in coordination with a university to be determined in the capital Ankara.
8		Blockchain		■	■			■		■				First of all, a Blockchain-based contract system can be deployed to ensure demand-side flexibility. Again, Solar PV panels can be included in the system to ensure recycling within the scope of "circular economy".
9		Renewable mini-grids								■				Considering the geographical situation, planning can be made for regions with high network operation and maintenance costs.
10		Supergrids				■								We are of the opinion that there is no need for this aspect regarding Türkiye, yet.
11		Flexibility in conventional power plants		■										After the digital infrastructure is strengthened and "big data" is established, the closing schedule of coal power plants can be determined.
12	Business Models	Aggregators						■			■	■		This market can be developed, with consumer protected contracts being developed.
13		Peer-to-peer electricity trading								■				This market can be developed, with consumer protected contracts being developed.
14		Energy-as-a-service							■					It is a topic that needs to be developed urgently. IoT will gain importance with the development of "big data". In particular, planning can be made for crowded cities.
15		Community-ownership models								■				Legal and technical infrastructure should be established and it should be put into use, especially for "summer house" dense areas. It can be started with the Pilot Zone application.
16		Pay-as-you-go models												For "summer house" dense areas, the project can be developed.
17	Market Design	Increasing time granularity in electricity markets	■	■	■							■		-
18		Increasing space granularity in electricity markets	■				■					■		-
19		Innovative ancillary services		■				■				■	■	Ancillary services deserve all kinds of developer investment, as their cost and importance are increasing day by day.
20		Re-designing capacity markets		■								■		It can be an alternative for Türkiye if it can solve the Capital Adequacy and Eligible Loan supply.
21		Regional markets			■	■								Infrastructure reinforcement works can be started with Greece and Bulgaria in the west and Georgia in the east.
22		Time-of-use tariffs							■					It is an infrastructure that needs to be developed in the face of increasing "solar PV" capacity on a regional basis.
23		Market integration of distributed energy resources						■		■				After the end of the feed-in-tariff incentive mechanism (final date 2030), infrastructure works should be started as it will be needed.
24		Net billing schemes							■		■			One of the most needed applications. However, it also requires a lot of pre-qualification.
25	System Operation	Future role of distribution system operators									■			Having realized the privatization of Distribution Regions (21 regions), Turkey has not yet achieved the expected efficiency from privatizations. Performance differences between regions should be resolved urgently.
26		Co-operation between transmission and distribution system operators						■						The fact that Distribution Companies are different from each other, both in terms of capacity and finance, raises concerns.
27		Advanced forecasting of variable renewable power generation	■						■					An important part of "Big Data" is weather forecast information and local based installation of renewable energy forecasting system.
28		Innovative operation of pumped hydropower storage		■										It is not yet seen as a need.
29		Virtual power lines					■				■	■	■	Infrastructure studies should be started as it will be needed after the end of the feed-in-tariff incentive mechanism.
30		Dynamic line rating					■							Within the scope of Turkey's "Net Zero Emission" target, the "Grid Operator" should continue its institutional and physical investment.

FLEXIBILITY SOLUTIONS		
Supply-Side	I	Decreasing VRE generation uncertainty with advanced weather forecasting
	II	Flexible generation to accommodate variability
Grid	III	Interconnections and regional markets as flexibility providers
	IV	Matching RE generation and demand over large distances with Supergrids
	V	Large-scale storage and new grid operation to defer grid reinforcements investments
Demand Side	VI	Aggregating distributed energy resources for grid services
	VII	Demand-side management
	VIII	RE mini-grids providing services to the main grid
	IX	Optimising distribution system operation with distributed energy resources
System Wide Storage	X	Utility-scale battery solutions
	XI	Power-to-X solutions

extending the base period of 10 years in the law for another 5 years will result in a great economic cost, especially after the Turkish Lira depreciates much more than the foreseen value against the US Dollar.

As a reflection of Turkey's efforts within the scope of EU membership, it can be said that although it takes the EU's energy legislation as an example, its failure to transfer its practical experience causes a relatively low renewable installation capacity.

Price incentives for the widespread use of RES can be maintained on a regional and resource basis for the future. In addition, together with the obligations such as "Paris Agreement" and "Green Deal", it is evaluated that the determinant of RES development cannot be purely incentives.

In order to increase the RES capacity, the first steps to be taken are; The "EIA is Not Required" application is to be abolished, and EIA Reports are to be requested from all projects, along with stating the requirement for "Cumulative Impact Analysis" on the basis of province and region, and the transition to the "Basin Planning" model.

As of December 31, 2020, when YEKDEM ended, a new era has begun for Turkey. Considering the Levelized Cost of Electricity (LCoE) development, it should be closely monitored whether Turkish Lira-based RE-ZONE/YEKA tenders made under free market conditions can continue the installation of RESs. If the performance of the that model is not at the desired level, a new model should be developed immediately.

As a last word, a new mechanism to be designed for Turkey within the scope of disseminating the use of RES should also be expected to answer the following questions: Should a carbon tax be introduced? Can nature be used loutishly on the grounds of climate change? Do RES have a benefit above nature since they are given incentives?

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Bioenergy Production by Anaerobic Digestion: Using on Campus Biomass and Food Wastes

M. Asif Rabbani and Tanay Sıdkı Uyar

1 Introduction

We know that fossil fuel is never to last forever and eventually we all will run out of traditional resources very soon so it's very important that we start relying on renewable energy resources as these are the resources that offer us abundant supply and will never run out.

The renewable energy resources consist of solar, wind, biomass, hydrogen, geothermal, ocean and hydropower. In this chapter we will discuss the bioenergy production using the biomasses produced by the leftover food.

The organic material which we get from plants and animals is known as biomass. It was considered as the major source of energy in USA in mid 1800s and still widely used by the developing countries for cooking and heating purposes. In 2020, biomass provided about 4532 trillion British thermal (TBtu) which counts for 4.9% of total energy consumption by USA and in this amount about 430 TBtu were only from biomass in municipalities whereas 2000 TBtu and 2101 TBtu were from biofuels

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and wood derived biomasses (Biomass explained—U.S. Energy Information Administration (EIA) 2021). The biomass energy uses natural and bigraded materials in order to produce energy which is environmentally friendly and the helps to reduce the greenhouse gases in the atmosphere. The use of biomass fuels is now widely used as an alternative for electricity and transportation.

The major threat to global economy and environment is the one third of food made for human consumption which than is then disposed as food waste. This wasted food can be utilized as a raw material for fuel and energy productions as it has physiochemical and biological nature thus facilitating bio-circular economy and reduction in the environmental impacts. The concept bio refineries as sites for production of combined fuel and value products from food waste is very feasible and practical for the sustainable environment. However, the classical and traditional technologies such as composting and anaerobic digestion cannot be considered out dated as they still can be used to maximize the benefits of food waste recycling and further research regarding techno-economic analysis for commercialization is the need of the time (Karthikeyan et al. 2017).

The growth of food production, packaging and supply industry which facilitate the production of sugars, grain flours, starches, dairy, fruits, vegetables, meats and breweries to be consumed by the humans is considered to be an important industry in modern society. Hence, for sustainable future the food products, consumer behaviors and the byproducts and wastes are studied for the shift in from fossil to clean fuels and greener environment. The biofuels are acceptable choice as a source of renewable energy due to its bio degradability and production of environmentally friendly quality exhaust gases. It is worth mentioning that biofuels are considered as one of the best advantageously important clean and sustainable fuel sources in order to limit the greenhouse gas emissions and clean air qualities. For environment and economic global stability, the importance of no carbon byproduct or carbon neutral and renewable biofuels cannot be negated. The bad impact on atmosphere by the massive food industry can significantly be reduced by using the bio fuel produced from the conversion of food processing wastes (FPW) besides reducing the energy cost for food processing as well (Zhang, et al. 2016).

According to Fatih Demirbas (2009), the term biofuel is defined as a solid, liquid, or gaseous fuels that are mostly produced from bio renewable feedstock.

The bioethanol and bio diesel are considered as the two global bio renewable liquid transportation fuels that can be used as an alternative to gasoline and diesel fuel and thus reducing the dependency on fossil fuels. The food crops produce bioethanol which is a good fuel alternative. The benefits of biodiesel have made it an attractive entity for green environmental.

2 Types of Biofuels Based on Biomass Conversion Technologies

The bioenergy can be produced by using biomass residues and waste but as the production cost is high so conversions methods are being developed in order to minimize the cost so the biomass residues and wastes can be utilized as fuel and an alternative to conventional fuels for transportation and energy needs. There are two basic conversion technologies to transform biomass namely the thermochemical i.e., gasification, liquefication and pyrolysis and biochemical i.e., anaerobic digestion, alcoholic fermentation and photobiological hydrogen production conversion techniques. Also, transesterification is considered as most economical way to produce biodiesel in large quantities (Lee et al. 2019).

The biofuels are categorized on the bases of production technology used into four basic generations namely first-generation biofuels (FGBs); second generation biofuels (SGBs); third generation biofuels (TGBs); and fourth generation biofuels.

2.1 Gaseous Bio Fuels

There are mostly two common gases which can be produced from bio waste and used as a source of clean fuel. The kitchen waste results in production of Biogas from anaerobic digestion process. The biogases are Methane and Hythane.

Methane: It is a clean source of energy and one of the most common constituents of biogas which has abundant potential to be an alternative fuel. It is produced by anaerobic digestion (AD) of Food Processing Waste (FPW). It is estimated about 29.5 GW of power around the world will be produced by globally by using the biogas run power generation facilities. The making of methane gas is done using hydrolysis, acidogenesis, acetogenesis, methanogenesis.

Hythane: The hythane is a mixture of methane and H_2 of which 10–25% is hydrogen by volume. It has been recognized as one of the most cost-effective biogas energies produced by using an anaerobic digestion (AD) process and food processing wastes (FPW). Usually, the two-stage processes for bio- hythane production using palm oil effluent, fruit vegetable waste, and starch wastewater is adopted and the research field is open for development of new methods.

2.2 Liquid Biofuels

The liquid bio fuels are made from biomass and can be used instead of normal traditional liquid fuels such as diesel and petrol in transportation sector and thus they can result in substantially reduction of greenhouse gas emissions in the transport sector (i.e., between 70 and 90% compared to gasoline) with only modest changes to vehicle technology and the existing fuel distribution infrastructure. Moreover, the biofuels can be classified in to first and second generations as discussed below:

The First generation liquid biofuels: refer to ethanol from sugar or starch rich crops etc., biodiesel produced from Fatty Acid Methyl Esters (FAME) from vegetable oils, and pure vegetable oil. The well established and known chemistry methods such as fermentation and esterification processes are commonly used for the production of these fuels. The automobiles uses Ethanol as a fuel and can be mixed with gasoline to form gasohol. We can significantkly use ethanol as an alternative fuel in the millions of existing vehicles by doing some minor or no changes in current used automobile engines as well. According to Services (2006) Rural Industries Research and Development Corporation (RIRDC), ethanol may be used as a fuel in several ways:

(a) In modern car engines we can use 10% ethanol blended with gasoline (E-10). No engine modifications are required in this case.
(b) In brazil modified engines use 22% ethanol (E22) as gasoline in many vehicles.
(c) Some vehicles in USA and Brazil also use pure, hydrous ethanol which is a combination of an azeotrope of 96% ethanol and 46% water.

For all cases the engine and fuel systems are specifically designed to utilize and operate with high levels of ethanol efficiently. Besides being used as a replacement of cionventional fuels, stationary power appliactions aslo use ethanol in fuel cells.

According to Akpan et al. (2008), the production of ethanol has an advantage over the petrolleum as the reserves of fossil fuels are diminishing with the passage of time but in case of biofuels this is not the case. The resources for biofuel production are constantly replenished by growing plants and thus continue supply is possible for unlimited period. As gasoline and fuel were in abundence so Ethanol fuel was not fully exploited before but as the prices are increasing for the fossil fuels besides the awarneness among the people regarding environmental pollution and green house gas emmissions the demand is shifting from fossil to ethonol as a prime source of energy for future transportations. Also the making of ethanol fuel from organic and food waste generated 0.86 L of 95%ethanol from 2500 g of old newspapers and maize substrates, which were respectively transformed to 42% and 63% fermentable sugar. Maize when used as a food waste results in more economic production of ethanol fuel due to provision of a higher percentage of fermentable sugar.

The Second-generation liquid biofuels: In this generation the production of biofuels is done from the feedstock that is not used as food or feed, municipal solid and liquid waste (using only organic part of the waste), forest and agricultural residues. Besides Methane fuels of this generation may include bioethanol and biodiesel produced from the crops which are grown not for food purposes but solely to be used as a raw material for energy production. These crops are also known as energy crops and for example Jatropha is used for second generation liquid fuels using conventional technologies. As the need to find alternative means to produce biofuels has increases so the hydro treatment of vegetable oils, animal fats or waste cooking oils has also been considered as a solution for replacing fossil fuels in transportation. The second-generation production facilities and technologies are more expensive than the first generation but the products are more sustainable with the potential for greater GHG emission savings compared to first generation biofuels. The third-generation liquid biofuel production is still in research and development phase and are significantly far from commercialization. The research is going on regarding the production of biofuels from algae, hydrogen from biomass, etc. or synthetic methane (EC 2015).

3 Global Food Waste

The food waste is defined as any food ingredient, raw or cooked, which is unwanted, or intended or required to be discarded as per the legal definition by the EU Commission on food waste (Trabold and Babbitt 2018). The Food waste is made up of organic remains which includes fruits, vegetables, meat, poultry, seafood, shellfish, bones, rice, beans, pasta, bakery items, cheese, eggshells, and coffee grounds. The use of anerobic digestion for both small scale residential and large scale industrial food waste for production of bioenergy has developed interest in government, public and private sectors of UK. There are numerous factors effecting the amount of food waste produced by a household including the house hold size and the behavior of the residents (Ventour 2008).

The main sources for food waste include the food industry, supermarkets, and educational and other government and non government institutions and organizations. It is worth mentionming that about 5.6 million tonnes of residential domestic level food waste is produced each year in England, 0.3 million tonnes in Wales, and in Scotland and Northern Ireland 0.6 and 0.2 million tonnes, respectively. In other words, every year there is about 6.7 million tonnes of food waste produced in the UK. Therefore there is a big potential of producing energy and heat from the food waste like any other organic materials. If we consider that about 255 kWh of exportable electricity might be succeeded from each tonne of food waste generated this corresponds to production of about 1,708 GWh of electricity each year (Krzywoszynska and Krzywoszynska 2014). Which is more than enough to meet the requirements of about 340,000 households in the UK only (Defra 2010). Since there are many benefits in terms of energy saving, environmental aspects and waste management therefore AD from food waste has been acknowledged as an ideal solution for waste management strategy in England.

The food waste treatment combining standard and new technologies provides fuel and energy that can minimize the fossil fuel demand besides increasing the food products that are averted for fuel and animal feed which in return helps for increase in fertile land and allocation of resources for food production mainly for human consumption. Hence keeping in mind the merits and demerits of the each technologies regarding conversion of food waste to bio energy, the selection of appropriate technology can be the first and most important step.

Also, the seasons, time, location, social and economic contstraints besides education, awarness and law should be considered prior to the selection of technology. According to Song et al. (2015), the selection of technologies should consider the typical composition of the food waste as well.

It can be seen from the above Figs. 1, 2, and 3 that fruits and vegetable are wasted at higher rates in Turkey, while dairy, eggs and bakery wastes are discarded at higher rates in Netherlands. For example, the bakery waste could be rather treated by incineration or by using biological ways to yield energy or valuable products while the fruits and vegetable type of waste are more suitable for anaerobic digestion that will have more environmental benefits in terms of saving greenhouse gas emissions, energy and bio-fertilizer recovery. The top five resources which make up more than

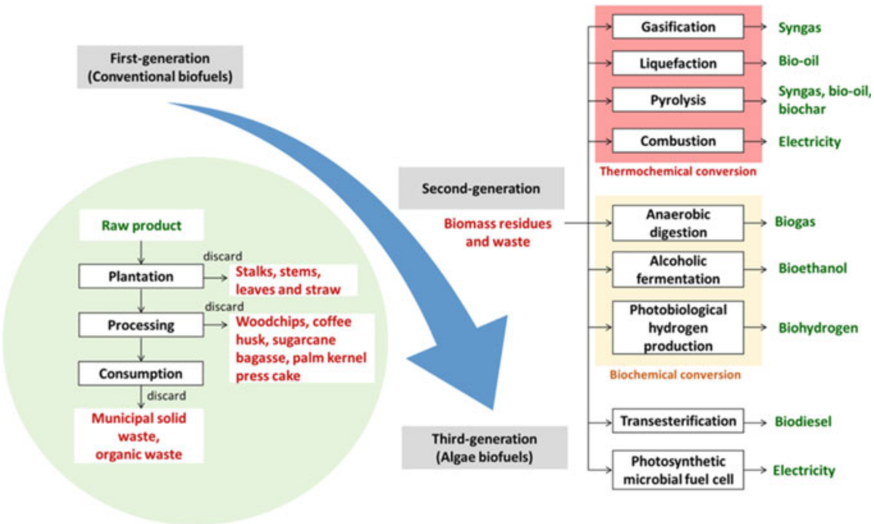
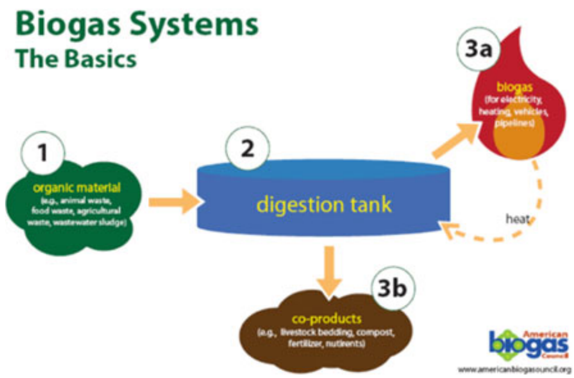


Fig. 1 Generations of biofuels courtesy (Lee et al. 2019)

Fig. 2 Biogas system



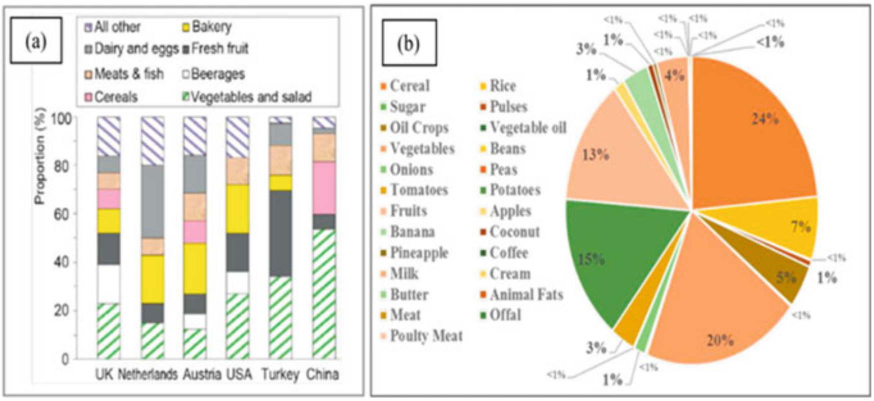


Fig. 3 **a** Food waste composition from different countries and **b** distribution percentage of different type of food components discarded as food waste (Song et al. 2015)

80% of the total food waste discarded annually includes cereals, vegetables, potatoes, fruits and rice.

3.1 Food Waste Policies and Regulations

In USA, 8% of the whole energy produced is used only in food industry where as studies have shown that over 27% of the food is discarded as a waste instead of being re-utilized as a source of clean energy. The food waste is one of the largest waste in USA and unfortunately only 3% is recycled. The food waste is dumped in a landfill for decomposition. This not only produces bad smell but also large amounts of methane gas which has 20 times more global warming potential than carbon dioxide. The suitable regulations regarding proper disposal and collection of major components of food wastes globally can help in more efficient utilization of food wastes into environmentally friendly fuels and energy conversions.

The most environment friendly process to produce biofuels is the recycling of food waste and is a much better substitute to growing crops for the purpose of generating biofuel. Moreover, using common crops like sugar cane and corn to generate biofuels creates havoc in the world wide food market as the prices of the required food products fluctuate to meet the demand for fuel (Jørgensen and Andersen 2012). In order to have a sustainable systems and "circular economy" the policies are made in such a way that the natural ecosystem for food chain is not disturbed by limiting the food waste but on the other hand enabling the flow of the organic waste materials as a raw material for the renewable energy source producing power and energy. These policies are required to support infrastructure and the future technological deployment regarding food waste to energy generation facilities. The food waste management in different countries is based on concept of prevention, recovery and recycling. The prevention is regarding the minimization of source reduction and after recovering the converting of food scraps and waste from oils and into animal feed, fertilizers or soil compost and into energy is done. Although food to waste framework do provide solution for landfill waste, green house gas emissions reduction by producing biogas, ethanol and bio diesels but at the same time implementation of these frameworks is not possible without the overcoming social, environmental, financial and technical hurdles. Also the involvement of government and local communities regarding waste stream management can not be ignored and must be taken into account for successful implementation. In USA, federal and state level policies are defined and promoted for wider adoption of food waste to energy technologies. All these policies are developed according to the conversion technologies and waste stream management in the region and every state has achieved different level of implementations accordingly. Also global policies are developed regarding food waste to energy as United Nations (UN) has agreed on the Global Sustainable Development Goals for 2030 which includes 50% per capita reduction of food waste in the consumer and retail sector while also minimizing losses occurring in food production and supply chains. The Food and Agriculture Organization of the United Nations (UN FAO) and many countries are making policies regarding the food securities, waste reductions and energy securities by financially supporting the food waste to energy projects in developing countries to promote renewable energy in electricity and transportation. The circular and regional economy policies have a vital role in bridging the gap between agriculture, industrial and waste management sectors to ensure food waste to energy pathway is successful (Ebner et al. 2018).

4 Campus Restaurants Food Waste

In university campus wasted food from the on campus restaurants can be collected and utilized for the production of bio energy that can be used as a fuel source for the on campus transportation shuttle service which can reduce the campus dependability on the fossil fuels besides making campus Green by lowering the Green House Gas (GHG) emissions.

In (Shahariar et al. 2017), detailed study on food waste management options and a case study of hope park campus, Liverpool hope university, united kingdom is presented. The main aim of the study was to estimate the amounts and types of food waste generated at Liverpool Hope University, Hope Park campus (UK) and to discover its on-site recycling potential through composting and/or anaerobic digestion. The results showed that about 89.07 metric tons of food is wasted yearly in Hope Park campus, Liverpool Hope. The mostly food waste items included the vegetables and the fruits by weight. Whereas bread, rice, pasta, and bakery products were the most frequently occurring food waste in comparison to meat, fish and dairy. It was suggested that the compositing is the better option for on-site food waste rather than anaerobic digestion however it is subject to the amount and nature of the food waste. Also anaerobic digestion (AD) is a desirable option for decomposable organic waste management from an environmental perspective because of the benefit of carbon savings.

As discussed earlier the food can be converted in to useful bio energy either in gas or liquid form. So here we will discuss the technologies being used for conversion of food produced on campus to the bioenergy which can later be used for power, heating and transportation purposes. In (Mohan and Jagadeesan 2013) the main research focuses on generating bio-gas from food waste produced by Mahendra Engineering College canteen in India using anaerobic digestion process. The most favorable recipe for maximum biogas production from the digested food waste has been investigated. The batch anaerobic thermophilic digestion test for approximately 90 days is used to determine the approximate biogas yields. The summation of methane and carbon dioxide produced over the specific experimental period determines the total biogas generated in the system. It was found that the biogas produced is a mixture of 76% methane and 24% carbon dioxide.

Also school lunchrooms and cafetarias are a major source of food waste and represent an ideal opportunity for recycling of foodwaste to useful energy instead of throwing in landfill. The details regarding the cafeteria waste were collected at three Florida schools. It was found that the food waste was the major proportion of the whole school waste and waste collected from the school's cafeteria waste streams ranged from 47 to 58%. The waste from the cafetaria included the milk, paper products like tissue, milk cartons, pasteboard, paper plates, and cardboard and also plastic wrap, packaging, and other utensils as a major components of the waste stream. Whereas, in cafteria metal and glass made the smallest portion of the waste stream. The students on average can produce food waste from 50.5 to 137.6 g.student^{-1}.day^{-1}.It was found that the total overall average for cafeteria waste generation among all three schools was 102.3 g.student^{-1} day^{-1}, with food waste alone contributing 52.2 g.student^{-1} day^{-1}.

The waste management can successfully divert the food waste by ending in landfills by reduction and recycling of food waste before it reaches the landfils. The composting or anaerobic digestion processes can be utilized in order to generate beneficial end products, including soil amendments and bioenergy. The 75% of food waste from cafetaria can be effectively recyled by this manner (Wilkie et al. 2015).

5 Technologies for Bio Energy Generation from Food Waste

In (Pham et al. 2015) details regarding different technologies that can be used for food-waste-to-energy conversion including biological like anaerobic digestion and fermentation, thermal and thermochemical technologies like incineration, pyrolysis, gasification and hydrothermal oxidation are provided which can be used effectively to convert organic bio mass into bioenergy which is a renewable and clean source of energy.

Following are the basic technologies applied regarding food waste to energy conversion for the clean environment (Fig. 4).

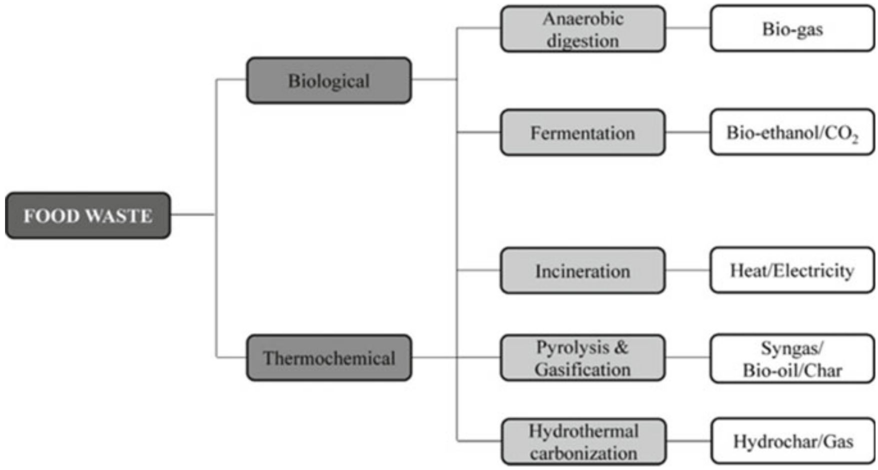


Fig. 4 Summary of food-to-waste technologies

In (Walker et al. 2015), proposed two step process is used to convert food waste items like corn, potatoes and pastas in a restaurant into useful ethanol. The low starch in the food results in low levels of ethanol and that can be increased by increasing the enzyme dosage levels.

The demand of biodiesels have also significantly increased around the world due to the fact that world is becoming more cautious regarding the use of fossil fuels and also the unpredictable international pricing and the impact on the environment. The waste cooking oils and fats, oils and grease are mostly the waste products not only produced at an industrial scale but also at domestic residential and small scale restaurants can be a considered as a valuable feed stock when pre treated for the mass scale production of environmental friendly bio diesel which can be used in transportation and energy sector. The biodiesel has is alternative to the conventional fuels due to its physical and chemical properties very much similar to the these. In order to reduce the raw material cost for the production of biodiesel waste cooking oil is considered as a cheaper feedstock as low quality and used cooking oil is mostly are mostly not required for production of biodiesels as they are with high impurities but as the population and so the consumption of edible oils has increased so recycling of the waste cooking oil can be used to produce renewable energy source for transportation fuel besides fixing the huge waste disposal problem for the wasted oil. Thransesterification process is consider sustainable besides cheap for the production of biodiesel from waste oil stream which is a triglyceride supply from domestic and food industry (Win and Trabold 2018). In this chapter we will mainly discuss anaerobic digestion technologies.

5.1 Anaerobic Conversion of Food Waste (FW) into Methane

As per (Rodecker et al. 1999); when bacteria produce biogas by decomposing an organic matter in an environment without air Anaerobic digestion occurs. The process involves three steps:

1. The enzymes are used in the process of Hydrolysis of the organic matter to produce biogas.
2. Fatty acids are produced by the transformation of the decomposed matters.
3. Transformation of the acids to methane and carbon dioxide by anaerobic bacteria is the final stage.

The most economic and environmentally friendly solution for decomposing the organic waste is Anaerobic digestion (AD). In this process organic waste is broken down in environment with no oxygen in order to form a gas mixture with consists of 50–70% methane,25–50% carbon dioxide by volume and other small quantities of hydrogen, hydrogen sulfide, ammonia and other gases in negligible quantities. This mixture of gas produced is called biogas.

The biogas production technology specifically anaerobic digestion can be applied to a range of organic wastes produced in agriculture, industry and municipalities. The Biogas produced from AD can be used to provide heat and power using the combustion engine. When the methane content in biogas is increased 97% by removing CO_2, water vapours and other impurities it can be used as a natural gas in vehicles and electric grids. Also the digestate which is an organic matter produced as a by product in anaerobic digestion process can be used as fertilizer or soil additive in a farm land (De Clercq et al. 2016).

There are various wasy to recycle Food waste and yellow grease and other waste greases can be converted into fuel for diesel engines. In Restaurants, byproduct of cooking oil can provide a steady supply of these fuels. This fuel produced is environmentally friendly and not only avoids generating more waste but helps in reducing the greenhouse gases to half by being used as an alternate for diesel fuels (Huynh et al. 2011).

In (Antonopoulou et al. 2020), study was conducted on dried house hold food waste (FW) collected by the local municipal council and bioconversion was done either by fermentization towards ethanol and hydrogen or by using the water to extract liquid rich in sugars and a solid residue which was later fermented separately. It was found that higher ethanol is produced when yeasts are used as catalyst, extraction process was useful in alcoholic fermentation as more ethanol is produced when separate fermentation of the soluble sugars and the residual solids is done. The enzymatic hydrolysis of dried house hold solid waste (FORBI) resulted in more quantities of Hydrogen. The energy recovery is very low when direct AD are used for FORBI as compared to when fermentation and successive AD are applied. It is found that extraction process and separate bioconversion resulted in more production of bioethanol and hydrogen.

Anaerobic digester is mostly used world wide to convert food waste into energy. The digetser decomposes organic food components using small organisms into methane gas which can be utilized to be used in power generators. It can be estimated that 260kwH of electricity can be produced from 1 ton of wet food waste, so we can say that about 8 billion kwH could be generated each year through this process based on the 30 million wet tons of food waste generated each year in the United States which can power over 1.3 million California households constituting 10% of the state (U.S. Energy Information Administration 2010).

According to (Global Methane Initiative, "Successful Applications of Anaerobic Digestion From Across the World 2013), the anaerobic digesters (AD) systems can be built according to the requirement and can be for small scale to large scale applications depending upon the quantity of the waste streams. The designs of the AD depend on the locations, environmental conditions and the outcome required at the installation facility and vicinity.

As an example of small scale AD we can take the Jan Kempdorp Abbatoir site in South Africa which uses cattle and bovine wastes and contributes not only in reduction of GHG emissions as demand from the grid is reduced by onsite electricity production but also is creating jobs and helping in economic and social growth of the society.

Also in Ogden, Utah, the Wadeland Dairy installed AD which utilizes 330,000 gallons of manure a day and also helps in efficient food management plan for the dairy, decreases the bad odors, and contribute in both generating income for locals and eliminate manure export costs (Fig. 5).

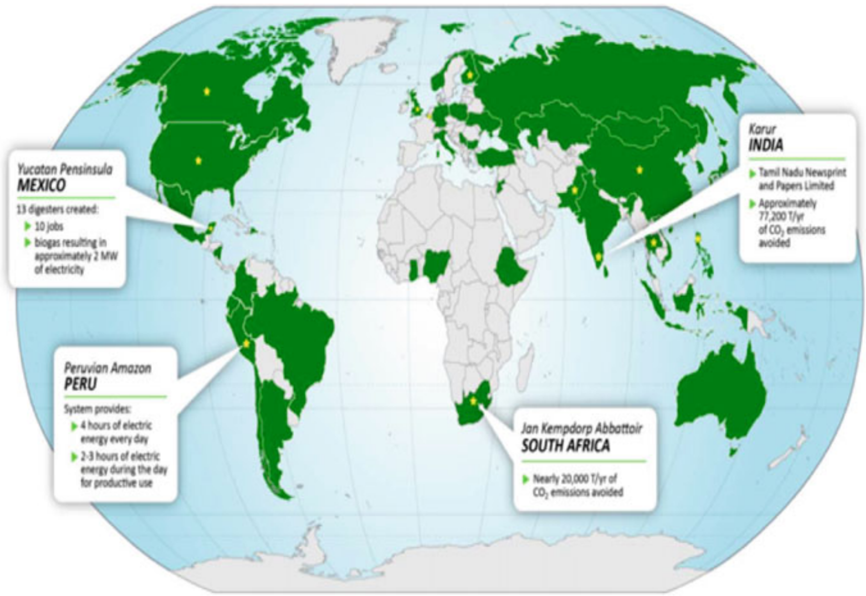


Fig. 5 Worldwide benefits realized by methane mitigation projects courtesy (Global Methane Initiative, "Successful Applications of Anaerobic Digestion From Across the World 2013)

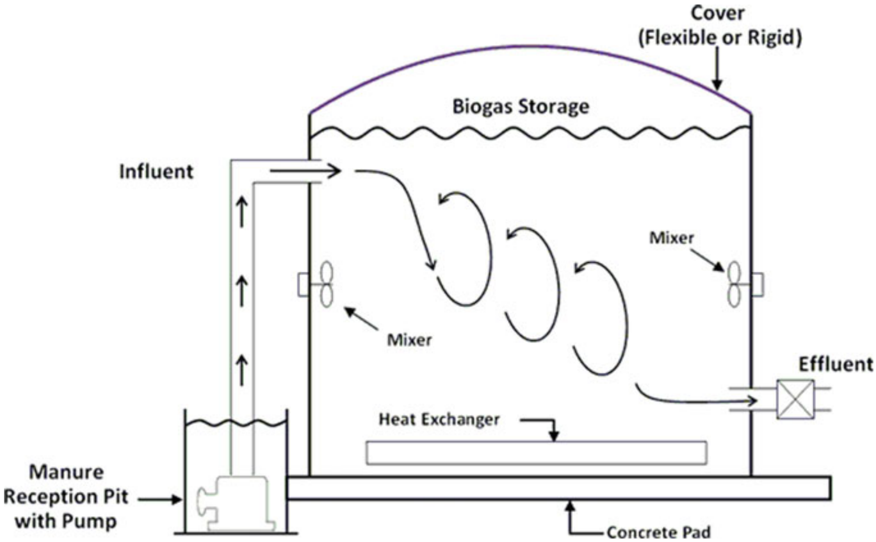


Fig. 6 Complete mix digestor

5.1.1 Anaerobic Digestion Technology Evolution

The process of decomposing of organic waste by using the naturally occurring a bacteria in atmosphere without any oxygen is known as "Anaerobic Digestion". This method of breaking down of organic waste is similar to the composting but in AD the process is carried out in air tight vessel and that also reduces the process time for less than a month. As a result of this method products we get are biogas along with the digestate and water as by product. Where, digestate is either in a solid or liquid forms that can be used as fertilizer, soil conditioner, cattle bedding, or even fuel.

In (Global Methane Initiative, "Successful Applications of Anaerobic Digestion From Across the World 2013), the design of Anaerobic digester system is keep on advancing due to the introduction of new technologies. Following are the types of the digesters used mostly.

Complete Mix

The construction of a complete mix digester is simple and easy and is built as an walled, heated tank with a mechanical, hydraulic or gas mixing system. The excreted manure is diluted with water for example waste water from milking center and manure is handled as slurry for the best performance. The motor or pump is used to mix contents of the digeter (Fig. 6).

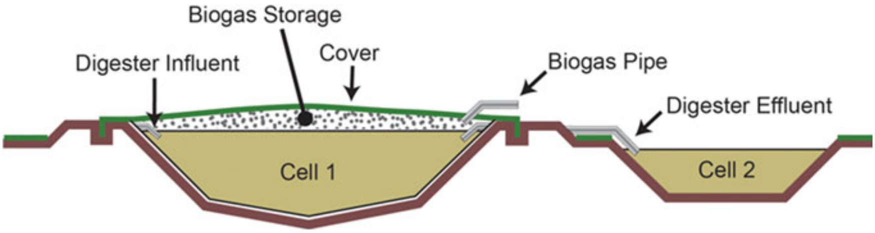


Fig. 7 Covered lagoon digestor

Covered Lagoon

The construction of covered lagoon systems is done with two cells which are required for efficient operation. The AD systems which use covered lagoon need less maintenance and can capture gas under an impermeable cover. In covered lagoon system only the first cell of a two-cell lagoon is covered whereas the other is usually uncovered. In order to accelerate the breakdown of manure in first cell the water level remains constant while for the second cell it may change.

Also the covered lagoons do need any heat and are affected by ambient temperatures. In order to have good methane production the temperature should not drop below 20 degree Celsius. As it is effected by the atmospheric temperature so it is not efficient in cooler regions but ideal for hot and warm regions for production of biogas (Fig. 7).

Plug Flow

In plug flow type digester a long narrow vessel with insulated walls and heated tank which is made of materials such as concrete, steel or fiber glass is used along with a gas tight cover to store the produced biogas.

In plug flow systems the manure moves through the digester does not mix longitudally but moves as a plug whenever new manure is added and that is why it in known as “Plug Flow”. As the manure flows into the digeter it changes the digester volume and same amount of material flows out. As the contents are thick so particle settlement at the bottom is prevented.

It is required to have total solid content of manure to be at least 10–20% for most plug flow digesters so extra biodegradable matter may be added in order to have the required solid content. The length of plug flow digestor is kept mostly 5 times more than their widths and recommended retention time for their contents is about 15 to 20 days (Fig. 8).

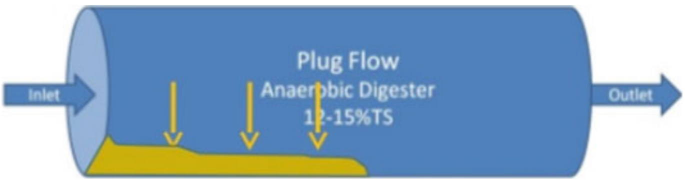


Fig. 8 Plug flow digestor

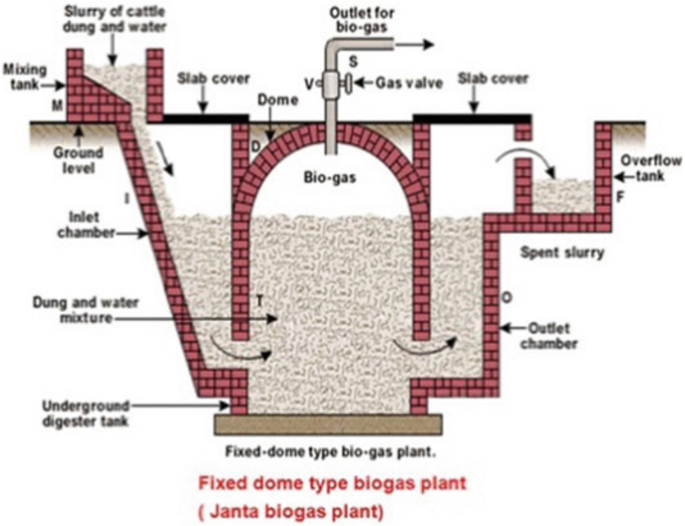


Fig. 9 Fixed dome digestor

Small Fixed Dome

The construction of the small fixed dome is different than the covered lagoon and plug flow as these digesters are constructed using an inlet trough, a lower fermenting tank with a firm, fixed collection dome which is used as a reservoir, and for some type of overflow relief. Although there are many designs used around the world but the most famous one is the Chinese design which is normally built of gas-sealed brick and using mortar or cement. It is widely used because of the durability and long life if built correctly as it has no moving parts. The main disadvantage is that they are constructed underground and therefore hard to do maintenance and cleaning when required. There is a lot of variations in the pressure of the outlet gas the reason being the process where methane collected in collection chamber is forcefully pushed out by using the pressure of the other methane which is not a stable or fixed process. In order to minimize and nullifying the gas pressure issues regulating device is commonly used that can help the biogas to be used for cooking or other applications (Fig. 9).

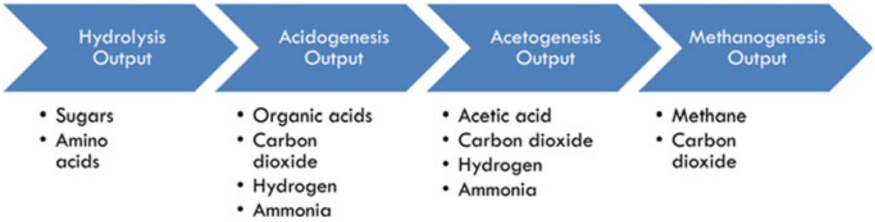


Fig. 10 Stages for anaerobic digestion

The anaerobic digestion process takes place in four-stages. The process can be achieved by either usning one container for all stages or sometimes by using separate containers, with different bacteria instrumental to each stage.

According to Ban (2014) the following are the main types of digesters can be classified as wet/dry, batch/continous and covered lagoons and tubular or fixed dome.

Mesophilic/Thermophilic

Depending on the temperature ranges two systems can be defined as Mesophilic and Themophilic systems for digeters.

Mesophilic systems utilizes less energy and can operate at temperatures of about 35 °C making the bacteria levels more stable but the processing time is remains much longer.

Thermophilic systems operate at a higher temperature (55 °C). These type of digesters are preferred to be used for dry feedstock, such as food waste (Fig. 10).

Benefits of Using Anerobic Digesters

The application of anaerobic digesters around the globe has proved that these systems provide low cost solution for environmental, social, and health benefits besides reducing the GHG emissions, controlling water pollution and waste recycling. These digesters are a source of unconventional and renewable energy, which can increase living quality of life in many areas of the world. These productions of biogas using AD are impacting the social, health and financial structures of the communities.

Although there are many benefits but the major concerns and barriers preventing the AD spreading as a valuable solution at a higher rates is because of the high capital and maintenance costs and lowering of profitability due to reduction in the prices of biogas. Other major hurdle is the education across the world regarding government regulations and installation criterias.

The potential of electricity production from Food Waste (FW) via one-phase and two-phase anaerobic digestion (AD) was reviewed in detail and econmic and energy benefits of bioenergy were provided (Thi et al. 2016). The main purpose was to compare economic and energy benefits of bio energy production with the benefits of other sources of renewable energy such as wind power (WP) and solar power (SP).In comparison with WP and SP, the utilization of electricity generation from FW- based

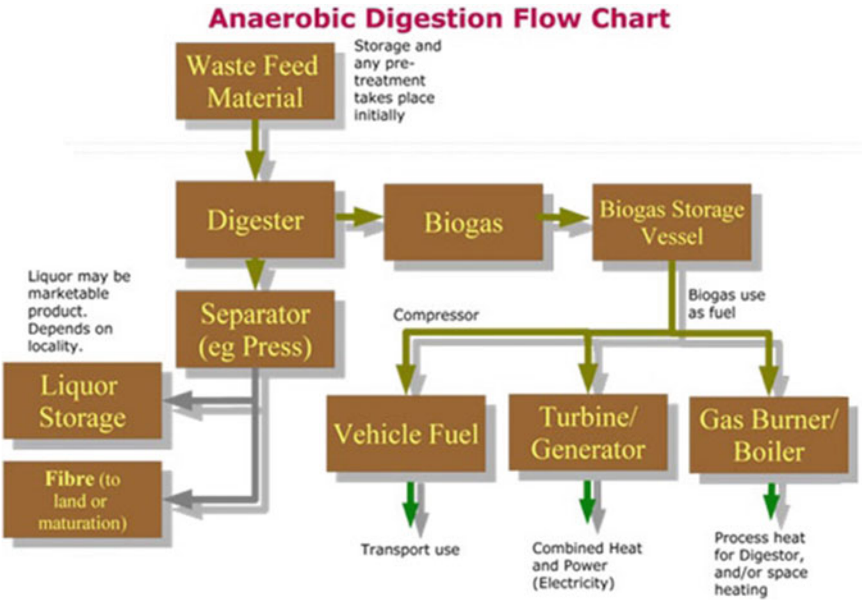


Fig. 11 Anaerobic digestion flow chart

bioenergy could reduce the energy costs such as levelized cost of electricity (LOCE) of food waste treatment in AD landfill (US$ 65 MWh^{-1}) and AD facilities (US$ 190 MWh^{-1}), which are lower than those of SW (US$ 130 MWh^{-1}) and WP off-shore (US$ 204 MWh^{-1}). This comparison can help countries to reduce the production costs of electricity, promotion of Foodwaste to bioenergy and effective food waste management issues. The implementation of bioenergy plants can help in provision of electricity to the areas where there is no conventional source of electricity available. Furthermore the bioenergy produced can be sent back to the grids and can generate profits for local communities as well (Figs. 11 and 12).

Stages of Anaerobic Digestion

Following are the main stages of anaerobic digestion:

- **Disintegration** The process of decaying material into smaller particles such as carbohydrates, lipids and proteins is called Disintegration and is the first step in anaerobic digestion.
- **Hydrolysis** is process of of depolymerization of the proteins, lipids and carbohydrates and converts them into simple sugars and amino acids. These enzymes can be degraded further in following steps of the process.
- **Acidogenesis** is also known as Fermentation. In this process volatile fatty acids, organic compouds and alcohols are formed but simple monomers.

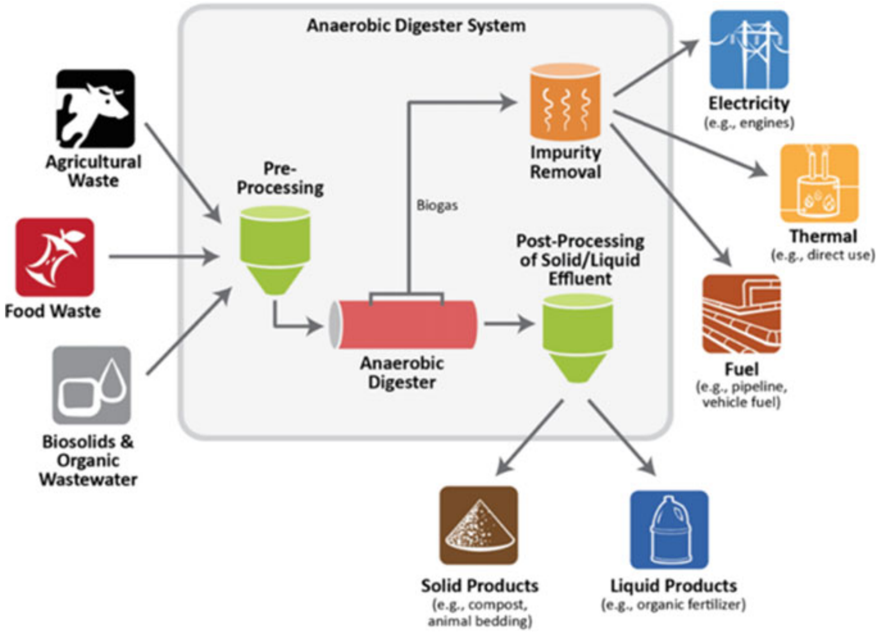


Fig. 12 Anaerobic digestion process (Global Methane Initiative, "Successful Applications of Anaerobic Digestion From Across the World" 2013)

- **Acetogenesis** is the phase where organic molecules and volatile fatty acids are converted into acetic. Also carbon dioxide and hydrogen are produced during this process. The reactions are caused by acetogenic bacteria.
- **Methanogenesis** produces the Methane as the final process in anaerobic digestion. In this phase, methane is produced from acetic acid by acetolastic methanogens or from hydrogen and carbon dioxide by hydrogenothophic methanogens.

5.2 Combined Heat and Power

The bio gas produced from anaerobic digestion can be a source for production of cheap electricity. Therefore we can use the bioenergy to produce both heat and power. In this case when the heating and power requirements are fulfilled by the same system, it's referred to as "combined heat and power or cogeneration".

The purification of Biogas results in the production of natural gas, compressed natural gas (CNG), or liquefied natural gas (LNG) which can also be used as the energy sources not only for production of heat and power but to drive the automobiles as well.

5.2.1 Benefits of Aneroid Digestion Integrated with Combined Heat and Power Systems (AD/CHP Systems)

When we use combination of AD/CHP then the cost can easily be converted into profits and benefits. Possible advantages of using such systems by municipalities include the following:

- The electricity produced is clean and helps the to offset purchase of utility energy
- Food waste can be recycled in an effective and clean way.
- Reduces volume of organic matter
- Reduces odors
- The byproducts can be used as fertilizer and/or soil amendment
- Economic benefits in terms of generating revenue.

5.2.2 Types of Generators

The generators are used to convert biogas produced by the anaerobic digesters into electricity and we can use microturbines, internal combustion engines and also fuel cells for this purpose.

The generators for CHP are selected on the basis of size and cost. According to Massachusetts Department of Environmental Protection (MassDEP) for different ranges we use different generators like in case of waste water treatment plants where processing of 6.8 million gallons per day (MGD) is expected we use microturbines, similarly when we have to do processing of 10.7 MGD we use fuel cells as it fulfills the minimum flow requirement for that. The large scale facilities where we need to process about 41.4 MGD, internal combustion engines are utilized for production of power and heat. The average costs per kilowatts for the generators are about $4,484 per KW for microturbines, $7,426 per kW for fuel cells, and $2,039 per kW for internal combustion.

Provision of financial aid and technical assistance for both public and private parties in order to encourage installations of AD/CHP systems is the goal of common wealth of Massachusetts state (Ban 2014).

5.3 Biogas Reactor for a Restaurant

The natural gas which is a form of fossil fuel is widely used in hotel and restaurant sector for cooking purposes in gas stoves. Also a huge amount of food waste is produced as a by product of restaurant operations which is mostly dumped in landfills by the municipality. So if the restaurants start using their wasted organic materials to produce bioenergy and gas it can not only save them money but also can help in making the environment clean and green.

In (Vasudevan et al. 2010) researchers developed a small scale biogas reactor for restaurants called the “Methanizer” that decomposes the organic waste and produces

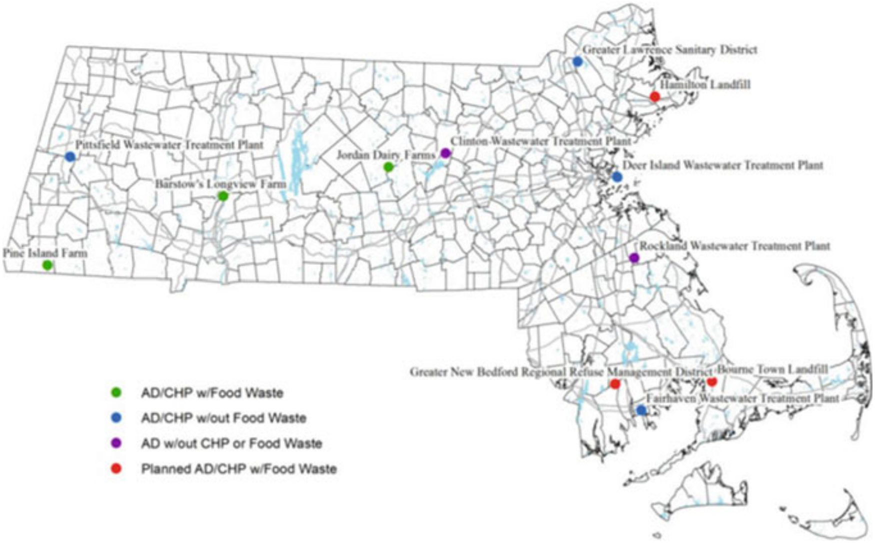


Fig. 13 AD/CHP installations in Massachusetts courtesy (Ban 2014)

fuel that would be able to power a gas stove. The utilization of the Methanizer can save restaurants money as they can utilize the food waste produced in restaurant to produce bio gas for the stoves and thus can reduce their impact on the environment.

Methanizer can be used for a small to medium sized restaurant. The working of methanizer is very simple and its very cheap to construct as well. The input to the reactor is the organic waste from the restaurant and the microbes are used to decompose the waste into the methane that can be used to fuel a stove. After doing feasibility study and analysis it was concluded that Methanizer would be technically and economically feasible and reliable solution to be installed in order to produce biogas. In the designing of the reactor a double tank system as shown in Fig. 13, was selected. This basically is to reduce the costs as well. In this design a smaller airtight tank can be used in combination with a large cheap tank and that allows for easier loading as well. Also the reactor was constructed as a batch-fed system meaning that organic waste can be added on a daily basis and then cleaned out on a biyearly or yearly basis. Also the installation, maintenance of the system makes it easier to use for the employees of the restaurant without undergoing any professional training.

Besides technical feasibility the energy and economic studies were also carried out on this design. It is concluded that a small scale restaurant would save 735 m^3/year of natural gas and a medium scale restaurant would save 1470 m^3/year using the Methanizer (Fig. 14).

However the economic analysis was not so affirmative. As the rate of return on investment was found as 15.5 years for a small scale restaurant a medium scale restaurant requires 7.7 years. As the gas prices are increasing yearly so this system can be very useful in future and the Return on Investment can reduce with the passage

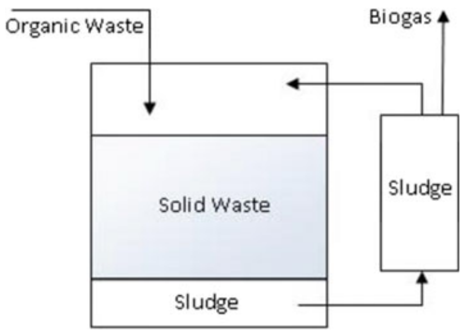


Fig. 14 Two tank reactor design

of time. So with much smaller investments and good rate on investment Methanizer can be used with benefits for food waste recycling and clean energy.

In (Tradler et al. 2018), a small scale hydrothermal carbonization plant (HTC) is used as an alternative for the biomass plants due to the fact that the wet, inhomogeneous waste are not suitable for the such plants. We can produce high quality hydrochar when a restaurant waste is heated to 200 °C for 6 h to get the fuel like properties similar to lignite which can be utilized as co-combustion. It is found that feed stock with high proteins and fats resulted in lower hydrochar as compared to feedstocks with high carbohydrate content. The small scale HTC for restaurants having 50L volume capacity can be fed by average food waste from restaurants with energy content of 23,000 kJ/Kg. The calaculated rate of return on investment for this type of HTC is approximately 8 years as found in the study.

5.4 Case Studies

In this section we will discuss the insatlled bioenergy plants and solutions which are using the organic waste materials to produce the clean energy.

5.4.1 Transforming Food Waste to Biogas: Sustainable Gator Dining

As discussed earlier the the food waste which is organic material in nature and abundly collected from restaurants, grocery stores, food processing plants can be utilized in order to produce biogas. Therefore in Graunke and Wilkie (2008) the analysis of the food waste stream from Broward Dining Hall (BDH), a campus dining hall at the University of Florida in Gainesville, has been done in order to find the potential for biogas production from the on campus food waste.

Experimental Methods

Following are the methods and steps involoved for the production on campus bio gas facility.

Food Waste Collection

The food waste was collected for 12 days. The food waste was separated as pre and post consumer waste. The kitchen waste (KW) is the considered as the preconsumer waste and the leftover after the students have eaten their meals is a post consumer waste called as plate scrap (PS) respectively. In PS we include uneaten food left on plates, along with napkins and paper cups with plastic lids. The plates will not be taken as wastes as they are to be reused and not thrown away thus the vast majority of the PS stream is just food waste.

The labeled garbage bins are used by the employees to separate and sorte the food waste. It is very important to separate non organic waste initially both from the kitchen waste and scrap waste. The food waste was weighted after specific intervals through out the day. The liquid waste left as Postconsumer drinks was separately collected as well.

In this study, the record was maintained and students were counted daily in order to to standardize results on a per capita basis. Also the subsamples were analyzed for organic content and bulk density besides standertizing of the plate and kitchen wastes.

Digester Design and Operation

The digester is constructed from reused polyethylene drums. The capacity of the digeter is 30 gallons. The standardized plate scraps was daily put into the digester and stirred so it mixed well.

The water displacement shows the measurement of produced biogas. In order to accelerate the decomposition process the digester was placed in a sun in an open area. In order to increase the solar absorption the digester is painted Gator blue so an average digester temperature at 30ºC is maintained successfully. The pH was monitored to ensure approximate neutrality (pH 7.0), which is ideal for methanogenesis.

Results

It is found that after a period of 12 days the average daily food waste from both the kitchen and consumers collected was 576 pounds and per consumer daily average was 0.35 pounds.

Also the liquid organic waste was also calculated and an average daily drink wastes totaled 0.43, 0.5, and 0.2 gallons for soda/juice, milk, and coffee, respectively.

The best thing was that the food waste constituted 95 percent which is highly decomposable into Methane. As the food waste stream was 95% organic so a very

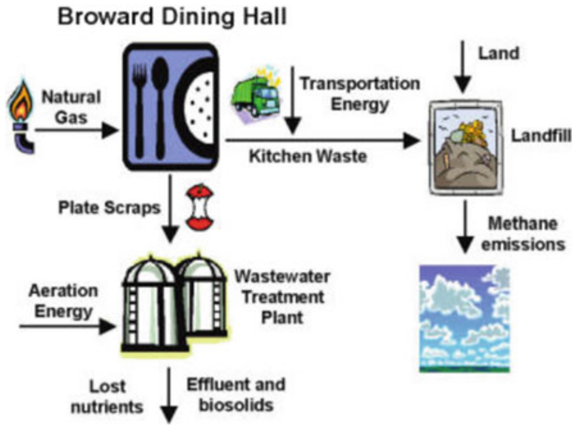


Fig. 15 Open-loop system of food waste disposal courtesy (Graunke and Wilkie 2008)

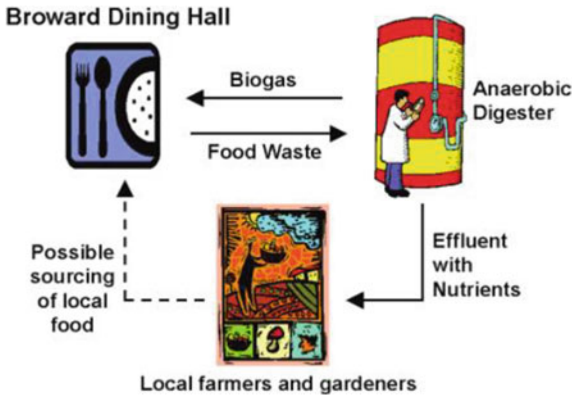


Fig. 16 Closed-loop system for sustainable food waste management courtesy (Graunke and Wilkie 2008)

high quality biogas was produced by stable fermentation process. It can be calculated that the biogas manufactured would be 1413 cubic feet of methane biogas per day or 918 cubic feet of methane (CH4) per day.

This production of biogas from converting food organic waste in this study demonstrates that this process can provide extra energy and gas to offset natural gas use at BDH.

As in this study the waste was collected for only 12 days so we can say that ideally, if collection of waste and measurement is taken for several weeks would result in more production of gas and accuracy can also increase.

The future plans are to shift the Gator dining from an open-loop system which is highly dependent on resources to a much sustainable closed-loop system as shown in Fig. 15 that will also conserves energy and nutrients, minimum external energy sources will be required along with the fewer sinks for waste. The biogas technology using the waste from food service industry can have a substantial impact towards a sustainable economy (Figs. 16 and 17).

Fig. 17 Michigan State University AD/CHP plant courtesy ("South Campus Anaerobic Digester | Anaerobic Digestion Research and Education Center (ADREC)" 2013)

5.4.2 Michigan State University Builds Combined Heat and Power System Using Anaerobic Digestion

The Michigan state university has made an energy transition plan in order to achieve sustainability, waste reduction and waste re-use. The construction of the South Campus Anaerobic Digester (SCAD) is a vital part of University's sustainable plan. The connection of the energy and sustainability plans is to achieve a 70% landfill diversion rate and reduce energy consumption by 15% and greenhouse gas emissions by 45%.

The SCAD is a 1,500 m^3, mesophilic, complete mix anaerobic digester Operating at 40 °C, with a 20-day residence time, the system utilizes between 20,000 and 22,500 mton of Pre feedstock to generate 1.5 million m^3 of biogas annually.

The anaerobic digeter is made up of a single tank and can utilize 17,000 tons of organic waste from the campus and near by areas to produce 2.8 KWh of electricity from the biogas per year. The installed digetster uses organic waste from the univeritry dairy farms, and wastes from various dinning halls and cafetarias on campus. It is also worth noting that the local restaurants and community also contribute in providing grease, oil and fats for the digester.

There are two tanks for collecting the feedstock. One is designed for manure and second for the materials. The delivery schedule is followed and keeping that in mind the blend of feed stock is pumped from the main reception tank to the central mix tank where the collected feedstock is standardized. It is important to increase the temperature of the material to 100°F before it enters the complete mix anaerobic digester using the heat exchanger.

The digester is an airborne steel tank with a liquid capacity of more than 450,000 gallons and a 25-day hydraulic retention time. The tank is air tight and sealed for biogas using a membrane. The content of digetsers are kept on well mixed continuously by the use of two hydraulically powered submersible mixers.

The produced biogas by the digester installed in university campus is supplied to a 450 kW combined heat and power (CHP) system. The produced electricity is utilized to power buildings on the south side of the campus. Whereas, the hot water produced by the CHP system is used to maintain the digester temperature at 100 °F and for provision of heat to the other buildings at the site.

The mixture of solids and liquid residual left after digestion (digestate) will be pumped to a solid–liquid separator. The solid waste is then composed and the liquid is then transferred to the digestate storage tank which is a steel tank with a 2.4 million-gallon capacity and above the ground. The space above the digestate to be used as biogas storage and reduce odors from the systems using thin membrane as a separator. The digestate produced can be used as a carbon-rich fertilizer. The SCAD provides many benefits, including renewable energy, emissions reduction, landfill and wastewater diversion and enhanced fertilizer with reduced pathogens, weed seeds and improved plant nutrient availability. Teaching, research and outreach activities regularly use the facility as well ("South Campus Anaerobic Digester | Anaerobic Digestion Research and Education Center (ADREC)" 2013).

Also, in Mydin et al. (2018) it was found that mini biogas power plant installed in Universiti Sains Malaysia can generate about 180 cubic meter methane gas and 600KW electricity per day when the food waste collected from cafeterias and canteens is 1000 kg/day and in Thi et al. (2016) found that the cost of energy produced using food waste is very low as compared to other renewable energy sources such as solar and wind energy.

The production of energy through food waste can also be used for effective food management besides reducing the electricity production costs and provision of bio fuels and gases.

5.4.3 Converting Food Waste to Renewable Natural Gas for Transportation: Sacramento Biodigester

The project for producing renewable natural compressed gas (R-CNG) from food waste using anaerobic digetser in Sacramento, California, is considered as largest commercial high solids food waste digetser project in USA. The digester is designed to divert 40,000 toms per year of organic waste to produce renewable natural gas and fertilizers. The project started in 2 phases in 2013. In the first phase building of a 25 tons/day organic waste capacity initial anaerobic digestor was completed and in second phase the digester tank capacity was further expanded to cater for 100 tons/day of organic waste. This project is considered as first of its kind in USA to produce R-CNG vehicle fuel using anaerobic digestion of food waste.

The Sacramento Biodigester is using thermophilic Anaerobic Phased Solids (APS) digestion system developed to handle different organic materials to produce high levels of biogas with minimum pretreatment requirement of the collected raw material. This technology is considered as energy efficient and readily savable (Fig. 18).

There are four hydrolysis reactors and one biogasification reactor in APS system. In hydrolysis reactors the organic material is broken down in to simple monomers which are further broken down to volatile fatty acids. These acids when react with methanogenic organisms are converted into biogas in bio-gasification reactor. In order to get constant gas output each hyrdolysis reactor is supplied with raw material at different schedules, so fatty acid formation is completed at different time span by these reactors resulting in stable supply to biogas reactor and constant level of gas is produced (Tomich and Mintz 2017) (Fig. 19).

Fig. 18 Sacramento Biodigester ("Clean World Expanding Sacramento Biodigester—Waste Today 2013)

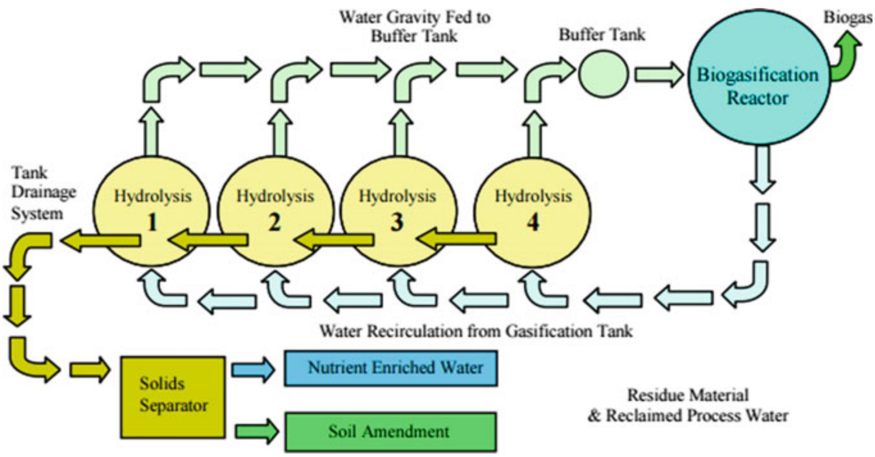


Fig. 19 The APS digester loop image courtesy (Tomich and Mintz 2017)

Fig. 20 Refueling station at the site (image courtesy of Cleanworld)

The gas separation technology is then used to refine the produced raw biogas which is then supplied to the fueling station. The fueling station has two 20,000-gallon equivalent storage tanks to store the excess gas as well (Fig. 20).

The main advantages of this project is that it provides public and private organic waste producers an alternative for disposing waste in an environmental and economic manner. This facility generates 700,00 diesel gallon equivalents (DGE) of renewable compressed natural gas and that helps in reduction of green house gas emissions by 20,500 tons annually besides production of over 10 million gallons of fertilizers and soil amendments.

We conclude that the Sacramento BioDigester is an example for the world to learn how zero waste economies can be achieved by commercialization of the researches done by the universities for the green environment. This project is a **Farm-to-Fork-to-Fuel model** where local community succesfully produce, consume and convert their organic wastes into sustainable “fuel” by products in form of R-CNG, fertilizer, clean air and cleaner land (CleanWorld Sacramento BioDigester Project 2012).

5.5 Life Cycle Impacts of Food Waste to Energy Conversion

The conversion of food waste into energy is a significant approach towards a sustainable economy. Unlike the first-generation crop-based biomass where land use, fertilizers and high energy inputs are required for the cultivation, food waste does not impact environment but instead it helps in disposing of the organic waste in a more productive and environmentally friendly manner in order to produce biogas or ethanol. The life cycle assessment is used to determine the environmental impacts when different conversion technologies are used for conversion of food waste to energy. As there are many technologies related to food waste to energy conversion so it is difficult to generalize the results. In (Win and Trabold 2018), the life cycle impacts of biogas and ethanol production from organic waste feed stock using anaerobic digestion (AD), fermentation, transesterification and other technologies such as bio electrochemical systems (BES), pyrolysis, and gasification has been discussed in detail. The global warming potential (GWP), fossil fuel consumption, urban air pollution, acidification and greenhouse gas emissions (GHG) and their impact on environment were evaluated for different technologies and concluded that AD provides the maximum rate of GWP reductions as compared to any other technology. The life cycle assessment (LCA) is mainly dependent on feedstock characteristics of the waste for different technologies. In order to have a sustainable solutions food supply chain stakeholder must also need to be educated regarding the economic costs and benefits and the social and environmental effects which are currently imposed by the existing policy and regulatory frameworks.

6 Conclusions

In this chapter we discussed the bioenergy as a renewable energy source and specifically how we can use the campus biomass and organic waste to produce biogas and fulfill university heating and power requirements. There are usually many restaurants, cafeterias, hostel dining halls and kitchens on any university campus and the students use these food facilities daily. The amount of wasted food is just lost without giving any positive social, technological and cultural impact on campus and education sector as a whole. This clean energy produced from the restaurant and food waste can be used not only for cooking meals but also as an alternative fuel source to run the campus shuttle service. The small-scale anaerobic digesters and combined heat power plants can help in the production of electricity that can help to reduce dependency of the campus on fossil fuels and thus make the environment green and sustainable. We can confidently say that AD/CHP plants can be installed on university campuses around the world in order to produce clean energy at a very cheap price for sustainable growth.

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Energy Storage Techniques for Renewables

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1 Energy Storage

Energy storage can be defined that to temporarily store energy in a storage medium for later use. The use of energy, and ES techniques are as old as human history. In ancient times, while people stored energy directly as food and fuel (wood, charcoal, etc.), they have been a significant part of energy systems for the last few decades. The term of "later" in the energy storage definition indicates the aims of the ES. ES techniques aim the followings:

- To balance the energy supply and demand profiles in the grid
- To decrease the energy consumption and costs
- To recover energy loses
- To compensate the deficiencies of availability of renewables due to their nature
- To reduce the capacity of the equipment used in the energy systems
- To shift the peak energy loads to the off-peak hours

ES systems can achieve one of them, most of them, or all of them. They solve the many challenges in the energy system used in all sectors and help to maintain better

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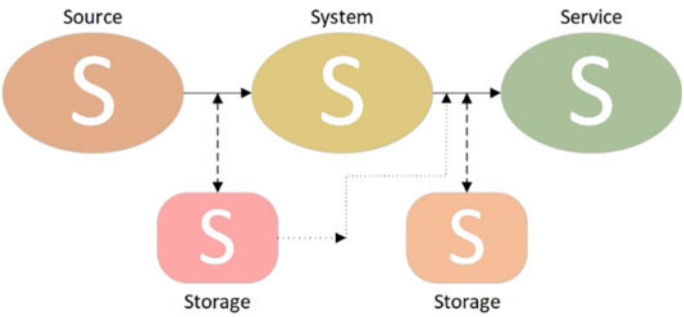

Fig. 1 The rule of 5S (3S + 2S = 5S). Modified from Dincer and Acar (2015)

sustainability. A conventional energy system consists of an energy source, a system and a useful output called the service. Those systems use a fossil fuel or energy source to convert it into a useful output. Due to limited sources of fossil fuels, intermittent use of renewable energy sources and energy security issues, today, the systems which are called multigeneration, integrated or smart energy systems have been appeared and commonly used in many sectors. On the other hand, environmental concerns have forced us to integrate renewable energy sources to meet energy demands or reduce fossil fuel consumption. ES systems are a unique solution for the common problems in each type of energy system. ES systems can be integrated between source and system or system and service. This is called the rule of 5S. Principle of 3S + 2S have brought up by Prof. Dr. Ibrahim Dincer for the first time (Dincer and Acar 2015). The illustration of the rule of 5S is given in Fig. 1. As can be seen from Fig. 1, ES systems can maintain a strong bridge between the energy source(s) and the demand(s). It explains how it should be done for a sustainable energy cycle. Thus, the energy demand items can be meet in a more sustainable way and enhance the use of renewables. The stored energy can be used directly in the service or used to meet another demand. Since both will reduce or remove fossil-based energy consumption, it will provide significant advantages.

1.1 Need for Energy Storage in Renewables

The ES techniques are able to be used for many purposes itemized previously in every sector that needs energy. When today's challenges in energy production, distribution and use are taken into consideration, ES techniques can be used from micro-scale to macro-scale. In the other words, they can be integrated into energy systems any methods, capacities, applications. For example, ice storage systems also called ice thermal ES systems, can be used to reduce the cooling cost of the buildings as well as reducing the chiller capacity by storing peak cooling loads. While they provide benefits on their micro-scale fields, they can help to manage the electricity grid loads on the macro-scale. Solar domestic hot water systems are one of the most common renewable energy and heat storage applications. They can meet the hot water demand of a single house at the micro-level as well as the demand of a community at the macro-level. The number of those examples may be increased. Here it should be noted that although ES systems are applied at the micro-level, they can provide unique advantages at the macro-level.

The ES systems are also a significant part of the renewable energy systems in order to solve the challenges in their use. Renewable energy sources are the energy source that has intermittent, fluctuating and unsteady availability due to their nature. In order to balance the mismatch between their active and non-active periods, to compensate for their fluctuating behaviour, and to extend their availability, the ES systems provide important advantages. For instance, in solar heating systems, in order to meet the heat demand with solar energy during the night-time or winter, it should be stored in the form of heat. Those applications of solar energy are one of the oldest ES techniques and renewable energy applications. As another example, flywheels, one of the mechanical ES methods, can balance the changes in wind energy for a short period. Pumped hydro energy and compressed-air storage systems are other examples of storing renewables in the form of mechanical energy. Flow batteries are used for renewable electricity applications. Examples of ES methods in renewable energy applications will be introduced with details in the following sections.

It is clear that ES techniques have a great potential to solve the issues in renewable energy systems and to extend their availability. The selection of the ES method and storage medium are significant for system performance. Therefore, they should be analysed and applied carefully. In the following sections, ES methods and their renewable applications are presented with their advantages and disadvantages. ES systems can provide the followings:

- To reduce energy costs
- To improve the efficiency of the devices in the system
- To extend the availability of the renewable energy sources
- To reduce the capacity and size of the equipment in the system
- To balance energy supply and balance profiles
- To increase the capacity of the generation
- To enhance the flexibility of operating conditions
- To reduce fossil-based fuel consumption
- To decrease the carbon emissions and environment impacts.

1.2 Working Principles of ES Systems

The working principle of a typical ES systems consists of charging, storing and discharging periods, as illustrated in Fig. 2. In the charging period, the energy source(s) is used for charging to the energy storage material(s). According to the type of energy storage methods and storage material; the temperature, phase, solution, or chemical composition of the storage material change. Charging period is performed when energy source is available, excessive, or cheap.

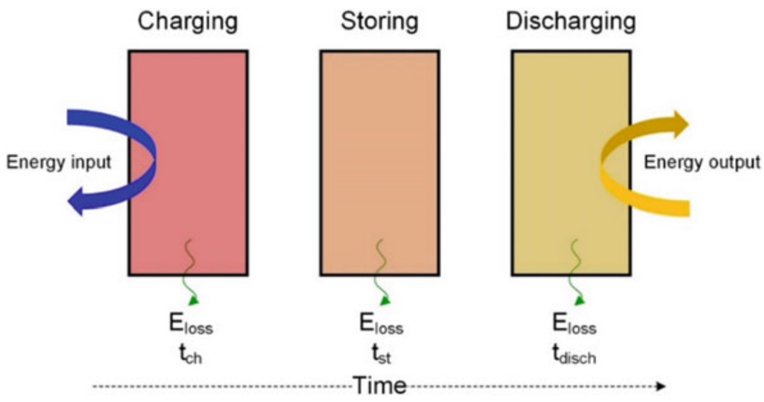

Fig. 2 Working principles of an energy storage system

The storage material is kept in a storage medium during storage period until energy is needed. The storage medium can be a manufactured volume such as special vessel, container, tank, balloon, etc. as well as natural volume such as mine, lake, pool, underground reservoir, etc. In some systems, there is no storing period. The charged energy is used for meeting the demand as soon as completed the charging period in the discharging period.

In the discharging period, when energy is needed, the demand item(s) is met by the stored energy. The process in the discharging period is reverse one in the charging period. The discharging period is performed when energy source is not available, during peak energy demand or expensive.

1.3 Energy Storage Methods

Theoretically, energy can be stored in each form of energy like kinetic, potential, heat, electricity, magnetic, etc. When practical applications and storing capacities are considered, ES can be divided into six branches, as shown in Fig. 3. Moreover, many ES methods are still under development. The material that storing energy is called "energy storage medium". ES methods and the type of ES mediums vary according to the purpose and capacity of the storage. Each of the ES methods and mediums has certain advantages, and also disadvantages depending on the area of using them. Therefore, they should be selected and applied carefully to the energy systems. In this chapter, ES methods using for storing renewable energy sources have been discussed with practical applications.

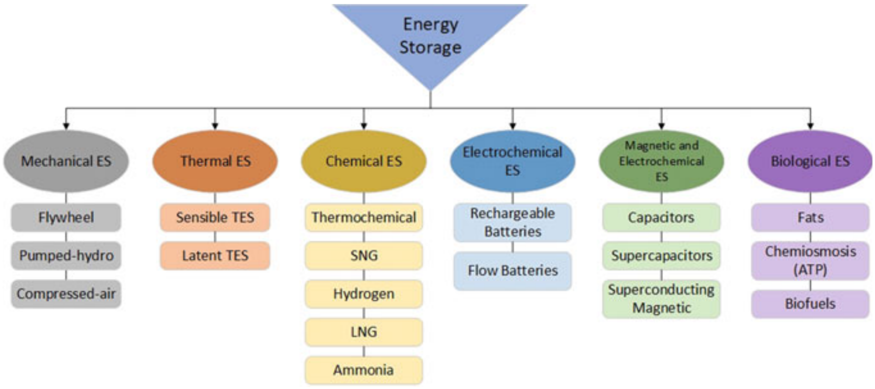

Fig. 3 The classification of energy storage methods

1.4 Mechanical Energy Storage Systems for Renewable

Mechanical ES systems store the energy by changing the potential or kinetic energies of the storage material. Energy can be stored in the form of kinetic energy by changing the linear or rotational velocities of an object. While the object's velocity is increased during the charging period, it reduces in the discharging period to generate power. When practical applications are considered, it is impossible to store energy in high capacities, since it requires long distances or large masses. When the energy is stored in the form of potential energy, the potential energy of an object or fluid is increased by elevating or compressing. In the discharging period, the power is generated by lowering the elevation or decompressing. When the practical applications are taken into consideration in the renewable energy application, the mechanical ES methods can be classified as follows:

- Flywheel
- Pumped-hydro ES
- Compressed-air ES.

1.4.1 Flywheels

Flywheel is an energy storage technique that stores energy in the form of kinetic energy with the rotational velocity of a flywheel. Figure 4 demonstrates the schematic of a typical flywheel used in the ES applications. The flywheel consists of a rotating mass call the flywheel rotor, bearing and motor/generator. Magnetic bearing is used to ignore the contact friction. A vacuum pump is used for removing the air inside the flywheel case to reduce the air friction. The working principle of the energy storage in the flywheel is the following:

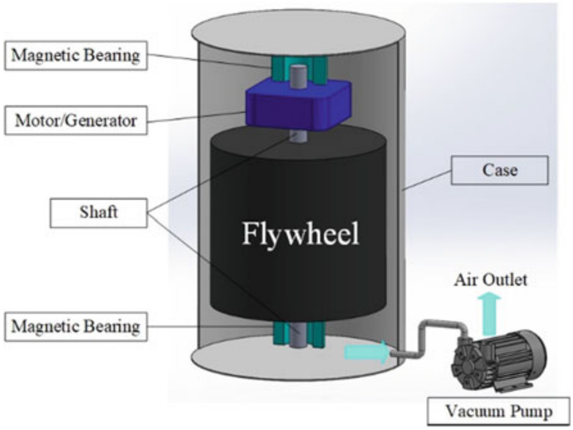

Fig. 4 The schematic of a typical flywheel. Adapted from Erdemir and Dincer 2020)

- **Charging period**: The angular speed of the rotor is increased by the electric motor. Thus, kinetic energy of the rotor increases. The charging period continues up to the maximum speed limit is reached.
- **Storing period**: Flywheel rotor rotates until energy is needed. Vacuum condition inside the flywheel case and magnetic bearing minimize the losses during the storing period.
- **Discharging period**: A generator is used for power generation. The kinetic energy transforms into electricity in the generator.

Energy content of the flywheel directly depends on mass and angular velocity of the flywheel rotor, as seen in Eq. 1.

$$E = \frac{1}{2} I \left(w_1^2 - w_2^2 \right) \tag{1}$$

Here, "I" is the flywheel's the moment of inertia. The rotor is the significant part of a flywheel as it stores energy within its body in the high rotational velocity. Additionally, the geometry of the rotor is one of the critical parameters for the energy storage performance of the flywheel. Today, the composite-based rotors are used for the strength of the flywheel.

Flywheels are a significant method to store energy for short period in a high-power capacity. Therefore, they are commonly used to balance the energy fluctuating in the wind turbines or meet the momentary high demands. Erdemir and Dincer (2020) has studied the use of flywheel in the fast-charging station for electric vehicles, as illustrated in Fig. 5. Flywheel has been integrated into the system in order to reduce the capacity of the PV panels and wind turbines. The main parameter that having an impact on reducing the PV panel and wind turbine capacities is the difference between the charging and discharging times. The overall energy efficiencies for the solar-based and the wind-based fast-charging stations are approximately 0.17 and 0.34, respectively. In the case studies, while the flywheels have achieved to reduce

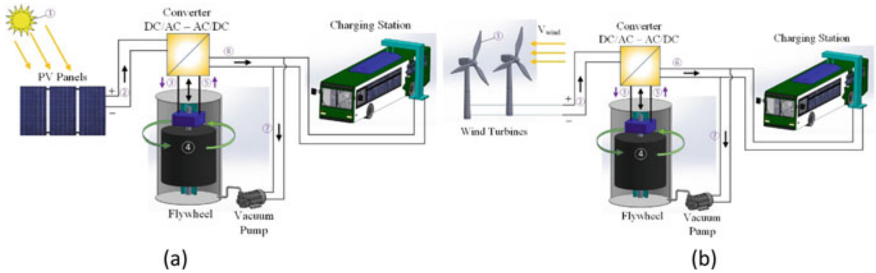

Fig. 5 The diagram of the flywheel integrated fast-charging station for electric vehicles **a** solar-driven and **b** wind-driven. Adapted from Erdemir and Dincer (2020)

by 60% of the power requirement of the system in Line 910 from Canada, they have decreased by 72% for Erciyes University Campus Ring from Turkey.

1.4.2 Pumped-Hydro ES Systems

Pumped-hydro ES is one of the technically simplest ES methods as people have been using these systems in hydropower systems for power generation for over 100 years. Therefore, it is the ES method with the highest capacity in the world today. When the total capacity of the ES systems around the world is considered, pumped-hydro systems have 97% of the total capacity of ES power and 99% of the stored energy around the world (Cheng et al. 2019). China has the largest capacity in the pumped-hydro ES systems, and there are more than 500 pumped-hydro ES facilities in the world, which is their capacities vary from a few MW to GWs (Zhu and Ma 2019). This is one of the most convenient methods to store renewables for electricity end-use in high capacities. The working mechanism of the pumped-hydro ES system is based on changing the elevation of the water, as shown in Fig. 6 The schematic of a pumped-hydro ES system. In the charging period, the water is pumped to a higher level when the energy source is available or there is excessive power output. The water is kept at that higher level during the storing period. When the energy is needed, the water flows down to drive a generator for power generation. It is possible to reach a full capacity power generation in a few seconds.

The maximum power to be able to generate from a pumped-hydro ES is calculated as

$$\dot{W}_{output,max} = \rho \dot{V} g H \tag{2}$$

Here, ρ denotes the density of the water, $\dot{V}$ is the flowrate of the water, g is the gravity and H represents the elevation between lower and upper reservoirs.

The power of the pump to be used in the system can be calculated as

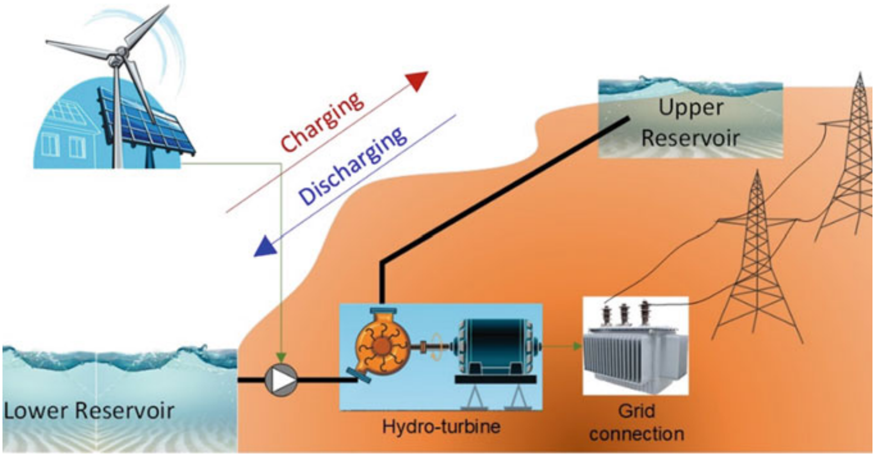

Fig. 6 The schematic of a pumped-hydro ES system

$$\dot{W}_{pump} = \frac{\rho g H \dot{V}}{\eta_{pump}} \quad (3)$$

The net power output from a pumped-hydro ES can be calculated as the following:

$$\dot{W}_{output,net} = \dot{W}_{max} \eta_{turbine} \eta_{generator} \eta_{piping} \quad (4)$$

$\dot{W}_{max}$ is the ideal power capacity of the system, given in Eq. 2. η denotes the efficiency of the system devices.

The overall efficiency of the pumped-hydro ES system can be calculated as the following:

$$\eta_{ove} = \frac{\sum_{t=0}^{t_{disch}} \left[\dot{W}_{output,net} t_{disch} \right]}{\sum_{t=0}^{t_{ch}} \left[\dot{W}_{pump} t_{ch} \right]} \quad (5)$$

The biggest obstacle for the pumped-hydro Es system is to find a location where has an elevation. The biggest obstacle for the pumped-hydro Es system is to find a location where has an elevation. The underground water reservoirs can be used in the location where has flat topography. Figure 7 shows an integrated system using a geothermal reservoir for pumped-hydro ES integrated with a district heating and ORC. The system in the Fig. 7 can be integrated with other renewable energy source such as solar, wind, etc. Thus, the power demand of the pump can be met reduced or ignored.

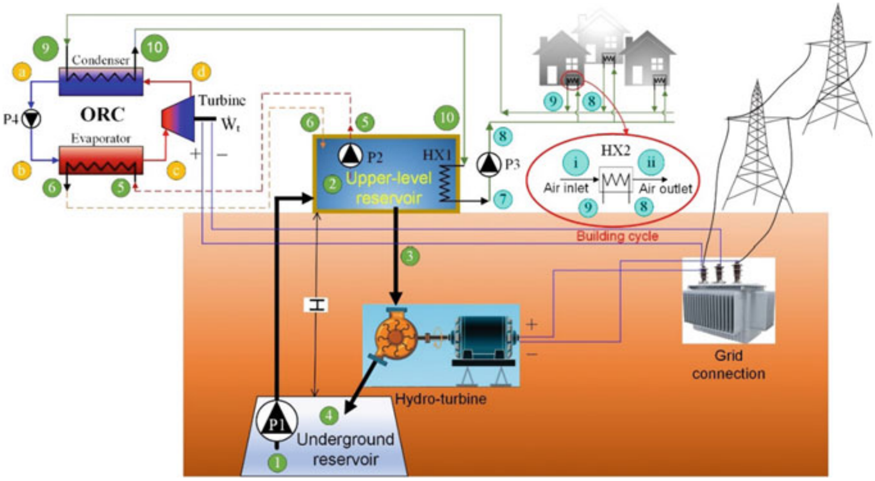

Fig. 7 The system diagram for an underground pumped-hydro ES integrated with a district heating and ORC for power generation. Adapted from Erdemir (2020)

1.4.3 Compressed-Air ES Systems

The working principle of the compressed-air ES is almost the same as the pumped-hydro ES. In the compressed-air ES, the energy is stored with the potential energy of the compression of the gas. In the charging period, the air is compressed into a large cavern, mine or pressured vessels. In the storing period, compressed air is kept until energy is needed. In the discharging period, the stored air expanses in the turbine for power generation. The compressed air can also be used in the air supply in the gas turbine. The compressed-air ES systems can be used for storing renewable energy sources in order to extend their availability or balance their imbalances.

The first compressed-air ES facility which has a 290 MW of the capacity has been built in 1978 at Huntorf in Hamburg, Germany. Air is compressed up to 47.7 kPa in two caverns which have a 283,179 m3 of the volume. The main problem in the compressed-air ES systems is irreversibility in the compressor. When the compressors are driven by renewables, it is possible to store the renewable energy sources in the form of electricity in the high capacity. Additionally, in order to reduce the irreversibility in the compressors, the intercooling should be applied, the heat can be recovered to meet the heating demands of the communities. Therefore, the overall efficiency of the system can be increased.

It is possible to use the submerged balloons as a novel compressed-air ES, has been announced by Hydrostor (n.d.), as shown in Fig. 8. In that system, the air is compressed into the submerged balloons. The biggest advantage of the use of the submerged balloons in the compressed-air ES is to provide isothermal compression as the surrounding water of balloons acts as a heat sink. Additionally, the hydrostatic pressure helps the compression to take place under isobaric conditions.

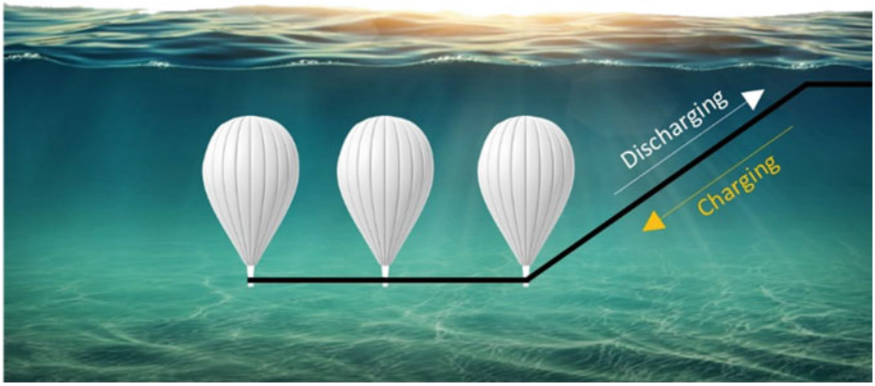

Fig. 8 The compressed-air ES with the submerged balloons

1.5 Thermal Energy Storage

Many studies are ongoing on thermal energy storage systems, which include thermal applications such as heating, cooling, and air conditioning. Many thermal energy storage systems were developed after the increase in the level of living standards and the degree of industrialization of countries. Thermal energy storage is the temporary storage of any energy type as thermal energy in a storage medium for use later. As a result of the change in the internal energy of the thermal energy storage material, energy is stored as sensible thermal energy storage, latent thermal energy storage, and thermochemical energy storage.

The basic working principle is the same in all thermal energy storage types. Firstly, any type of energy is converted into heat energy and then stored in a storage unit. If it has to be kept waiting, it is done so with the least possible loss in the storage unit; and finally, the stored energy is taken from the storage unit and used. These three processes are called energy charging, storing, and energy discharging, respectively.

1.5.1 Sensible Thermal Energy Storage

In sensible thermal energy storing systems, energy is stored by changing the temperature of the storage medium, which are water, air, rock bed, brick, and sand soil, etc. It is based on the change in the temperature of materials. When energy is to be loaded, the temperature of the storage material is changed (increased or decreased), and the temperature is changed LTES in contrast to the change in the loading period in the discharge period (decreased if it was increased in the loading period, increased if it was decreased). The energy loaded and discharged in sensible thermal energy storage systems can be calculated easily with the following basic equation.

$$Q = m \cdot C_p \cdot \Delta T = \rho \cdot C_p \cdot V \cdot \Delta T \tag{6}$$

As seen in this equation, the most important parameter in sensible thermal energy storage is the density and specific heat of the setting. Materials that have a high heat capacity and density must be preferred as storage materials to store more energy in the smallest possible volume.

1.5.2 Latent Thermal Energy Storage

The heat transfer that is needed for materials to change phase is called "latent energy". The latent heat exchange is usually much greater in the matter that has the same volume than the sensible heat exchange. If water is taken as the example here, there is a 16 times difference between the amount of heat energy required to change the temperature of the water at a rate of 5 °C and the heat energy amount when it changes from ice to water (Fig. 9). Usually, Latent Thermal Energy Storage (LTES) is preferred in large-capacity systems because of its great advantage in terms of volume. Since the small storage volume will reduce the surface area of the storage medium, it will also reduce the amount of heat loss from the storage to the environment. The storage material used in LTES systems is called Phase Change Material (PCM). Examples of commonly used PCMs include water/ice, salt solutions, and some polymers. As well as these, eutectic salts may also be used widely as PCM along with paraffin and zeolite. LTES systems are divided into Low-Temperature and High-Temperature LTES systems according to the phase change temperatures of PCMs employed in the system. Also, the systems storing energy in cold form for cooling and air conditioning systems are called "cold thermal energy storage" systems.

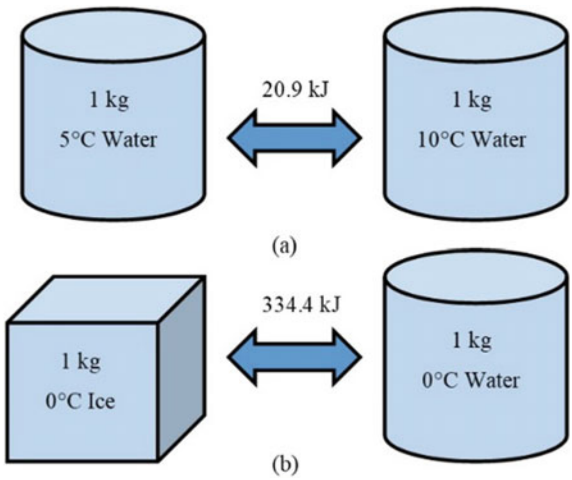

Fig. 9 Heat storage capacity of the water **a** sensible and **b** latent

1.5.3 Chemical Energy Storage

Chemical energy storage is well-known method because it includes many other methods under its name, such batteries, ammonia, LNG etc. The details of this topic will be discussed later. The results of the accomplishments so far shows that the solution for energy storage might be chemical based since it can be stored in small areas and for some of them production potential is unlimited due to its unlimited raw materials, such as ammonia because hydrogen and nitrogen can be found almost everywhere in big amounts.

1.5.4 Thermochemical Energy Storage

Heat energy can be converted into chemical energy and stored for a long time. The principle of thermochemical heat storage is based on the storage of heat in chemical bonds in reversible reactions in two or more chemical compounds, which can react exothermically. The life span of the storage system is unlimited in principle. Since chemical reactions that yield high heat value occur during reversible decomposition and fusion of chemical bonds, the heat storage capacity is usually high.

Systems storing heat with the Thermochemical Method are more complex when compared to Latent Heat Storage Systems. The possible interactions of the components of the system are important. The most important characteristic of the method is that the chosen reaction is reversible. Storage of heat with the thermochemical method can be performed with reversible chemical reactions, chemical heat pumps (absorption heat pumps), and thermochemical heat pipes. The stored heat is recovered exothermically in heat storage with reversible chemical reactions by using an endothermic absorbing reaction. The reaction products that appear at the reaction temperature are stored separately, the heat can be recovered by mixing the products again and by adding catalysts if required. A schematic representation of Thermochemical storage of solar heat using ammonia is given Fig. 10.

1.5.5 Thermal Energy Storage Techniques in Renewables

Thermal Energy storage is one of the fundamental technologies for energy conversion. Therefore, it is very significant in engineering applications. Thermal energy storage is mostly preferred in heating and cooling applications. The history of thermal energy storage is as old as human history. Since ancient history, people have been collecting and storing ice to use later. Nowadays there are many applications of thermal energy storage from solar energy to air conditioning systems.

Many different applications of thermal energy storage have been developed and implemented from past to present. One of the oldest and mature applications in terms of utilizing renewable energy sources as a thermal energy storage application is solar hot water systems. In solar hot water systems, hot water storage tanks are used to carry on to benefit from solar energy at night when the sun is not active. The hot

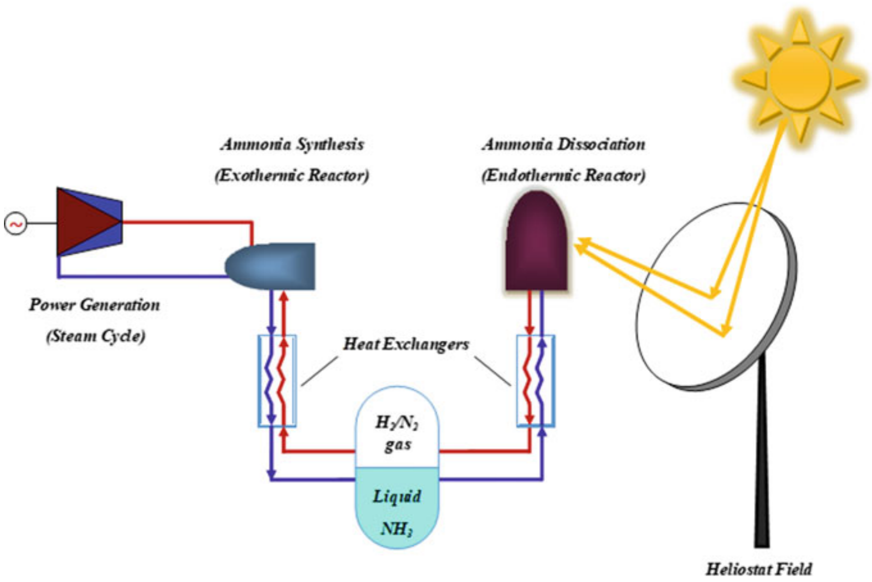

Fig. 10 Thermochemical storage of solar heat using ammonia. Adapted from Lovegrove et al. (2004)

water obtained during the day is kept in hot water tanks to utilize later. Since water has diversity of practical and thermodynamic features, besides its ready availability relative harmlessness and compatibility with a wide accessibility of equipment for its storage and handling, it is commonly used for storage material. Water is generally kept in an insulated storage tank or in small capsules, approximately all of TES systems necessitate heat exchanger to charge and discharge energy. There are many studies in the literature about sensible TES and its solar energy application.

Erdemir and Altuntop (2018) investigated experimentally heating of the indoor sports hall with solar energy as illustrated in Fig. 11. Thermodynamic performance of the sensible thermal energy storage in water filled PET bottles was investigated experimentally in this study for October and November. 5120 pieces 1.5-Lt water filled PET bottles were utilized in thermal energy storage unit in this study. Energy charging and discharging periods were 7:00–17:00 and 17:00–22:00 respectively. Total energy and exergy efficiencies has been found as 79.85% and 51.89% for October and 69.95% and 46.26% for November. As a result of the study, it has been concluded that utilizing water filled PET bottles to storage medium in solar energy heating systems is a convenient method.

The selection of heat storage method is based mainly on the heat storage time, economic feasibility, and operating conditions. Determining a heat storage method, the efficiency, and the economy of a heat storage to be used for any purpose depends on the design of the system. In general terms, the volume that is needed to store heat is reduced if heat storage materials that have large internal energy variations per unit

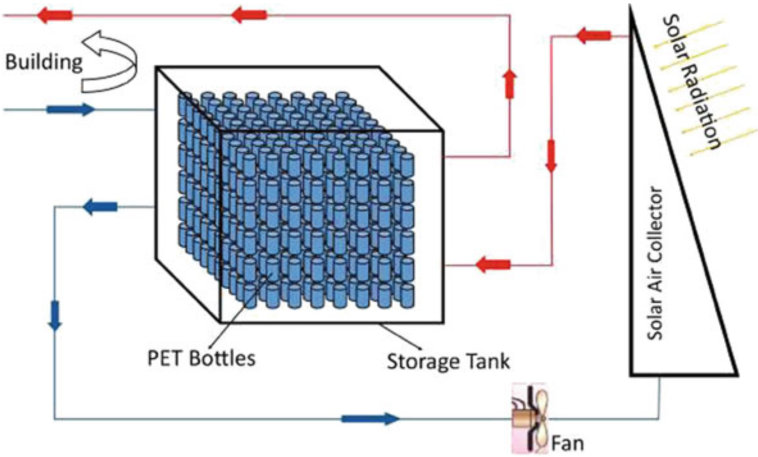

Fig. 11 Schematic view of the sensible TES system which consists water filled PET bottles. Adapted from Erdemir and Altuntop (2018)

volume are used in the design. The characteristics, which must be sought in a heat storage system can be listed as follows;

- The heat storage capacity must be high for the unit mass or unit volume of the heat storage material.
- The heat storage material must have suitable characteristics in the operating temperature range.
- The heat that is stored in the system must be fully recoverable.
- Multiple storages and recovery cycles must be performed without a decrease in heat storage and recovery efficiency.
- The heat storage material must not be corrosive, toxic, and flammable.
- The system must be cheap and have a long-life span.

Thermal energy storage is generally used for heating and cooling to resolve the matching problem between when the energy source is active and when it is required. There are many applications for which thermal energy storage types are used. There are heating and cooling applications in which PCM are used frequently in thermal energy storage systems.

- PCM that have melting and solidification points from temperatures below 0–5 °C are used in cooling.
- PCM that have a melting point between 5 and 15 °C can be used for cold storage.
- PCM that have a melting point that is close to room temperature can be used to keep the temperature of closed areas constant on a daily basis.
- PCM that have a melting point between 20 and 35 °C are used in heating systems along with heat pump systems.
- PCM that have a melting point between 20 and 35 °C can be used as storage materials in solar heating systems.

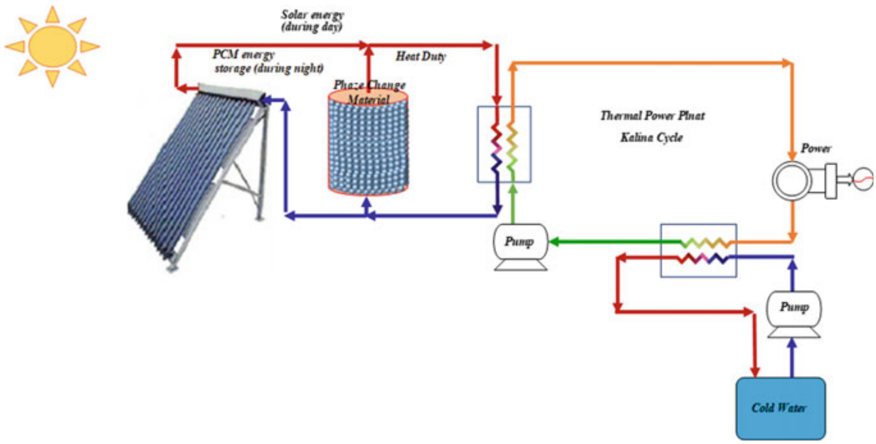

Fig. 12 The schematic of the Kalina cycle integrated with a thermal energy storage system. Adapted from Mehrpooya et al. (2018)

- PCM that have a melting point between 40 and 60 °C can be used as storage material for solar heating systems for day and night usage.
- PCM that have a melting point between 60 and 95 °C can be used in capsules in hot water systems.
- PCM that have a melting point that is higher than 25 °C can be used in heating systems during non-peak hours.
- PCM that have a melting point between 100 and 175 °C can be used as storage material in condensed solar energy systems.

The thermal energy storage systems have been used together with the "Kalina Cycle". Heat energy is converted into mechanical power with Kalina Cycle by making use of the working fluid that consists of at least two different components. The schematic representation of the Kalina Cycle and the thermal energy storage application using PCM are shown in Fig. 12.

1.6 Synthetic Natural Gas

Synthetic natural gas is a version of a natural gas. The difference between them is natural gas gathered from nature itself like wells, but synthetic natural gas produced rather than being gathered (Katla et al. 2020). It serves for the same purposes, such as it can be used in the same devices and stored in the same place. Figure 13 presents how SNG can be produced. First, there has to be a primary energy source like wind turbines then hydrogen can be gathered and combined with other carbon-based gasses, for example biogas. After, the purification there will be a natural gas which can be used inside grid system. This system might work out as a energy storage unit

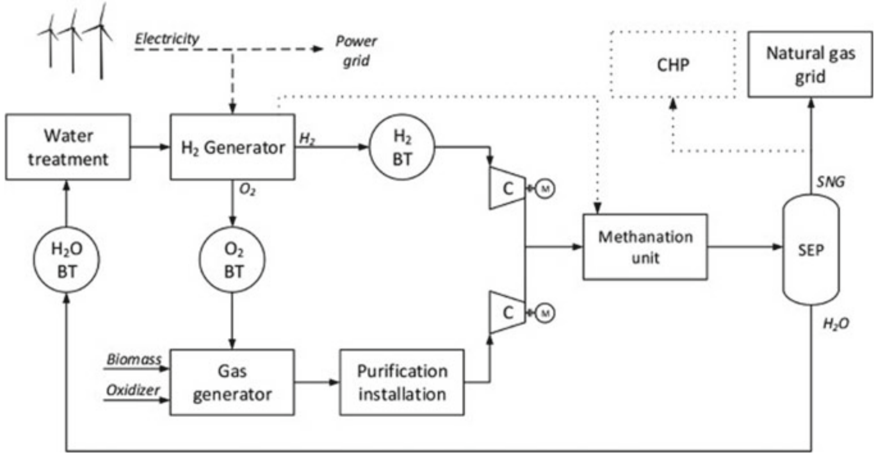

Fig. 13 Synthetic gas production. Adapted from Katla et al. (2020)

if you have extra energy in your system, like wind power at night. On the contrary, SNG does not seem to be used an energy source comparing NG due to economic reasons.

1.7 Hydrogen

World changes every day in many perspectives for lots of reasons. One of things which stays same is increasing energy demand and it pushes governments to consume more and more. It came to a point that plain consumption of fossil fuels cannot be tolerated anymore by livings and world itself. Governments have changed their rotation to cleaner and stable energy resources which can satisfy a country's entire needs. That's where hydrogen comes on the scene. There is no other resource which can replace multipurpose hydrogen. Even though, electric seems to be like its biggest rival, it cannot totally be used for everything, due to economic, transformation losses and storage reasons. This part of the book will look into how hydrogen can be stored and used.

Hydrogen is in gas formation under 24 Co temperature and 1 bar pressure. Most of the time, it is used in gas formation but density of it is really low, so its storage would a disadvantage in that perspective. According to this information, it gets transformed into liquid and pressured gas, but keeping it as a solid is not possible in application yet. There are two ways to make a gas to turn into denser or liquid which are lowering the heat and making the pressure higher. As it is expected, in both ways the energy has to be spent to receive them and to maintain them. Approximately, the energy needs for a kilo of hydrogen to be turned into liquid is 10 KWh/Kg (Berstad et al. 2021). Steel storage units on market cannot contain such a high pressure, so the jacket needs to get thicker to tolerate the high pressure. This creates a big conflict for carrying a clean energy source because the carrying device gets too heavy to bear equal worth of energy comparing others, such as natural gas. This condition pushes us to use more technological solutions, for instance aluminium tank forced with composite fibres which has been displayed at Fig. 14 (Momirlan and Veziroglu 2002). Composite tank with high pressure storage is most common and well-known method so far in the application comparing to low temperature alternatives, since it is harder to keep it at the same condition for long time, it is better to use put it up on to a live system like cities gas lines, so there will be less storage times. On the other hand, Nasa began storing hydrogen for space shuttles long before current applications, and it had the biggest hydrogen storage unit of its time to use on space missions because hydrogen is an excellent choice for energy capacity comparing its alternatives (Sass et al. 2010).

Hydrogen has the biggest potential for next generation urban life Fig. 15 (Department of Energy US 2020). It is potentially cleanest energy source due to its exhaust gas which is water. Moreover, hydrogen is the most common element on earth and reachable energy source for almost on entire world. On the other hand, the biggest problem of hydrogen source is being a secondary energy resource and there will be always a need to have a primary energy source to convert from. Furthermore, each convert has its own efficiency number which adds up to the cost and it makes harder to make hydrogen more commercial, for example to receive hydrogen in the first place there has to be a primary energy source which can be coal, oil, natural gas, solar, wind nuclear, then another effort will be spent to pressurise the gas, so it will take less space. This process approximately goes back the same way when it is needed to be used, which are depressurization then depends on the need it goes through hydrogen fuel cell or it goes for a direct burning process. This process approximately works around 70–80%.

Hydrogen energy cycle has been presented by Prof Dr Turhan Nejat Veziroglu at 1976 for people to understand how a big scale hydrogen cycle can be worked

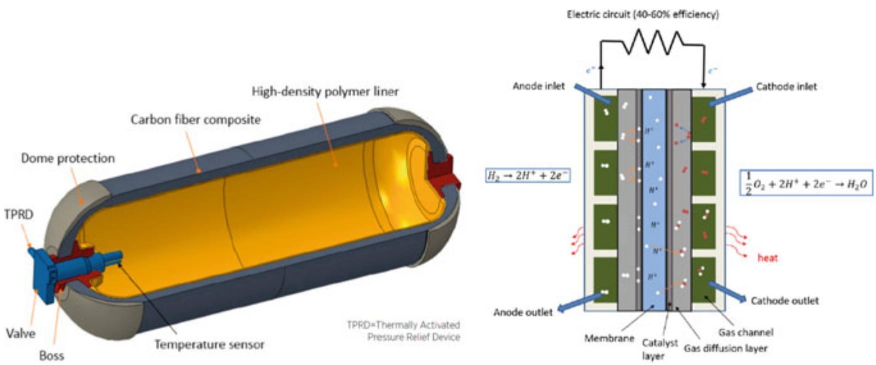

Fig. 14 Figure for composite tank and a fuel cell. Adapted from Ehite (2019) and Rivard et al. (2019)

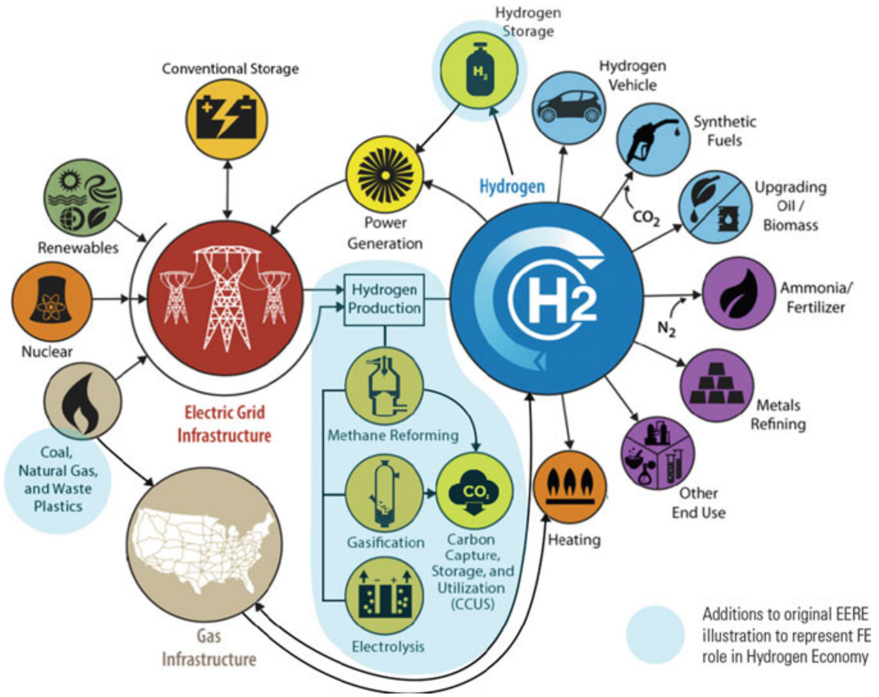

Fig. 15 Hydrogen cycle. Adapted from Department of Energy US (2020)

out and applied our lives Fig. 15. Big hydrogen storages would be essential for this application (Momirlan and Veziroglu 2002).

In the result of all this, hydrogen is a great way of storing energy for big scale and usage. It can be applied for everything in a city which we already currently have directly or indirectly, such as having hydrogen powered burners instead of natural gas, and hydrogen powered cars rather than fuel, electric and LPG, moreover the extra green energy will be saved as hydrogen, so it can be used later. Last but not least, hydrogen has the least pollution between all the other energy sources and even the exhaust of this cycle is valuable for people to use. Even though, hydrogen has been on the table for a while it is still a young technology comparing others and there is room for further improvements. Moreover, developed countries like Germany has accepted its hydrogen law and their path to embarrass this new technology getting decided while these lines are written (Issue et al. 2021). Germany authority has also published a document to announce its strategy about hydrogen (BMWi 2020). At the end, hydrogen is a great energy source for humanity and between big energy crisis and heavy pollutions, it winks at humanity as a possible hero.

Principle of the rule of 5S (Fig. 1) is clearly seen from Fig. 15. Here, the 3S represents, source which gets to be used to obtain hydrogen, system helps energy to be used and gathered H_2 for usage and service means providing H_2 to necessary places to be used, such as electricity, heat, hot water, cooling, fuel, and fresh water,

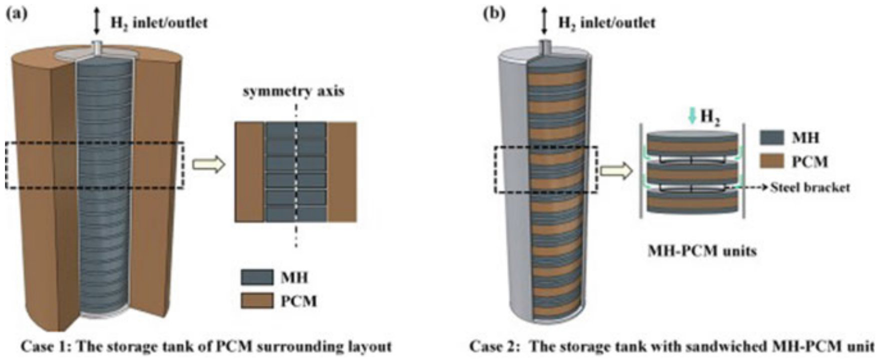

Fig. 16 Metal hydride hydrogen storage. Adapted from Ye et al. (2021)

for their utilizations in various sectors, including industrial, residential, commercial, chemical/petrochemical, agriculture, transportation, and utility. Additionally, the 2S is an important part of this cycle because there are many fluctuations at demand cycle, so to comply production and demand there should 2 storages between these points (Fig. 16).

Hydrogen can be stored in many different ways to be used later and one of the promising technology is metal hydride (Mat and Kaplan 2001). In this technology, there is a connection between hydrogen atom and metal. The positive side of this method is having big mount of hydrogen with a lower energy maintenance and the downside is being so heavy since it is actual full metal tubes. Even though, it is hard to use for mobile units there are places which turns into opportunity for it, for instance electric generators for buildings might be an option.

Nanotube storage is another method which can be used to keep hydrogen with low maintenance. It is a promising technology for big and small scales, but the technology still has place to improve (Das et al. 2021).

1.8 Liquid Natural Gas

Natural gas is a well-known energy resource and commonly used in many countries. Middle east and North are gifted with this natural resource. However, not every geography is blessed with these kinds of natural resources, so they have to be delivered from one location to another continuously which requires an efficient storage system. Unlike, secondary energy resources, natural gas can be gathered from gas wells as a primary energy resource. It naturally contains hydrocarbon and its' primary ingredient is methane. There are also other gasses happen to be seen in the mixtures which are carbon dioxide, nitrogen, hydrogen sulphide or helium.

LNG is quite useful for personal usage and industrial usage. LNG has been used for many reasons, such as heating systems (burners), energy plants (gas turbines) and energy carrier for Hydrogen. Energy capacity per kg for LNG and NG is 53.6 MJ (Dutczak 2018). It is a gas formation under atmosphere pressure and need to pressurized to be liquefied and it is around 1 ATM at -162 Co. This pressure can be contained in steel tubes. Storing of LNG process begins from wells and get carried until where it used or to a transfer point where it can be pressurized which mostly in a harbour. The transfer from well to harbour gets done with pipelines or the specially equipped trucks. The liquefied natural gas gets transferred into big gas carrying ships and goes where it will be needed. In many situations, this liquefied natural gas stored as liquid on the harbour or as a gas on the natural salt mines (Zheng et al. 2020). Even though, the piping investment is big to do, it becomes the cheapest way to transfer natural gas in big amounts. Natural gas also gets stored in the supply stations before it gets used like local natural gas supplier and petrol stations.

LNG is a good energy source in many ways, for instance;

- It is a cleaner than coal and patrol from environmental perspective.
- It has cleaner working environment from the process perspective.
- It is safer than others from safety perspective since it kept inside the metal tubes all the time.
- It is also really flexible to use inside the process because its usage conditions.
- Unlike other resources, natural gas can be stored easily and cheaper.
- It is also a process friendly energy source because it can be easily integrated into automation.
- It can be also used as an energy carrier for hydrogen.
- Even though natural gas can be captured from wells, it can be produced as well (Synthetic Natural Gas).

All these reasons for having LNG are quite enough to have in our lives. Some of the problems of having natural gas are;

- It is not an available natural source at everywhere, so it has to be carried continuously.
- It can be also challenging for strategic perspective to be used.
- It is still not the cleanest energy source.

LNG is a quite a good way to store NG and it can be safely suggested in a point of need.

1.9 Ammonia

Ammonia has nitrogen and hydrogen as an its ingredients with the formula NH3. Ammonia is a colourless gas with a distinctive characteristic of a sharp smell. It is also well-known chemical in many industries, agriculture, chemistry, stone wool production etc.

Ammonia has been used before in ancient Egypt as well as a heating source and its remaining found on the ceilings (Touzeau et al. 2014). It is poisonous to be used in that way because nitrogen burnings which has been known as NOX occurs during the burning and it is harmful for Ozone layer too. Even though, it doesn't get used as a heating source directly anymore, it is still a good way of energy carriage which is Hydrogen. Moreover, Hydrogen can be used to produce electricity and direct burning.

Ammonia is in gas formation under room temperature and atmospheric pressure. On the other hand, it can turn into liquid form at -34 Co and it is not too hard to be maintained, so it gives flexibility of more application on the field (Al-Breiki and Bicer 2020). Batteries give us ability of having remote devices which makes our life really easier and having remote energy stations can allow us to have reach anywhere we want without concerning absence of power supply, as an example phone operators need to cover almost everywhere to be able serve people better, but there is not always available power line to have the power from. Supplying power solar panels and wind don't always cover the energy need of devices, so there should be some energy storage methods, so it can work none-stop. That's where Ammonia appears to be a good solution for this kind of problems because it is easy to be used, and stored, moreover it is accessible, as an example electricity which gets produced from renewable sources put in use to run nitrogen and oxygen generators then when they combined it can keep as an energy reserve inside the system Fig. 17. Furthermore, new electric car trend is coming rapidly, but it is main blockage to make it more common remains as unresolved issue which is charging stations and ammonia might be a good solution for remote charging stations. Ammonia can provide a sustainable future for any off-grid system power need, additionally it doesn't always have to be a business solution, it can be applied for summer houses, mountain houses as well. On the other hand, there are alternative solutions for similar situations, like lithium battery storages, but for same capacity, the initial investment would be huge comparing ammonia.

There is an application has been given at Fig. 18. As it has been presented, there is use of solar panels for an additional power and this power gets used to compress air and forced to cool down to heat a residential area. After, the cooling process it continues to expansion area and leaves other gasses but Nitrogen. On the other side,

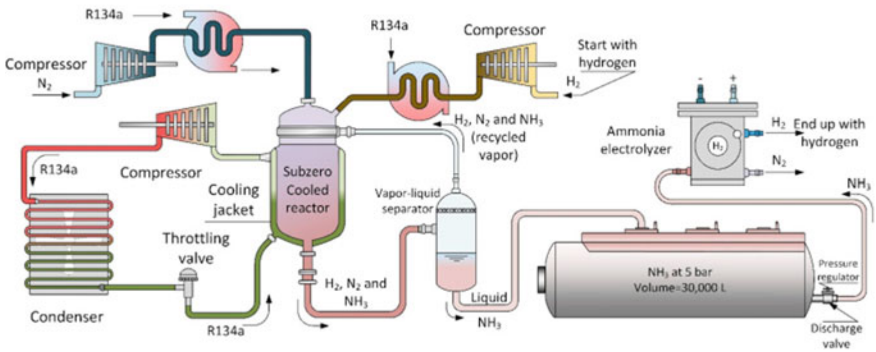

Fig. 17 Ammonia production cycle (Al-Zareer et al. 2019)

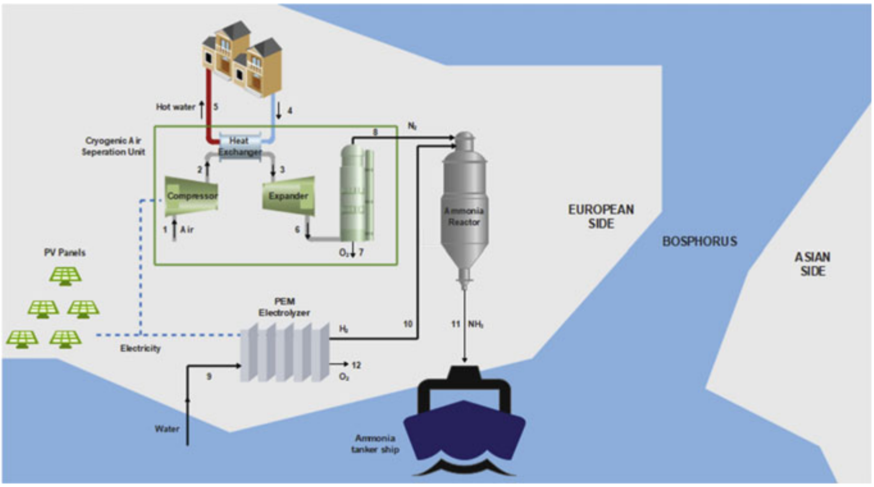

Fig. 18 An example for ammonia production from renewable sources (Ozturk and Dincer 2021)

PEM Electrolyser uses unlimited water from beautiful Bosporus (Istanbul Channel) and separates hydrogen from oxygen. Later on, nitrogen and hydrogen combined at Ammonia reactor and it can used where ever it is needed. That's a good example of a renewable energy cycle, solar power has been used to store energy and in the same time commodities had access to hot water and there is no significant pollution has been detected while it gets done.

1.9.1 Electrochemical Energy Storage

An electrochemical reaction process happens between a solid electrode and substance with electrons. Electron movement triggers electric current and this electron from one element to another known as oxidation–reduction. There are two types of electrochemical cells: galvanic, also Voltaic, and electrolytic. Galvanic reaction happens to be more spontaneous comparing to electrolytic cells. As usual, there are positive and negative for electrochemical batteries as well, being low cost and non-toxic materials are advantages while being non-recyclable, weak leakage (weak acid reaction with zinc), short shelf time, unstable voltage when battery runs down and low power.

Batteries are life changing inventions for human histories, it helps humanity to pass on mobilization faster and easier. It is a clean way of storing energy with high efficiency numbers for long time. Batteries are being used almost any possible point of our lives to make it easier for us, such as mobile phones, electric cars, regular engine vehicles (ignition batteries), lawn mowers, toys, off grid systems, UPS systems, laptops, tablets etc. Their capabilities are undeniable and they have been getting improved by private companies and scientists constantly to overcome some of its difficulties, so they will have a stronger ground in lives.

We have already chemical batteries defeated almost every aspect of our lives because they have high storage efficiency comparing their rivals which is approximately 99%. They don't require big background equipment to support their system which gives advantage of having more power for less volume. There are also various batteries for different usage and needs, for example Pb (Lead), Na, Li batteries. All these battery kinds have different purposes, Pb batteries have been used for cars because it is reliable and cheaper, Li-ion batteries have been chosen phones, laptops, EV because it has a big power for same volume. On the other hand, having chemical batteries are not that innocent, they have some chronological problem which needs to be solved, as a beginning it is a chemical composition with constant reaction going on inside it, so they can get effected from heat, humidity, physical intervention etc. These kinds of inside reactions may end up with explosions and it is a health hazard for people, as an example cell phone explosion may cause serious injuries due to its chemical contains.

There are numerous applications of batteries and there is no need to be talking about all of them since they are already in our lives. On the other side, there are some solutions which we cannot see every day because their application is in big scales and quite new (Rodrigues and Chen 2016). Even though, batteries seem like expensive solution in big scales, it is a quite reliable solution for energy storage. Most of the humanity lives on big continents and it is easier to transfer electricity rather than building another power plant. This line is very true for most cases, but sometimes lines extend so much and there can be energy drops or simply there can be a island which is far enough to send the electric with cables. As a result, power-wall solution comes out as a good solution. Can we have this solution with other storage alternatives? It might be possible, but batteries do not need to be converted so they will not get effected from electric fluctuations and there will be no power down.

1.9.2 Magnetic and Electromagnetic Energy Storage

The concept of activating the magnetic field to store electrical energy can be realized using superconducting magnetic energy storage technology. Schematic diagram of superconducting magnetic energy storage system is given Fig. 19. Without the need for a conversion into mechanical or chemical forms, electrical energy can be stored in a magnetic field in this type storage systems. The superconducting magnetic energy storage may be possible by inducing the DC into superconducting coil cables with zero resistance to current flow. Generally, superconducting coils are made of niobium titanate filaments, exposed to very low temperature (−70 °C). In terms of MW capacity, the total efficiency in commercial applications is very high though there is possibility for higher energy consumption in cooling and the associated resistance losses occurring in solid-state switches when system is operating (Kalaiselvam and Parameshwaran 2014).

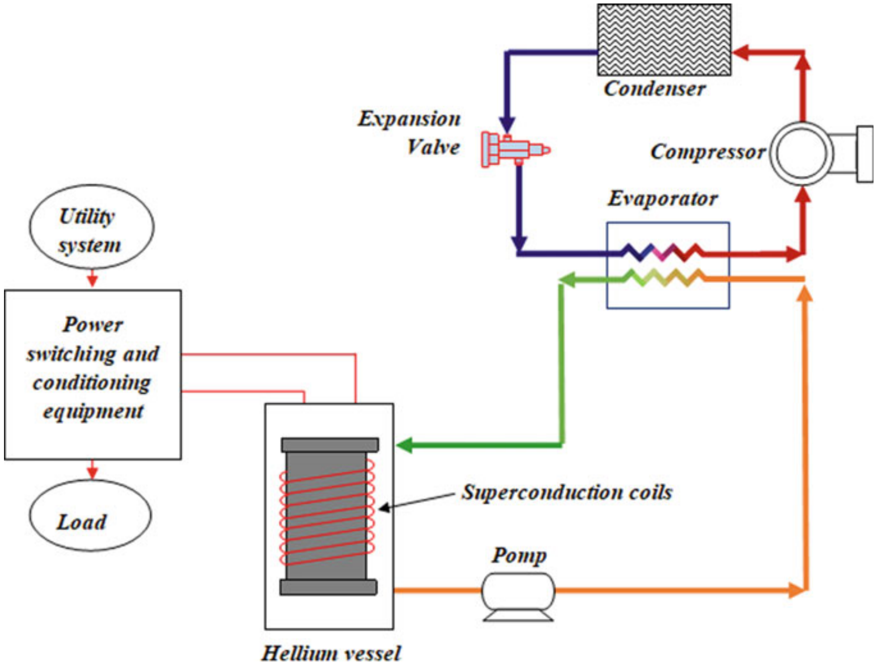

Fig. 19 Schematic diagram of superconducting magnetic energy storage system. Adapted from Kalaiselvam and Parameshwaran (2014) and Lovegrove et al. (2004)

2 Conclusions

This chapter has presented series of energy storage methods and their applications. Since the world's hunger for energy is getting bigger every day, there will be a bigger need of storing it. The applications will depend on what is needed and there will be some obvious choices for that need. Energy density of all the well-known sources have been presented at Fig. 20. Some sources have distinctive characteristics, and it can be observed with a simple observation. Depends on where will be used the choices can make difference, such as non-mobile units and submarines do not mind about the weight, so they can use heavy solutions, on the other hand it makes difference for cars, so there has to be lighter solutions and busses are easier to apply these kinds of solutions because of that. Even though, we have all these methods and applications, there are still room for them to be used more efficiently and effectively. Energy gathered based on consumption of other sources and it has been well-known it is limited. The world will pass on renewable resources eventually and it cannot be done without energy storage and this technology needs to be invested more to catch up the renewable trend.

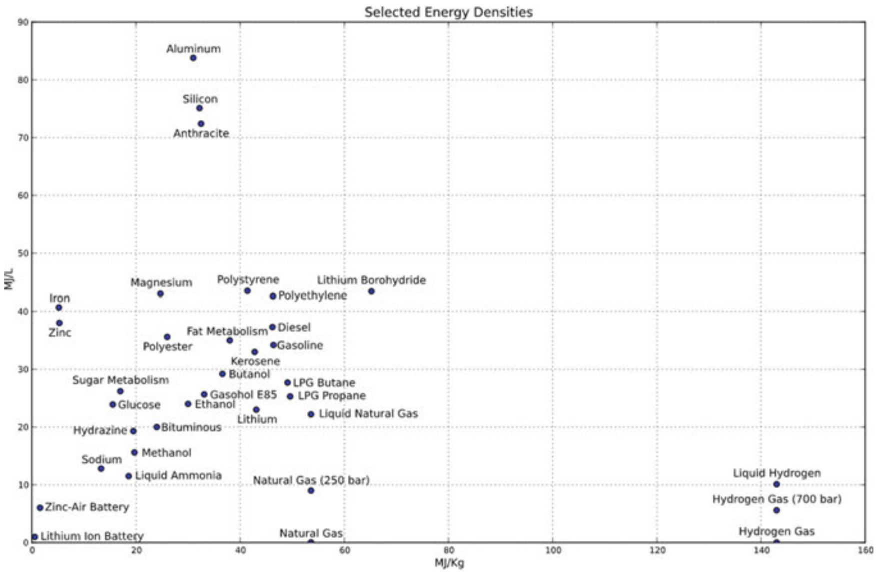

Fig. 20 Energy density of most known energy sources (Dutczak 2018)

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Performance Improving of Low Temperature Geothermal Sources with the Assist of a Solar Pond

Hatice Karakilcik, Ayhan Atiz, Mustafa Erden, and Mehmet Karakilcik

Nomenclature

A	Surface area (m^2)
c	Specific heat capacity (J/kg °C)
E	Energy (MJ)
I	Solar radiation (W/m^2)
$\dot{m}$	Mass flow rate (kg/s)
U	Heat transfer coefficient (W/m^2K)
T	Temperature (°C or K)
$\dot{Q}$	Heat (W)

Greek Symbol

Δ	Difference

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Subscripts

in	Inlet
log	Logarithmic
loss	Thermal losses
out	Outlet
sur	Surface
sys	System
tot	Total
u	Useful
up	Upper
w	Water

Abbreviations

EES	Engineering equation solver
HSZ	Heat storage zone
NCZ	Non-convective zone
UCZ	Upper convective zone

1 Introduction

Due to high demand of thermal energy in the globe, thermal energy is generated from many different sources in today worlds. For example, geothermal sources and solar energy can be good candidates for thermal energy generation. Turkey is one of the countries that have many geothermal sources and solar energy zones (Turkey Geothermal Inventory 1996). Geothermal resources can be used for different purposes. For example, while electricity is produced directly via flash turbine from high temperature geothermal sources, low temperature geothermal sources can be used for space heating namely houses, greenhouses and pools as well as electricity also generation via organic Rankine cycle (ORC) (Atiz et al. 2019; Karakilcik et al. 2019; Yuksel et al. 2020; Atiz et al. 2021a, b). If the ORC is integrated with a solar energy system, electricity production of the ORC can be improved (Hung et al. 2010).

Also, these useful products from the geothermal power-based multigeneration system are primarily power, heat, cooling, hot water, fresh water, heated air for drying, and hydrogen. To generate these outputs, the present multigeneration system consists of six sub-plants, namely the Kalina cycle, hydrogen production subsystem, cooling cycle, drying process, fresh and hot water production plants (Yüksel et al. 2018).

Solar energy is a renewable, clean and unlimited resource. Nowadays, it is realizable to meet the electricity needs with solar technologies such as photovoltaic panels that convert solar radiation into electric energy directly. Furthermore, solar collectors are used to produce thermal energy for many thermal processes. In addition, solar pond is a well known system to harvest and store solar energy (Abdullah et al. 2016). The thermal energy stored in the HSZ of a solar pond can be used for many purposes (Date et al. 2013). There are many studies on thermal energy production from solar radiation via single or multi thermal systems. There are many studies related with solar pond. The temperature a solar pond closely relates with the salt content, solar absorption ratio and the heat loss. The gradient of salty layers and protecting the pond from polluting environmental influences are important factors in that to ensure the stability of the pond (Karakilcik et al. 2006). One of the important factors affecting the amount of stored heat energy in the solar pools is the shading effect. The less the solar pools are affected by the shading, the higher the storage zone temperature (Karakilcik et al. 2013). As the dimensions of the pond increase, the shading effect decreases. Therefore, to design a solar pond with the least shading effect, the pool should be large enough (Bozkurt and Karakilcik 2015a). Solar ponds consist of three separate layers namely upper convective layer (UCZ), non-convective layer (NCZ) and HSZ. Heat energy can be drawn from the NCZ and HSZ layers of the solar pond except UCZ (Khalilian et al. 2018). Thanks to the thermal energy obtained from solar radiation, it is possible to generate a considerable amount of electricity (Ding et al. 2018). The performance of a solar pond increases when it is supported by any kind of solar collectors. For example, it is found that the performance of a solar pond increases when it is supported with a flat plate solar collector (Bozkurt and Karakilcik 2012). In addition, the heat storage performance of a solar pond significantly increases when supported with a solar collector such as evacuated tube solar collectors (ETSCs) (Atiz et al. 2015).

When the literature is examined, there are systems that are integrated with a solar pond and different types of solar collectors. However, there are few studies in which a solar pond and a geothermal source are integrated. Therefore, this study focuses on the thermal energy production performance of a low temperature geothermal source integrated with a solar pond. The proposed system comprises low temperature geothermal sources, a solar pond and a hot water storage tank. The main aim behind the present work is thermal energy production with this integrated system.

2 System Description

As seen in Fig. 1, the unified system includes low temperature geothermal sources, a solar pond, a heat exchanger placed in the HSZ and an insulated hot water storage tank. The general purpose of this system is to produce and store hot water for industrial processes at high flow rates. The system is generally based on raising the temperature of the low temperature geothermal water, which absorbs the heat energy stored in the HSZ as it passes through the heat exchanger placed in the HSZ. Therefore, the heat

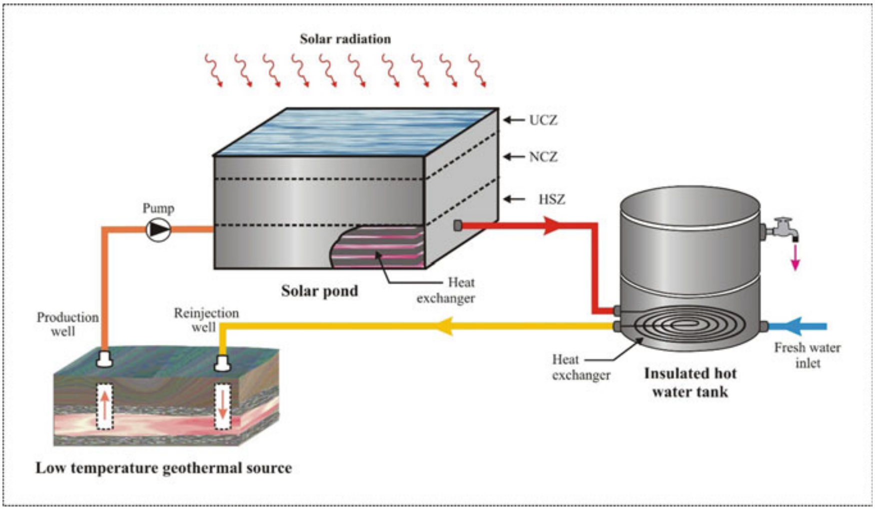

Fig. 1 Schematic of the geothermal-solar system

storage performance of the solar pond plays a key role to determine the performance of all over the system. The dimensions of the solar pond are assumed as 20 m × 20 m × 2.4 m. In this study, three separate geothermal sources, each with a mass flow rate of 0.75 kg/s and outlet temperatures of 40, 50 and 60 °C are assumed to be used. In addition, the temperature of the HSZ is taken as 80 °C.

3 Analysis of the System Components

3.1 Solar Pond

Solar radiation is a clean and renewable source to produce heat energy and electricity. Solar pond is an important application that harvests solar radiation and stores it as heat energy for a certain time in order to produce both electricity and hot water for many industrial processes. As shown in Fig. 1, a solar pond has three water layers as UCZ, NCZ and HSZ. The UCZ layer contains only fresh water and it is necessary to add water from time to time instead of the water that reduces by evaporation. The NCZ consists of several brine layers with increasing salt density from top to bottom to trap the heat energy in the HSZ layer. The HSZ contains the highest salty water, and this is the region where the most heat energy is stored (Atiz and Karakilcik 2018).

3.2 Energy of the Solar Pond

The total solar energy reaching the solar pond can be expressed as follows:

$$\dot{E}_{sp} = IA_{sp} \tag{1}$$

where I is the solar radiation, A_{sp} is the surface area of solar pond. The solar energy is attenuated by the UCZ and NCZ from top to bottom and the remaining part of solar energy is absorbed and stored in the HSZ. Absorbed energy in the HSZ can be found by (Bozkurt and Karakilcik 2015b).

$$\dot{E}_{HSZ} = \dot{E}_{HSZ,in} - \dot{E}_{HSZ,loss} \tag{2}$$

where $\dot{E}_{HSZ,in}$ is the solar energy reaching the HSZ and $\dot{E}_{HSZ,loss}$ is the loss energy from the HSZ.

3.3 Heat Exchanger

Heat exchangers are devices that perform heat transfer between two fluids at different temperatures without intermixing. It is widely used in heating systems, air conditioning systems, chemical processes and power plants. The mixing of fluids during heat exchange usually avoid by a pipe type intermediate surface having good heat conduction (Cengel 2006).

Heat exchanger used in solar ponds is an indirect contact heat exchanger. The heat transfer ratio in a heat exchanger must be known in order to find the amount of heat extracted from the HSZ. So, the heat transfer rate in a heat exchanger is given as:

$$\dot{Q} = UA\left(\Delta T_{log}\right) \tag{3}$$

where U and A are the heat transfer coefficient and the surface area of the heat exchanger, respectively. The logarithmic average temperature difference (ΔT_{log}) is given as:

$$\Delta T_{log} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \tag{4}$$

where ΔT_1 is the temperature difference between the HSZ and input water temperature to the heat exchanger while ΔT_2 is the temperature difference between the HSZ and output water temperature from the heat exchanger. Thus ΔT_1 and ΔT_2 are given as:

$$\Delta T_1 = T_{HSZ} - T_{exc,out} \tag{5}$$

$$\Delta T_2 = T_{HSZ} - T_{exc,in} \tag{6}$$

where T_{HSZ} is the temperature of the HSZ. $T_{exc,in}$ and $T_{exc,out}$ are the input and output water temperatures for the heat exchanger.

Hence the rate of heat energy taken from the HSZ can be expressed as:

$$\dot{Q} = \dot{m}_w c_p \left[T_{exc,out} - T_{exc,in} \right] \tag{7}$$

Since the Eq. 3 and the Eq. 7 are equal to each other, the following form is obtained:

$$UA_{sur} \Delta T_{log} = \dot{m}_w c_p \left[T_{exc,out} - T_{exc,in} \right] \tag{8}$$

Here, c_p is the specific heat of the geothermal water. Although this coefficient varies slightly depending on the temperature, the value calculated according to the average of the inlet and outlet temperatures of the water can be used in the calculations.

4 Results and Discussion

In this chapter, the temperature of the water coming from the geothermal sources, each with an outlet temperature of 40 °C, 50 °C and 60 °C is upgraded by utilizing solar pond that have total aperture area 20 m × 20 m × 2.4 m. The temperature of the HSZ is considered as to be 80 °C. To analyse the systems related with solar energy, it is important to know the amount of solar radiation reaching the system. So, the solar radiation data used in this study are obtained from Adana Meteorology Station.

As seen in Fig. 2, monthly averages of solar energy reaching the horizontal surface and environment temperature for Adana are given. The average energy of solar radiation and environment temperature are taken as 792.66 MJ/m^2, 735.48 MJ/m^2 and 531.89 MJ/m^2 and 28.2 °C, 28.7 °C and 26.1 °C in July, August and September, respectively.

In Fig. 3, the variations of the solar energy reaching the solar pond between the hours of 08^{00}–18^{00} for each of the dates 1th July, 1th August and 1th September are given. For these days, the highest average amounts of solar energy reaching the solar pond are 354.88 kW, 346.76 kW and 323.24 kW, respectively. The total amounts of solar energy reaching the solar pond are found as 10,108.8 MJ, 9716.11 MJ and 8717.47 MJ, respectively.

Figure 4 shows the relationship between depth and corresponding solar energy ratio reaching the layers of the solar pond. The absorption function of the light for the solar pond is obtained from reference (Hull 1980). Significant amount of light energy loss is seen in the first 30 cm from the surface. According to the absorption

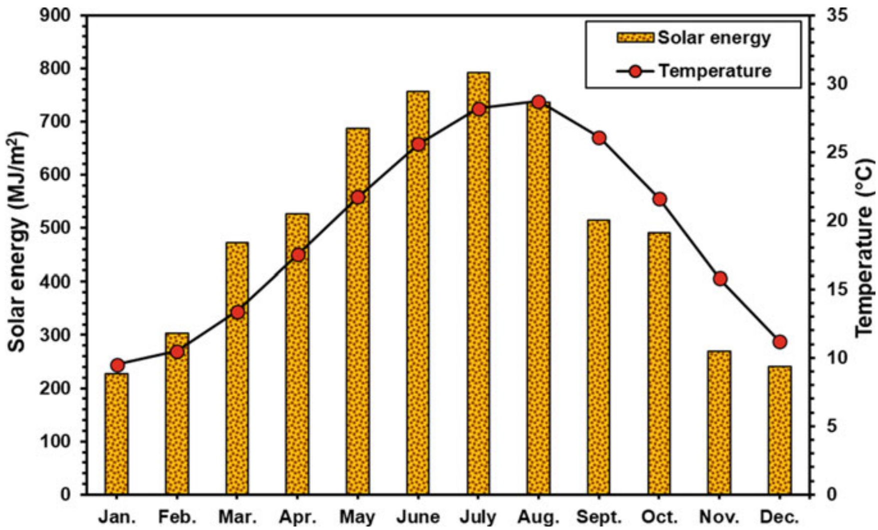

Fig. 2 Monthly averages of solar energy reaching the horizontal surface and environment temperature

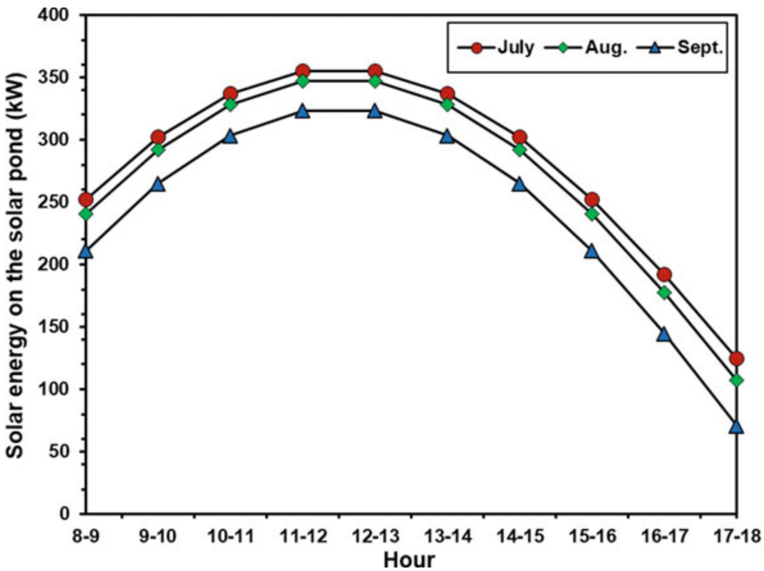

Fig. 3 Daily energy variations of solar radiation on solar pond

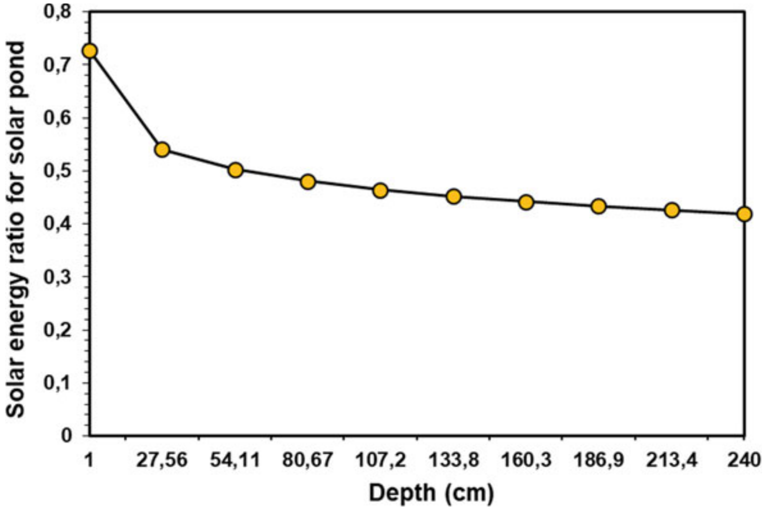

Fig. 4 The relationship between depth and solar energy ratio for the solar pond

function, 44.23% of the light reaches the HSZ. The rest of the light energy is trapped in the UCZ and NCZ.

Figure 5 shows the relationship between depth and density for the solar pond. Since there is no salt in the 20 cm thick UCZ layer at the top of the pool, the salt density is zero. It is clearly seen that the salt density increases throughout the NCZ layer from a depth of 20 cm to a depth of 160 cm. Salt density is constant throughout

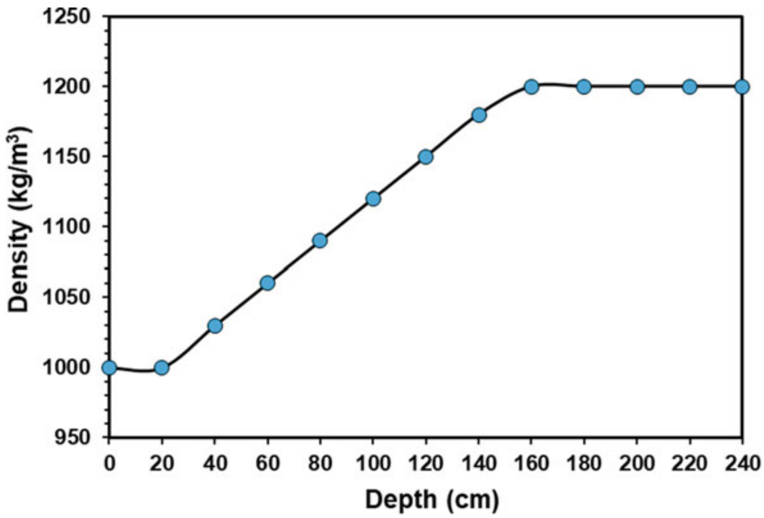

Fig. 5 The relationship between depth and density for the solar pond

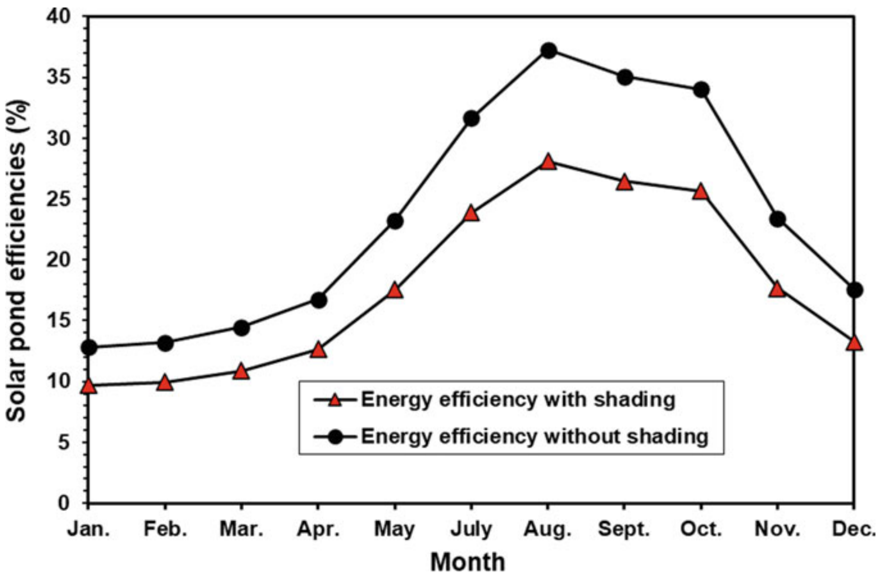

Fig. 6 Energy efficiency of the solar pond with and without shading

the HSZ layer from 160 cm depth to the bottom. The density of HSZ is 1200 kg/m^3 while the density of NCZ varies from 1030 kg/m^3 to 1180 kg/m^3. In order to store solar energy at the bottom of the pond, layers with different salt density are formed.

Shading effect decreases the efficiency of a solar pond. So shaded and unshaded energy yields for a solar pond must be different. Of course, the amount of solar radiation incident on the solar pond also plays a key role on the efficiency of a solar pond. As shown in the Fig. 6 (adapted from reference Karakilcik et al. (2013) the solar pond reaches its highest efficiency in August while it reaches its lowest efficiency in January. Since the solar pond used in this study is very large, it is accepted that the pool is not affected by shading. According to Fig. 6, in July, August and September, the solar pond reaches the highest efficiency values of 31.65%, 37.25% and 35.07%, respectively. Therefore, these three months are preferred in this study.

Outlet temperature of the heat exchanger placed in the solar pond is affected by instant solar energy, environment temperature and also geothermal input fluid temperature. The temperature of the geothermal fluid reaching the heat exchanger is considered as 40 °C, 50 °C and 60 °C, respectively. Figures 7, 8, 9 show the outlet temperature of the heat exchanger from 8 a.m. and 18 p.m. for 1th July, 1th August and 1th September.

As shown in Fig. 7, the instant maximum outlet temperature of the heat exchanger for July were upgraded from 40 to 55.28 °C, from 50 to 65.28 °C and from 60 to 75.28 °C between the hours of 11^{00}–13^{00}, respectively.

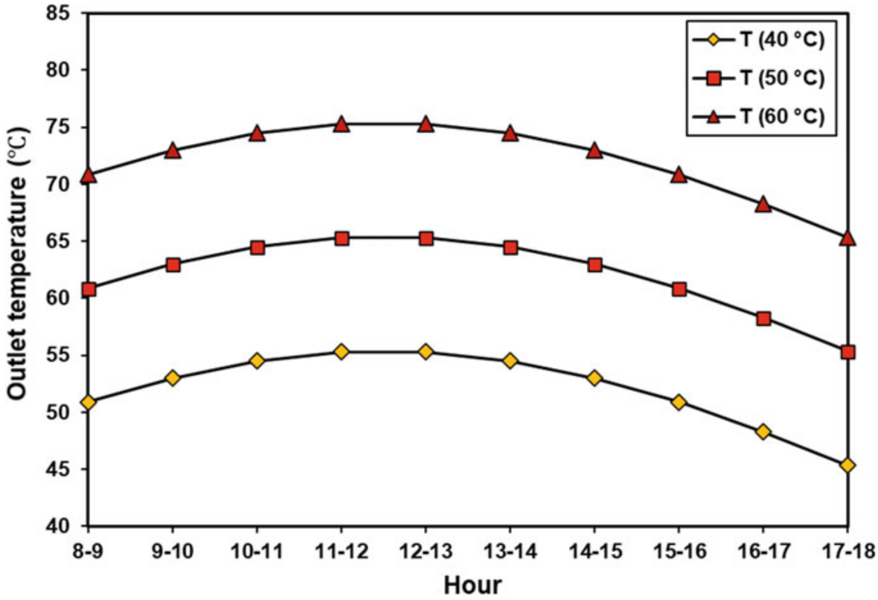

Fig. 7 Outlet temperature of the heat exchanger in 1st July

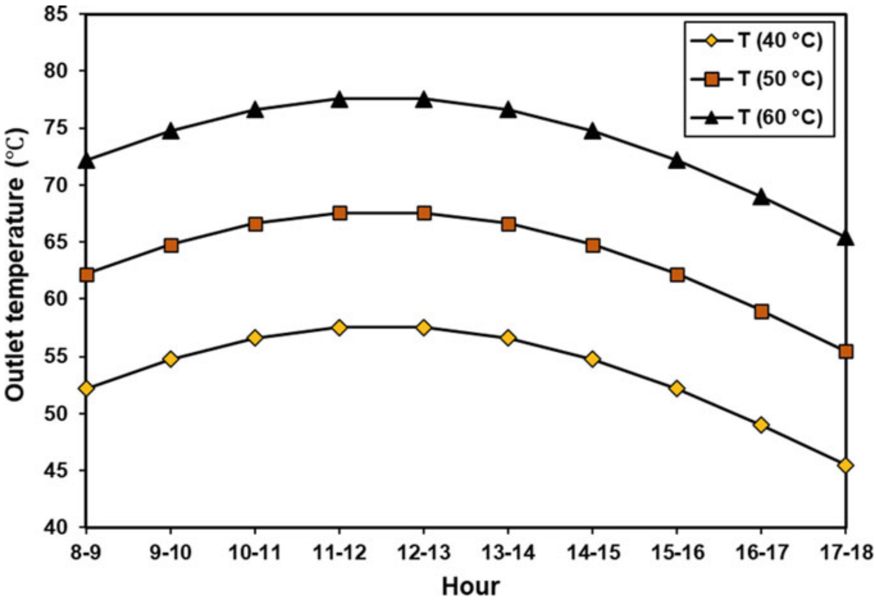

Fig. 8 Outlet temperature of the heat exchanger in 1st August

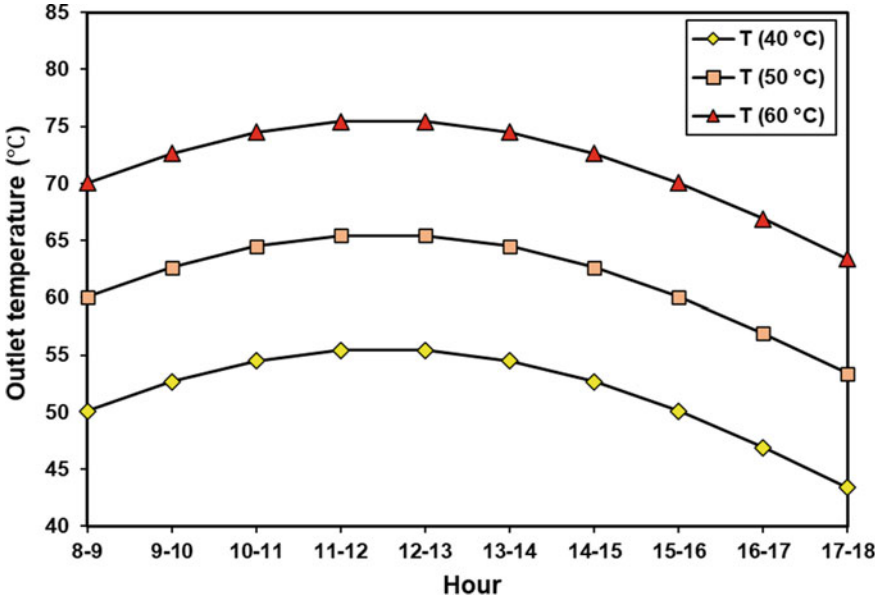

Fig. 9 Outlet temperature of the heat exchanger in 1st September

Figure 8 shows that the instant maximum outlet temperature of the heat exchanger for August increased from 40 to 57.57 °C, from 50 to 67.57 °C and from 60 to 77.57 °C between the hours of 11^{00}–13^{00}, respectively.

As shown in Fig. 9, the instant maximum outlet temperature of the heat exchanger for August were upgraded from 40 to 55.42 °C, from 50 to 65.42 °C and from 60 to 75.42 °C between the hours of 11^{00}–13^{00}, respectively.

The solar energy stored in the HSZ upgrades the temperature of water that coming from geothermal source. As the solar energy varies during daytime, the outlet temperature of the heat exchanger also varies. The highest output temperature is achieved between the hours of 11^{00}–13^{00} h, when the solar radiation is the highest value for 1st August.

5 Conclusions

In this Chapter, the effect of thermal performance of the solar-geothermal system is investigated for thermal energy production and storage. The system consists of a solar pond, three low-grade geothermal resources and storage tank. It is seen that there is a significant increment in the temperature of the low-grade geothermal water via the solar pond that stored solar radiation as thermal energy. Thus, the produced high temperature water is stored in the storage tank. As a result, it is found that the significant amount of thermal energy is produced by solar pond and geothermal sources in this system. Increasing thermal energy production by using solar energy technologies integrated with geothermal resources is extremely important in today's world. If the performance of the integrated system can be progressed much more, thermal energy can also be produced more efficiently. Thus, the produced thermal energy can be used in such systems namely greenhouse heating, electricity generation and industry.

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Thermal Energy Storage Performance Analysis of Different Model Solar Ponds

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Nomenclature

A	Surface area (m^2)
CSP	Cylindrical solar pond
E	Heat energy
F	Absorbed energy fraction at a region of
h	Solar radiation ratio
HSZ	Heat storage zone
$\dot{I}$	Incident solar radiation (W/m^2)
k	Thermal conductivity (J m^{-1} °C^{-1})
L	Width of the RSP
n	Refractive index
NCZ	Non-convection zone
UCZ	Upper convective zone
Q	Heat energy
r	Inner radius of the CSP

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R	Thermal resistance of the side-walls (°C/J)
RSP	Rectangular solar pond
T	Temperature (°C or K)
X	Thickness of inner zones (m)

Greek Symbols

η	Efficiency
Δ	Difference
δ	Thickness where long-wave solar energy is absorbed (m)
θ	Angle (rad)
Δx	Thickness of horizontal layers (mm)

Subscripts

a	Ambient
b	Bottom
dw	Down
in	Input
L	Layer
m	Mean
out	Output
p	Paint-wall
ps	Painted metal sheet for first layer
r	Reflection
s	Sheet-iron thickness (mm)
salt,w	Salty water
sol	Solar
st	Stored
sw	Side wall
p	Paint-wall
ps	Painted metal sheet for first layer
r	Reflection
up	Just above zone
w	Width
wa	From water to air

1 Introduction

Solar energy is the cleanest, cheapest, endless and renewable energy source. There will be no carbon or sulfur released by renewable energy sources to the environment. Today, the importance of the renewable energy sources is increasing day by day (Dincer 1998). Currently, large amount of harmful gases are released as side-effects of using energy sources. This cause in a greenhouse effect on the world, both damaging the atmosphere and causing the world to warm up more. Therefore, the share of world renewable and clean energy sources in energy consumption should be increased. For this, the production and storage of heat energy from solar energy technologies is one of the important issues (Dincer and Rosen 2011).

Thermal energy generation systems that can work with renewable energy sources are systems designed for heating, drying and producing hot water. Some of these systems are solar collectors, solar focusers, drying systems and solar ponds. The most important feature that distinguishes solar ponds from other thermal energy systems is heat storage. Solar ponds not only generate heat but also have the potential to store heat. The most important advantage of these systems is that the energy source is the sun. Solar energy is a renewable, clean, cheap and abundant energy source. System components do not require advanced technology. However, it has some disadvantages. The energy performance of these systems is very low, especially because the solar energy is not continuous and the system technologies cannot be developed at the desired level. Therefore, new scientific research and develop studies are needed.

If the advantages of solar ponds are developed and the disadvantages are diminished, the need for thermal energy can be even met efficiently with semi-daily solar energy. For this, various researches should be done on solar ponds to improve them. In this respect, solar ponds that both produce heat from solar energy and store it for a long time have the potential to stand out.

After the idea of making an artificial solar pond similar to a natural one was first put forward by Kalecsinsky, it was shown for the first time in Israel by Bloch that energy can be stored in an artificial salt gradient solar pond (Tabor 1964). In some later studies, it has been found that the bottom temperature of a lake in Oroville (Washington) reaches 50 °C in summer and the bottom temperature of the Lake Vanda in Antarctica reaches 20 °C. A natural lake near Eilat in Israel, which has existed for 300 years, was found to act as a solar pond and was defined as a solar pond in 1967 (Tabor 1981). The first pioneering work was initiated by Tabor at the National Israel Physics laboratory in the late 1950s. At the same time, Tabor with his colleagues conducted research in several solar ponds. They noted that the bottom temperature at the small lake beds was 103 °C and the collector efficiency was 15%. Laboratory studies have been carried out to understand solar ponds experimentally as well as theoretically (Gar 1985).

A 10 m × 10 m × 2.5 m solar pond was built by Kayalı in 1984 at Cukurova University to heat a greenhouse (Kayalı 1986). In the measurements made by Kurt on this pond, it was seen that the lowest temperature was 28 °C in winter, and the highest temperature was 64 °C in summer (Kurt 1989). Similarly, in the measurements carried out by Karakılçık in 1991, it was observed that the temperature of the storage area was 64 ºC in August and 24 ºC in December (Karakilcik 1991). After that, a new insulated prototype solar pond with dimensions of 2 m × 2 m × 1.5 m was built by Karakilcik at Cukurova University Campus, and since September 1995, a computerized automation system was mounted and temperature distributions were obtained both experimentally and theoretically (Karakilcik 1998).

Kayali et al. developed a theoretical model that can give an indoor and outdoor temperature distribution of a rectangular surface uninsulated solar pond at any time. They used one and two dimensional heat equations derived by the finite difference method for salty water and soil. These simulation equations were solved for local temperature values using software. This modeling was compared with the experimental solar pond temperature profiles. It was observed that the temperature profiles reached in the model are in harmony with the experimental data (Kayali et al. 1998).

Jaefarzadeh described the performance of a salt gradient solar pond at laboratory scale. Comparing with the experimental results, it was seen that the temperature and concentration profiles as a function of depth were in good agreement. But it has been reported that the brine rises from the lower layers to the upper layers with the increase in temperature over time (Jaefarzadeh 2000).

Erosion of the salt gradient zone was investigated using a small experimental solar pond. By observing the heat flow in the heat preservation layer, it was seen that vertical temperature differences play a role in the formation of erosion in the gradient zone (Li et al. 2001).

Bryant-Colbeck's equation has been proposed to estimate the net solar radiation at certain depths in solar ponds (Husain et al. 2004).

A one-dimensional mathematical model is proposed for the stability of the density gradient and the study of salt diffusion in solar ponds, and the finite difference method and the diffusion coefficient depending on temperature and salt density are used to solve the salt diffusion equations. In addition, the effect of the thickness of these layers on the usable energy stored in the storage zone was analyzed. Moreover, the rate of rise of the dense salt water injected into the solar pond was investigated (Angeli and Leonardi 2004).

Ouni et al. successfully operated a closed-loop salt gradient solar pond in the south of Tunisia for one year and then they developed a new model (Ouni et al. 2003).

Considering the effect of temperature on diffusion, a one-dimensional mathematical modeling of the difficulties in developing the salt concentration profile in solar ponds has been developed and examined with the finite difference method. As a result of the solution of the diffusion equations with the finite difference method, it was determined that the temperature affects the molecular diffusion and as a result causes the deterioration of the salt slope. Therefore, it has been suggested to inject dense brine between the storage area of the pond and the non-convection zone in order to ensure the stability of the salt slope (Angeli et al. 2006).

The temperature distribution of an insulated solar pond during daytime and night hours was investigated experimentally and theoretically. When the experimental and theoretical measurements were compared, they were found to be in good agreement.

However, significant temperature differences were detected between daytime and night in the layers of the solar pond. It has been determined that these are caused by sudden decrease in ambient temperature at night (Karakilcik et al. 2006a).

In the experiment conducted in two different small solar ponds under laboratory conditions, it was observed that placing a porous material at the bottom of the gradient zone reduced the distortions that would occur as a result of diffusion (Karim et al. 2011).

The performance and stability of a small solar pond were analyzed experimentally and numerically. Experimental results were shown that the average daily temperature of the pond rises rapidly up to 54 °C in twenty days (Ould Dah et al. 2010).

The efficiencies and temperature distributions of conventional solar pond (SP) and integrated solar pond systems (ISP) were investigated experimentally. Temperature measurements were made at different locations and times in the pond with a data collection system connected to a large number of temperature measurement sensors. It has been confirmed that the heat storage efficiency of the solar pond can be increased by integrating solar collectors (Bozkurt and Karakilcik 2012).

The effect of shading effect on energy efficiency in a small solar pond was investigated experimentally. Hourly temperature measurements were taken and recorded with the data collection device placed horizontally and vertically on the insulated side walls inside the pond. In order to better understand the energy performance of the pond, a shading model was developed and the model results were compared with the cases without shading effect. As a result, it was stated that pond efficiency would decrease with the increase in shaded areas (Karakilcik et al. 2013).

It has been stated that parameters such as transparency, thickness and salt density distribution of the brine layers forming the non-convection zone are important parameters affecting the thermal performance of the solar ponds. The specific heats of the salt layers, which vary depending on the temperature and density, were calculated for different months of the year. According to these parameters, monthly average heat distribution rates stored in the inner parts of the pond were determined (Karakılçık 2016).

The thermal performances of two different solar ponds with some different structural parameters and performance evaluations, such as aboveground and underground were compared with the performance of an experimental solar pond. It has been determined that the performance of the solar pond, which is partially installed in the ground by using appropriate insulation materials, is better than the one installed above the ground (Sogukpinar et al. 2018).

It is seen that experimental studies on solar ponds are still very insufficient. Therefore, scientific studies should be carried out on more advanced and new model solar ponds.

In this study, the energy performances of cylindrical and rectangular model solar ponds are examined. The temperature distributions of the layers of the solar ponds were recorded in order to determine the heat storage performance of the solar ponds. One of the most important motivations for this study is that there has not been enough research on the performance comparison of two different models of solar ponds.

2 The Experimental Solar Ponds

The solar ponds are a combined solar energy system that converts solar radiation reaching the pond surface into heat and can store it for a long time. The most important advantage over solar collectors is that it can store heat for a long time. In this respect, it is an efficient solar energy system. Generally solar ponds are divided into three zones as follows:

The first zone, upper convective zone (UCZ), is the fresh water layer at the top of the pond. This zone fed with fresh water protects the cleanness of the pond, and meet the lost water due to evaporation.

The second (middle) zone, non-convective zone (NCZ), is composed of salty water layers whose brine density gradually increases from top to bottom. NCZ is the key to the working of a solar pond. It allows an extensive amount of solar radiation to penetrate into the storage zone.

The third zone, heat storage zone (HSZ), is composed of salty water with highest density. Considerable part of the solar energy is absorbed and stored by this bottom region. HSZ has the highest temperature, and hence, the strongest thermal interaction occurs between this zone and the insulated bottom-wall (IBW) and insulated side-walls (ISW) surrounding it.

In experimental solar pond studies, amount of solar radiation reaching the pond and temperature distribution through the pond are measured to determine the energy efficiency of solar ponds.

2.1 Solar Radiation Reaching the Solar Pond

In solar pond studies, devices such as pyranometers or solar cells are used to measure the daily amount of solar energy reaching the horizontal surface where the solar pond located. These devices work connected to a computer and the data they collect is recorded. Solar energy measurements are measured and recorded instantaneously or hourly in joules or W/m^2 units. The solar energy measuring system should be located close a place to the solar pond. If this cannot be done, data from the nearest meteorological station can be used. Solar energy data is important for determining the performance of solar ponds.

2.2 The Measurement of the Temperature

The experimental temperature distributions were measured by using temperature sensors which are J type thermocouple. These sensors were placed into the inner zones as well as the inlet and outlet of the heat exchanger. Hence, the temperature distribution profiles of these regions at any time were experimentally measured by a data acquisition system. To measure the temperature distributions of various regions, the temperature sensors were placed into the inner zones, starting from the bottom. The data acquisition system was connected to a computer for data recording, monitoring and processing. The temperatures of the inner layers of the pond, air and inlet–outlet of the heat exchanger were measured on an hourly basis throughout the months.

2.3 The Measurement of the Density

The experimental density distributions were measured by using hydrometer. To measure the density distributions of various layers, the slim hoses were placed into the inner zones. The salty water samples of the layers were withdrawn through siphon and measured by using hydrometer.

3 Experimental Procedure of the Cylindrical Solar Pond (CSP)

In this work, we present an experimental investigation of the energy performance of a cylindrical solar pond (Fig. 1). It is cylindrical solar pond with a radius of 0.80 m and a depth of 2 m. The walls of the pond were plated with the iron-sheets in 5 mm thickness, and in between with a glass-wool of 50 mm thickness as the insulating layer (Karakilcik et al. 2006b).

As seen in Fig. 1, three main zones of the CSP are given as Upper Convective Zone (UCZ), Non-Convective Zone (NCZ) and Heat Storage Zone (HSZ). UCZ is the

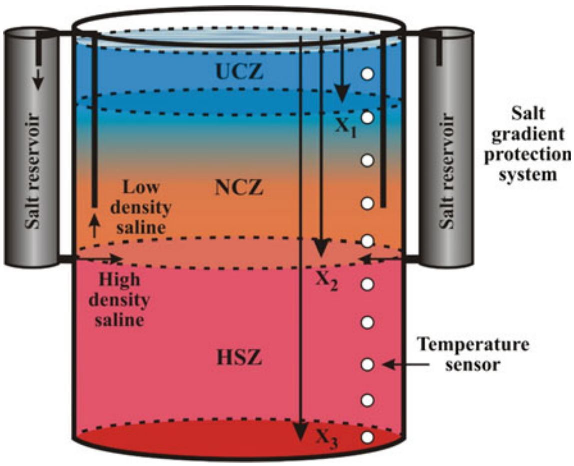

Fig. 1 The cylindrical solar pond (CSP)

fresh water layer at the top of the pond. This zone is fed with fresh water to maintain the cleanliness of the pond and replenish the lost water due to evaporation. NCZ is composed of salty water layers whose brine density gradually increases towards HSZ. The NCZ is an important zone to the working of a solar pond. It allows an extensive amount of solar radiation to penetrate into the storage zone while inhibiting the propagation of long-wave solar radiation from escaping because water is opaque to infrared radiation. HSZ is composed of the highest density. Considerable part of the solar energy is absorbed and stored by this bottom zone.

Figure 1 shows a schematic representation of the cylindrical solar pond. The cylindrical solar pond's inner zones possess different density levels of salty water. The thicknesses of the UCZ, NCZ and HSZ are 0.20, 0.80, 1.00 m, respectively. The temperature measurement sensors were placed at 0.10, 0.30, 0.50, 0.70, 0.90, 1.10, 1.30, 1.50, 1.70, 1.90 m heights.

3.1 The HSZ of the CSP

Firstly, highly density salty water is prepared in a large plastic tanks in order to form HSZ of the solar pond, and then the salty water is rested in the tanks up to a period of time until clarify before filled in HSZ of the CSP. After finish the processing, the salty water is filled by pump through plastic hose up to NCZ. Density of the HSZ is homogenous at beginning. Since this region is the most dense and hottest region, salt molecules tent to move to the less dense environment by diffusion. Salt erosion can begin at the upper surface of the HSZ closest to the NCZ. So, top of the HSZ's density decreases from 1185 to 1165 kg/m^3. However, if the same density of salt water is injected from the outside into the deteriorated point, the deterioration is corrected and the salt gradient can be maintained. As seen in Fig. 1, X_3 is the distance from surface to bottom of the pond.

3.2 The NCZ of the CSP

NCZ is composed of salty water layers whose density gradually decreases from bottom to top. For this, NZC is formed layer by layer from the highest density to the lower one by preparing salt water solutions of different density. Density of layers of the NCZ varies from 1165 to 1030 kg/m^3. As seen in Fig. 1, X_2 is the distance between bottoms of NCZ to the surface of the pond.

3.3 The UCZ of the CSP

Finally, the last zone is fed with fresh water to meet the water lost due to evaporation. As seen in Fig. 1, this zone is called Upper Convective Zone (UCZ) and X_1 is the height of UCZ. The zone can be needed maintenance by time by, because of the environmental dirties. Therefore, the dirty water in this area is siphoned away and replaced with clean water.

4 Experimental Procedure of the Rectangular Solar Pond (RSP)

In this work, an experimental investigation of the energy performance of a solar pond (with a surface area 4 m^2 and a depth of 1.5 m) which was built at Cukurova University in Adana, Turkey is presented. The system was filled with salty water to form three zones (upper convective, non-convective and heat storage) accordingly. A data acquisition device was used to measure and record the hourly temperatures at various locations in the pond (distributed vertically within and at the bottom of the pond, and horizontally and vertically within the insulated side-walls).

Figure 2 shows a schematic representation of the rectangular solar pond (RPS) with the surface area 4 m^2 and a depth of 1.5 m. The side walls of the RSP were plated with the iron-sheets in 5 mm thickness, and insulated with a glass-wool of 50 mm thickness. The solar pond's inner zones possess different density levels of salty water. The thicknesses of the UCZ, NCZ and HSZ are 0.1, 0.6, 0.8 m, respectively. Two salt gradient protection systems are placed on the side walls of the RSP, facing each other (Karakilcik 1998).

In order to see the temperature variations during daytime and night 16 temperature sensors were placed at the different locations in the pond. Hence the temperature distribution profiles of these locations at any time were experimentally obtained. The temperature sensors were placed starting from the bottom at 0.05, 0.30, 0.55,

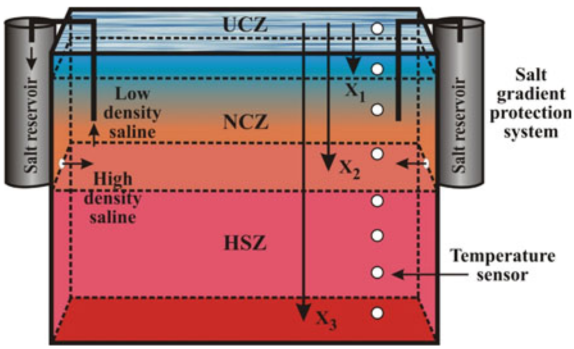

Fig. 2 Rectangular solar pond (RSP)

0.70, 0.80, 1.05, 1.35, 1.50 m heights. The data acquisition system was connected to a computer for data recording, monitoring and processing. The inner and wall temperatures of the pond were measured hourly during day and night times. The sensors consisted of 1N4148 semi-conductor devices with coaxial cables in different lengths between 17 and 20 m with a measurement accuracy of ± 0.1 °C in the temperature range of 0 °C to 120 °C (Karakilcik et al. 2006a; Bozkurt 2012).

4.1 The HSZ of the RSP

Firstly, highly density salty water is prepared in the plastic tanks in order to form HSZ of the solar pond, and then the salty water is rested in the tanks up to a period of time until clarify before filled in HSZ of the RSP. After that the prepared salty water is filled up to NCZ. High amount of solar energy is absorbed and stored in the HSZ. Density of the HSZ is homogenous at beginning. Since this region is the densest and hottest region among another layers, salt molecules are tent to transverse to the less dense environments by diffusion. However, if the same density of salt water is injected into the deteriorated point, the deterioration is corrected and the salt gradient can be maintained.

4.2 The NCZ of the RSP

The second zone is NCZ between HSZ and UCZ. It is composed of salty water layers whose brine density gradually decreases from bottom to top. Density of the layers in this zone decreases from 1165 to 1030 kg/m^3.

4.3 The UCZ of the RSP

Finally, the last zone (UCZ) is fed with fresh water to meet the water lost due to evaporation. The density of the UCZ varies between 1000 to 1030 kg/m^3.

5 Energy Analysis of the CSP and RSP

The determination of stored heat energy is generally complicated due to some conditions e.g., pond dimensions, brine density, insulation, thicknesses of the zones, shading area effect, heat transmission and absorption characteristics for the layers. To calculate the stored heat energy in CSP, the temperature distribution of the zones should be measured. The temperature variations of layers depend on incident solar radiation reaching the horizontal surface, rates of absorption by the layers, local climate conditions, pond structure, time, and insulation specifications. Some of the solar radiation incident on the solar pond is absorbed by the UCZ and NCZ layers, and the rest reaches the HSZ. So, the temperature of HSZ is increased and a temperature gradient develops in the zone.

5.1 Energy Balance Equation of the CSP

The stored thermal energy in the heat storage zone of the CSP can be written as:

$$\Delta E_{\mathrm{st,HSZ}} = E_{\mathrm{in}} - E_{\mathrm{out}} = E_{\mathrm{sol,HSZ}} - \left(E_{\mathrm{up}} + E_{\mathrm{dw}} + E_{\mathrm{sw}}\right) \tag{1}$$

where $E_{sol,HSZ}$ is the total solar energy reaching the pond surface, E_{up} is the heat loss from HSZ to NCZ. E_{dw} is the total heat loss to the down wall from HSZ, E_{sw} is the total heat loss to the side wall of HSZ.

The energy efficiency for heat storage zone (HSZ) of the CSP is given as (Bozkurt et al. 2014):

$$\eta_{\mathrm{HSZ,CSP}} = \frac{\Delta E_{\mathrm{st,HSZ}}}{E_{\mathrm{in,HSZ}}} = 1 - \frac{E_{\mathrm{up}} + E_{\mathrm{dw}} + E_{\mathrm{sw}}}{E_{\mathrm{sol,HSZ}}} \tag{2}$$

$$E_{up} = \frac{k_{salt,w}A}{\Delta x_L}\left(T_{m,HSZ} - T_{m,NCZ}\right) \tag{3}$$

$$E_{dw} = \frac{k_{dw}A}{\Delta x_{dw}}(T_b - T_a) \tag{4}$$

$$E_{sw} = \frac{k_{sw}2\pi L_{HSZ}}{ln\left[\frac{r_{out}}{r_{in}}\right]}\left(T_{m,HSZ} - T_a\right) \tag{5}$$

$$E_{sol,HSZ} = \beta \dot{I}_{CSP}A[(1-F)h(X_{HSZ} - \delta)] \tag{6}$$

where $k_{salt,w}$ is thermal conductivity of the salty water, A is the surface area of HSZ. Δx_L is the thickness of between HSZ and NCZ's middle point. $T_{m,HSZ}$ and $T_{m,NCZ}$ are the mean temperature of HSZ and NCZ, k_{dw} and k_{sw} are the thermal conductivity of the down and side wall, Δx_{dw} and r_{in} and r_{out} are the inner and outer radius of side wall of the CSP, respectively. T_b and T_a are the temperature of bottom and air temperature, respectively. L_{HSZ} is the thickness of HSZ, $\dot{I}_{CSP}$ is the solar energy reaching the horizontal surface (W/m^2) of the CSP, A is the surface area of the pond (2.0096 m^2), F is the absorbed energy fraction at a region of δ-thickness and h is the solar radiation ratio function.

The relationship between incident angle and refraction angle obeys the Snell's law, where $sin\theta_i = nsin\theta_r$. For air–water interface, $n = 1.33$. On the other hand, the transmission coefficient for air–water interface, is calculated from $\beta = 1 - \mathrm{R}$ where R representing reflectance, which is depending on the incident angle of sunlight and it varies slightly with radiation wavelength, time of the day, water temperature and salinity (Ding et al. 2016). For unpolarized light, as given by Fresnel's equation as $R = 0.5\left[\frac{sin\theta_i - sin\theta_r}{sin\theta_i + sin\theta_r}\right]^2 - 0.5\left[\frac{tan\theta_i - tan\theta_r}{tan\theta_i + tan\theta_r}\right]^2$. The angle of incidence of sunlight varies significantly with the location from which it reaches the surface.

To approximate the solar energy absorbed in the storage zone, the water absorption function, $[h(X_{HSZ} - \delta)]$ of sunlight and the transmittance coefficient (β) are used. Also β is the fraction of the incident solar radiation that enters the pond, and is written using an expression

$$\beta = 1 - 0.5\left[\frac{sin\theta_i - sin\theta_r}{sin\theta_i + sin\theta_r}\right]^2 - 0.5\left[\frac{tan\theta_i - tan\theta_r}{tan\theta_i + tan\theta_r}\right]^2 \tag{7}$$

where θ_i and θ_r are the angles of incidence and refraction.

The ratio of the solar energy reaching bottom of the pond (X_3) is given by Bryant and Colbeck (1977) as:

$$h = 0.727 - 0.056ln\left[\frac{(X_{HSZ} - \delta)}{cos\theta_r}\right] \tag{8}$$

5.2 Energy Balance Equation of the RSP

The stored thermal energy in the heat storage zone of the RSP can be written as:

$$\Delta Q_{\mathrm{st,HSZ}} = Q_{\mathrm{in}} - Q_{\mathrm{out}} = Q_{\mathrm{sol,HSZ}} - \left(Q_{\mathrm{up}} + Q_{\mathrm{dw}} + Q_{\mathrm{sw}}\right) \tag{9}$$

where $Q_{sol,HSZ}$ is the total solar energy reaching the pond surface, Q_{up} is the heat loss from HSZ to NCZ, Q_{dw} is the total heat loss to the down wall from HSZ and Q_{sw} is the total heat loss to the side wall of HSZ (Bozkurt 2012).

The energy efficiency for heat storage zone (HSZ) is given as;

$$\eta_{\mathrm{HSZ,RSP}} = \frac{\Delta Q_{\mathrm{st,HSZ}}}{Q_{\mathrm{in,HSZ}}} = 1 - \frac{Q_{\mathrm{up}} + Q_{\mathrm{dw}} + Q_{\mathrm{sw}}}{Q_{\mathrm{sol,\ HSZ}}} \tag{10}$$

$$Q_{up} = \frac{kA}{\Delta X_{HSZ}}(T_{HSZ} - T_{NCZ}) \tag{11}$$

$$Q_{dw} = AR_{ps}(T_{HSZ} - T_b) \quad (12)$$

where ΔX_{HSZ} is the thickness of the HSZ of the pond is given as;

$$\Delta X_{\text{HSZ}} = (X_3 - X_2) \quad (13)$$

$$Q_{sw} = A_{ps,HSZ}R_{ps}\left(T_{HSZ} - T_{sw,HSZ}\right) \quad (14)$$

where $A_{ps,sw}$ is the surface area of the painted metal sheet on the side walls surrounding of HSZ.

R_{ps} is the thermal resistance of the painted metal sheet surrounding the first layer is given as;

$$R_{ps} = \frac{k_p k_s}{S_p k_s + S_s k_p} \quad (15)$$

where k_p and k_s are thermal conductivities of the paint and iron-sheet, and S_p and S_s are the corresponding thicknesses.

$$Q_{solar,HSZ} = \beta \dot{I}_{RSP} A[(1 - F)h(X_{HSZ} - \delta)] \quad (16)$$

where β is the fraction of the incident solar radiation that enters the pond which is given at the Eq. 7. $\dot{I}_{RSP}$ is the solar energy reaching the horizontal surface (W/m^2) of the RSP, F is the fraction of the incident solar radiation absorbed by the pond's upper layer. A is the net surface area of the HSZ and h is the solar radiation ratio function which is given at the Eq. 8.

6 Results and Discussion

In Fig. 3, the annual distributions of the monthly total solar radiation reaching the horizontal surface area and the surface area of the CSP are given. Depending on the surface area of the CSP, the rate of solar radiation reaching inner regions varies. This affects the temperature distribution, the amount of heat stored of the CSP and its performance. As seen in Fig. 3, the solar radiation reaching the horizontal surface area is the lowest in January with 218.48 MJ/m^2 and the highest in July with 705.26 MJ/m^2. The surface area of the cylindrical solar pond (CSP) is 2.0096 m^2. The radiation reaching the UCZ was calculated as to be the lowest of 439.06 MJ in January and the highest of 1417.3 MJ in July. Some of the solar radiation is reflected from the surface of the UCZ and the rest is refracted in the salty water layers and some of it is absorbed by the layers depending on the depth, and also some of it reaches the

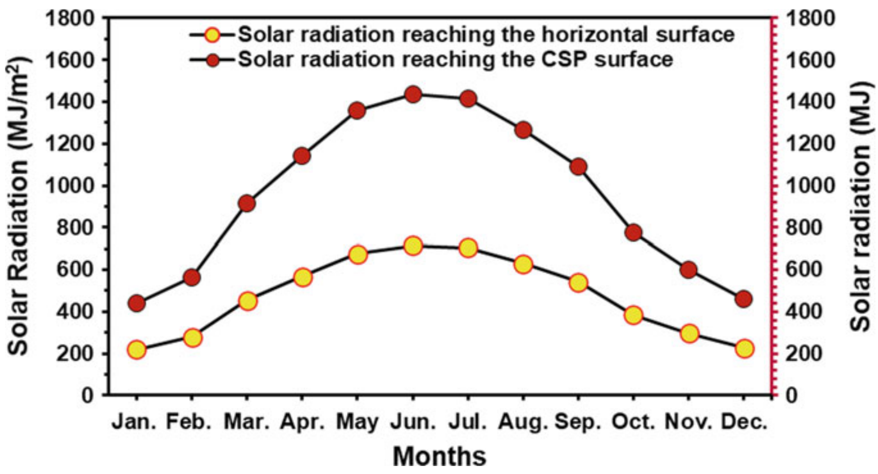

Fig. 3 The monthly total global solar radiation in Adana, Turkey (Adana Meteorology Regional Offices 2010) and reaching the CSP surface

HSZ. Almost all of the rays entering the HSZ are absorbed here and stored in the form of heat. However, the net solar energy reaching on the heat storage zone (HSZ) is reduced due to the sidewall shading of the CSP. Therefore, in the design of the solar pond, its dimensions and geometry should be designed by considering the side wall shading effect. In order to reduce the side wall shading effect, solar ponds with inclined side walls should be preferred. The less the shading effect, the more solar energy the inner areas of the pond will benefit from and its performance will increase.

In Fig. 4, the annual distribution of the total solar radiation reaching the unit surface area (1 m^2) and the surface of the experimental solar pond (4 m^2) by months is given. The solar radiation reaching the inner regions of the RSP is bigger than CSP. This positively affects the temperature distribution and performance of the RSP. As seen in Fig. 4, solar radiation coming to the horizontal surface area is the lowest in January with 146.75 MJ/m^2, while it is at the highest value with 752 MJ/m^2 in July.

In Fig. 5, it can be seen that the salt gradient in the NCZ occurred sometime after the CSP started to work. However, the density difference between the layers at 90–110 cm is large. The flow direction of salt diffusion between these two salt water layers is from the lower layer (90 cm) with higher density to the upper layer (110 cm) with lower density. This is a natural process for solar ponds. With the help of the salt gradient protection system, the layers are protected by the injection of more than 90 cm of dense salt water. Thanks to this process, the salt gradient is very easily controlled. The region from the base up to 90 cm upwards is a very dense salt water region. This region is the heat storage region. The density of this region decreased slightly from 1190 kg/m^3 to 1181 kg/m^3 in 4 months due to salt diffusion. Because from February to April, the salt density increased with the increase in temperature in the HSZ. It was observed that this deterioration in the density distribution was corrected by the injection of very intense saline into the HSZ. The inclined region

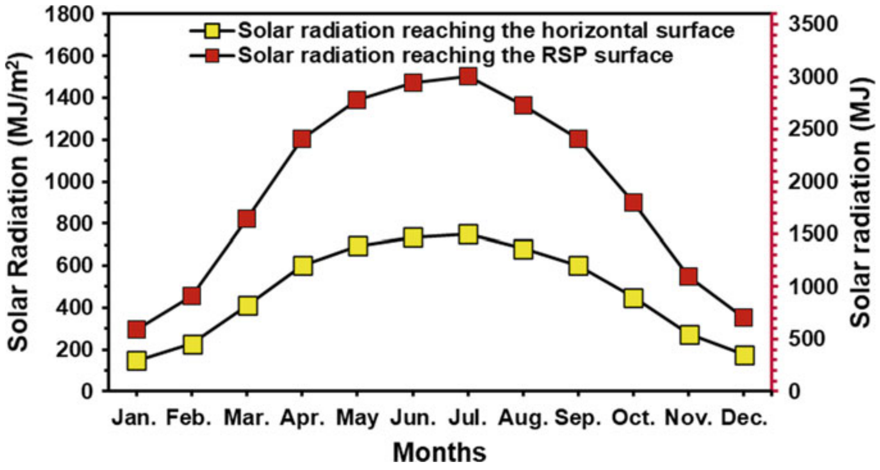

Fig. 4 The solar radiation reached on the horizontal surface and the RSP

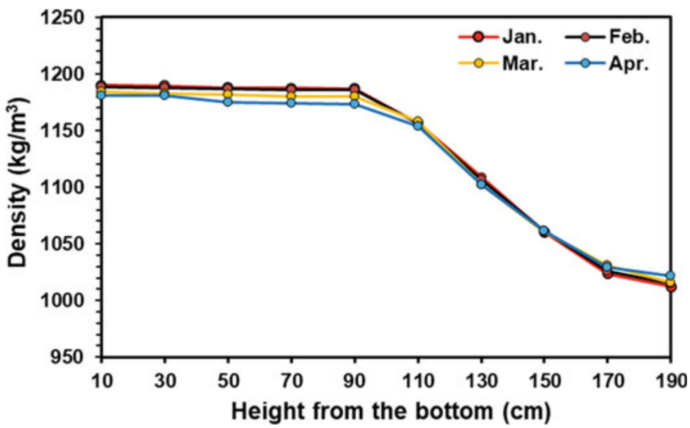

Fig. 5 Density distributions of the CSP from January to April

between 110 and 170 cm is NCZ. While the density distribution of the layers forming the gradient was 1156.5 in February and 1023 kg/m^3 in April, it was measured as the highest 1154 kg/m^3 and the lowest 1029 kg/m^3 in April. The difference between the highest and lowest densities in the 4 months from February to April is negligible. Despite the increasing salt diffusion with the increase in temperature, the salt gradient is preserved thanks to the protection system.

In Fig. 6, the density distributions of the CSP from May to August are presented. Despite the increase in temperature in the HSZ, it was observed that the salt diffusion losses recovered very quickly from May to August and the layers were repaired. As seen in Fig. 6, the density of HSZ was kept between 1186 and 1172 kg/m^3 from the

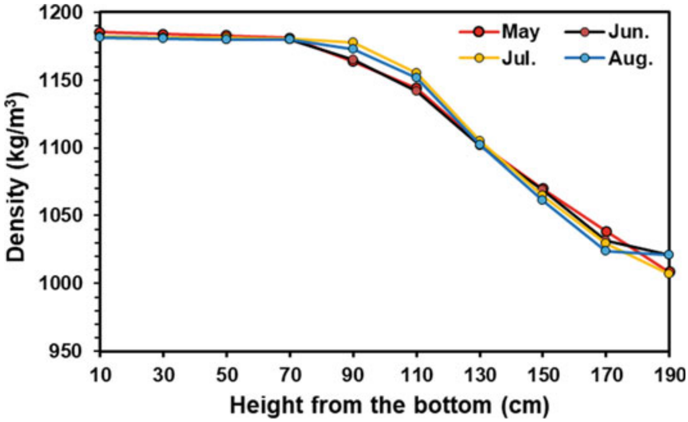

Fig. 6 Density distributions of the CSP from May to August

base of the HSZ to the 70 cm. Thus, the densities in the 90 and 110 cm layers, where salt diffusion is most effective, were kept between 1164 and 1151 kg/m^3, and the deterioration in these plates was partially prevented. Density distributions between 110 and 170 cm show a decreasing linear variation between 1144 and 1024 kg/m^3. It has been observed that the density of UCZ increased to 1021 kg/m^3 with the upward salt diffusion at the base during the period from May to August.

As seen in Fig. 7, the density distributions between 10 and 90 cm change between 1182 and 1170 kg/m^3 in September and 1187–1183 kg/m^3 in December, despite the saline injection during the period from September to December. With the high salt diffusion in September, the salt density distributions improved up to 90 cm and became almost homogeneous. Density distributions in UCZ vary between 1011 and 1019 kg/m^3. NCZ is the most important region that affects the heat storage

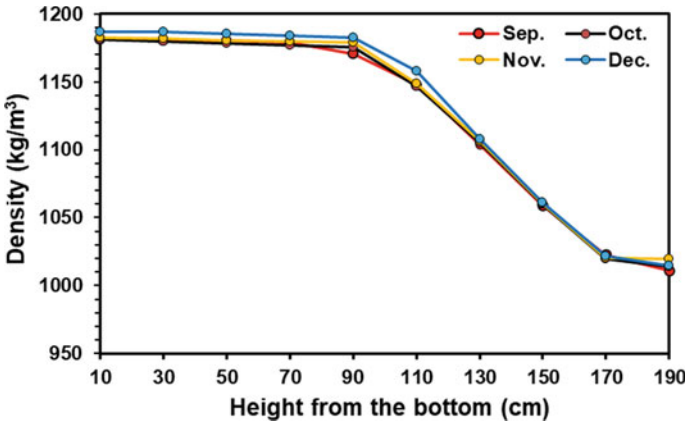

Fig. 7 Density distributions of the CSP from September to December

performance of HSZ. The deterioration of the salt gradient in the NCZ means the deterioration of the temperature gradient. It is the most important region that prevents the transfer of heat upwards by convection and acts as a thermal insulation region.

Figure 8 shows the salt concentration distribution of the interior regions of the RSP (HSZ, NCZ, and UCZ) from January to April. With the increase in temperature in the HSZ from January to April, the density distribution start to deteriorate from the upper part. It was observed that the density from the base to the top decrease from 1200 kg/m^3 to 1172 kg/m^3. This is due to salt diffusion from its upper part to the NCZ with the temperature increase in the HSZ. At the same time, a salt gradient was observed in the NCZ, the region between 80 and 135 cm. Although the salt gradient was preserved, the most salt diffusion density difference occurred in the layers adjacent to the HSZ, where the density is highest, and the NCZ, where the density is lower (at 70–80 cm). This is the region where the most salt diffusion takes place from the very salty layer to the less salty layer. The salt gradient zone is a non-convection zone, prevents heat loss by convection and acts as a thermal insulation zone. The densities of the salt gradient regions in the NCZ decreased linearly from 1134 kg/m^3 to 1029 kg/m^3 in January-April, forming a smooth gradient. No significant deterioration was observed in this sloping region. There was salt diffusion from the NCZ to the UCZ and the density of the UCZ slightly increased.

Figure 9 shows the salt concentration distribution of the interior regions of the RSP (HSZ, NCZ and UCZ) from May to August. It has been observed that with the increase in the amount of heat stored in the HSZ since May, its temperature has also increased. While the temperature of HSZ increased, the density distribution of HSZ decreased from 1193 kg/m^3 to 1159 kg/m^3. The most salt diffusion was detected between the adjacent layers (70–80 cm) of the HSZ and NCZ, where the difference in temperature and density was the highest. The densities of the salt gradient areas in the NCZ are in the form of a smooth gradient, decreases linearly from 1112 kg/m^3 to 1032 kg/m^3 in May–August. No significant deterioration was observed here. The densitiy of UCZ

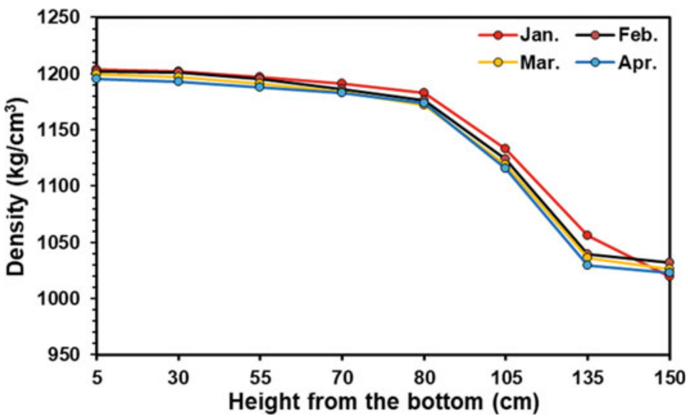

Fig. 8 Density distributions of the RSP from January to April

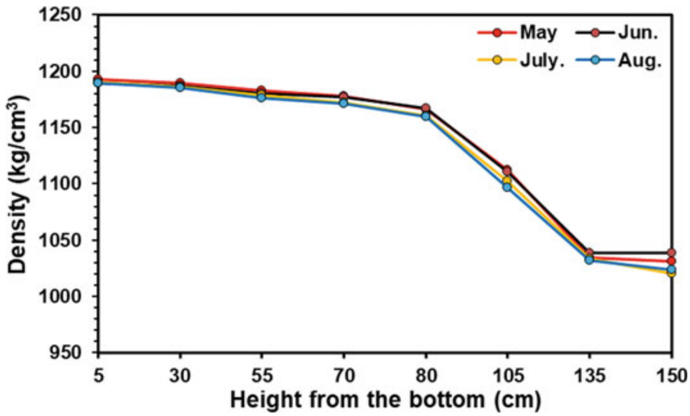

Fig. 9 Density distributions of the RSP from May to August

increased from 1031 kg/m^3 to 1039 kg/m^3 from May to June. Although the slightly salty water is replaced with fresh water, its density still increases to 1020 kg/m^3 in July and 1023 kg/m^3 in August. That is, there has been some salt diffusion from NCZ to UCZ.

Figure 10 shows the salt concentration distribution of the inner regions of the RSP from September to December. The density distribution of HSZ is between 1191 kg/m^3 and 1173 kg/m^3. This is because of salt diffusion from the upper part of the HSZ to the NCZ could not be adequately prevented during the summer months. However, it is seen that the salt gradient of the NCZ between 80 and 135 cm is not disturbed. The most salt diffusion occurred between 70 and 80 cm between adjacent layers of HSZ and NCZ, where the density difference is highest. It was determined that a rapid salt diffusion occurred with the increase in temperature from the very salty layer to

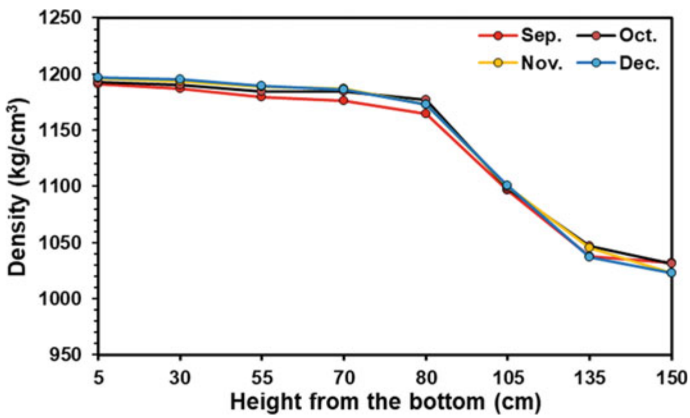

Fig. 10 Density distributions of the RSP from September to December

the less salty layer. The density distributions of the salt-gradient layers in the NCZ decrease linearly from 1112 kg/m^3 to 1032 kg/m^3 from September to December, and no significant deterioration in the salt gradient was observed. The densitiy of UCZ increased from 1031 kg/m^3 to 1039 kg/m^3 from May to June. Although the slightly salty water is replaced with fresh water, its density still increases to 1020 kg/m^3 in July and 1023 kg/m^3 in August. In other words, there was some density increase with salt diffusion from NCZ to UCZ. However, it has been preserved thanks to the salt gradient protection system connected to the NCZ. Along with the seasonal decrease in ambient temperature from September to December, the temperature decrease of HSZ also reduces salt diffusion. In addition, with the help of the protection system, the density distribution of the inner regions has started to improve again.

In Fig. 11, the temperature distributions of the inner regions of the CSP (UCZ, NCZ and HSZ) by month are given. The temperatures in the interior regions of the CSP, which started to store heat in January, were 10, 12 and 16 ºC in January, respectively, and reached a maximum value of 30, 40 and 42 ºC in August. With the seasonal decrease in the ambient temperature starting from September to December, the temperature of the inner parts of the pond also started to decrease. In December, it dropped to 14, 16 and 20 ºC, respectively. The region where the sun's rays are first absorbed is the UCZ. While the temperature of the UCZ increases a lot during the daytime, it comes back to thermal equilibrium with the environment at night. However, the temperature distribution and heat storage capability of the NCZ, which is located just below that, is better since there is no direct contact with the environment. In the heat storage region (HSZ) below the NCZ, its temperature is higher than that of the NCZ as it starts to store heat increasingly since January and reached its maximum value in August.

In Fig. 12, the temperature distributions of the inner regions of the RSP by months

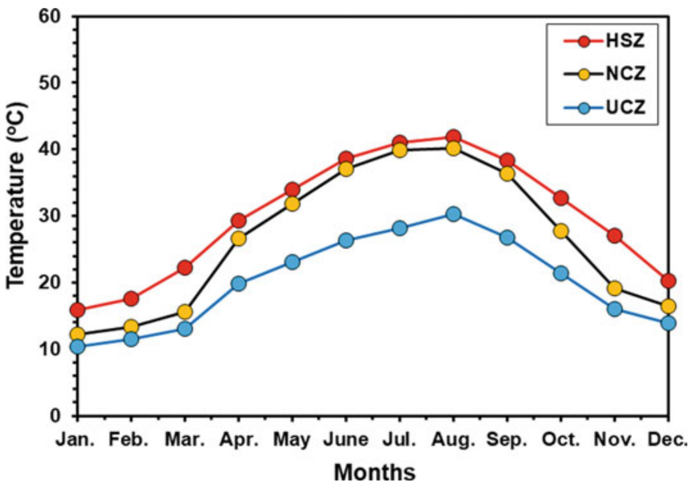

Fig. 11 Temperature distributions inner zones of the CSP

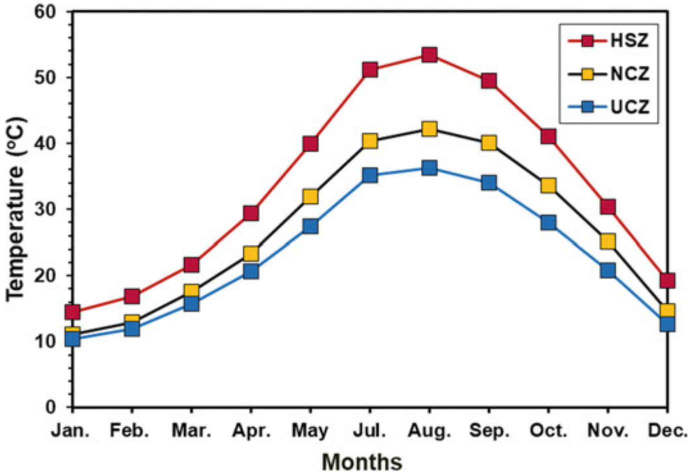

Fig. 12 Temperature distributions inner zones of the RSP (Karakilcik et al. 2006a)

are given. However, temperature distribution measurements could not be made in June. The temperature of the interior regions of the RSP (UCZ, NCZ and HSZ), which started to store heat in January, was the lowest with 10, 11 and 15 ℃ in January, and the highest with 36, 42 and 54 ℃ in August. The temperature of the inner parts of the pond began to drop with the the ambient temperature has decreased seasonally since September. In December, it dropped to 13, 15 and 19 ℃, respectively. It has been observed that the temperature of the layers has also increased with the increasing environmental temperature and increasing solar radiation since March.

As shown in Figs. 13 and 14, the energy efficiency of two different model solar ponds (CSP and RSP) was compared. The yields of CSP and RSP in January were

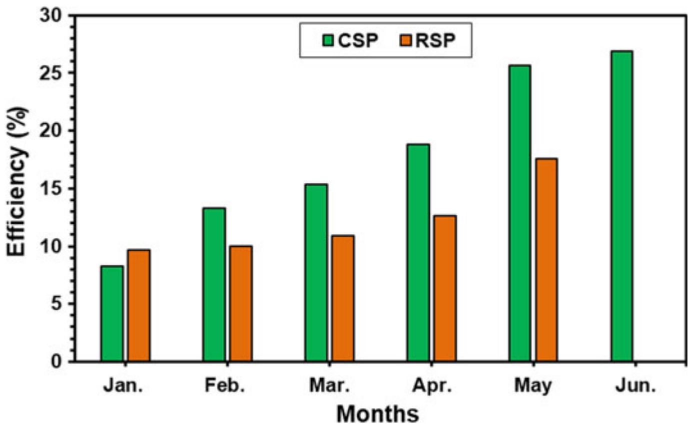

Fig. 13 Energy efficiency of the CSP and RSP from January to June

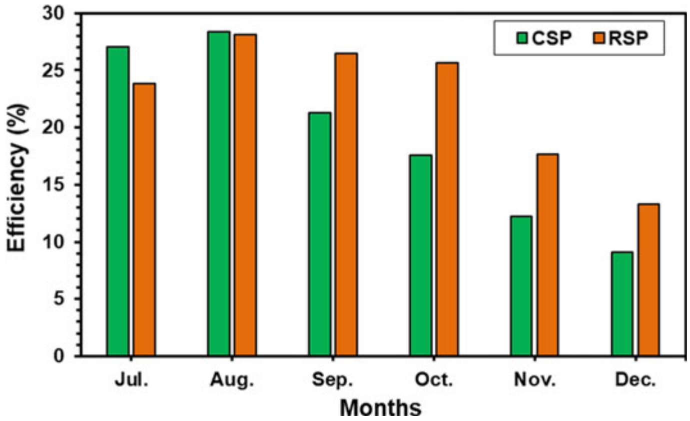

Fig. 14 Energy efficiency of the CSP and RSP from July to December

calculated as 8.27% and 9.68%, respectively. From February to July, CSP was found to be more efficiently than RSP. The yields of CSP and RSP in July were 27.07% and 23.88%, respectively. The highest efficiecy was obtained in August as 28.41% and 28.11%, respectively. In August, the energy efficiency of RSP and CSP was found to be equal. From September to December, the efficiency of CSP decreased compared to RSP. The efficiecies were found to be 21.26% and 26.47% respectively in September and 9.09% and 13.28% in December. It has been concluded that intensive changes in the dimensions and inner regions structions of the solar ponds are effective on the energy efficiency.

7 Conclusion

In this Chapter, the performance of two different model solar ponds (CSP and RSP) was investigated. It has been determined that the inner parts of the ponds of different sizes show similarities in terms of density and temperature distribution. In both ponds, an increase in the amount of stored heat was observed from June to August. With the increase in stored heat, the brine flow from the HSZ to the NCZ accelerates as the temperature rises. This cause more distortions between the layers where the density and temperature difference were large. In other words, it caused more distortions between the layers where the density and temperature difference were large. It has been observed that salt diffusion is more especially in summer months (June–August). In both CSP and RSP, it has been determined that the salt density deteriorates are easily repaired with the salt slope protection system. With the preservation of the salt slope, it has been observed that the heat in the heat storage area can be stored longer in the winter months. The method used to protect the salt slope has been successfully applied in both ponds. RSP received more solar energy because it has a larger surface area and volume than CSP. CSP is 40 cm deeper and the heat insulation zone is 20 cm thicker. Sidewall insulation is double compared to RSP. Thanks to this feature, it worked more efficiently from February to July. However, RSP, whose efficiency started to increase from September, performed better until December. It has been determined that the low shading area of the RSP is one of the important factors that increase its performance. For these reasons, it is necessary to design solar ponds well and to use quality insulation materials.

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Operation Adjustment of a Cold Thermal Energy Storage

Andrew Lake, Behanz Rezaie, and Nader Javani

Nomenclature

DE	District energy
GHGs	Greenhouse gasses
TES	Thermal energy storage
UI	University of Idaho
A	Cross sectional area (m^2)
α	Thermal Diffusivity (m^2/s)
β	Volumetric coefficient of thermal expansion (1/K)
Bi	Biot Number
C	Specific heat of a fluid (kJ/kg-K)
D_i	Diameter of tank
Δ	Delta, difference between initial and final values
δ	Wall thickness
E	Thermal capacity
E_{max}	Maximum thermal capacity
η	Efficiency
Fo	Fourier Number
g	Gravity

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Gr	Grashof Number
h	Specific enthalpy (kJ/kg)
H	Height of the tank (m)
h_o	Convective value (W/m^2-K)
k	Conductivity (W/m-K)
kw	Conductivity of the wall (W/m-K)
L	Length (m)
$\dot{m}$	Mass flow rate (kg/s)
μ	Viscosity (kg/m-s)
P	Pressure (kPa)
Pe	Peclet Number
Pr	Prandtl Number
Ψ	Specific exergy (kJ/kg)
$\dot{Q}$	Heat transfer rate (kW)
ρ	Density
Re	Reynolds Number
Ri	Richardson Number
s	Specific entropy (kJ/kg-K)
T	Temperature (°C or K)
t	Time (s)
T_{max}	Maximum return temperature (°C or K)
TES	Thermal Energy Storage
V	Velocity (m/s)
$X^{\cdot}$	Exergy rate (KJ/kg)
Z	Height (m)
η	Efficiency

Subscripts

0	Reference Property
b	Boundary
C	Charging
cw	Chilled water
D	Discharging
en	Energy
f	Flow
int	Internal
Q	Heat transfer
sys	System
w	Work
x	Exergy

1 Introduction

In order to establish a sustainable energy system for providing energy needs, the environmental impacts should be minimized (Dincer and Rosen 1999). Thermodynamic laws state that reversible processes are required for a sustainable system and minimizing energy waste. Due to current outcomes of energy resources usage and catastrophic impacts on global warming, it is going to be a collective decision among policymakers, industry sections, and all interrelated sectors to exploit energy resources in a completely sustainable manner. In the latest world leaders' summit, COP26, stark messages such as "digging our own graves" were announced which show what a critical stage is currently the current is waiting for humanity (https://news.un.org/en/news/topic/climate-change). Due to the intermittency of renewable energy systems and the importance of employing carbon-free energy resources, different energy storage technologies have been developed in recent years. Technically, without the energy storage approach, renewable energy resources would have a very small penetration through the energy grids. Once the producers can assure that, their produced energy will not impose a grid instability and can be stored safely and securely for later use, they will be more motivated in this regard. To give an example, we can consider Germany as a leading country in the renewable energy section, since the electric grid is not strong enough to handle such a high load and cannot afford electric energy transmission from the North to the Southern regions of the country. This, in turn, leads to renewable energy curtailment. The same rationality is prevalent in neighbouring countries. Therefore, there is an inescapable need for feasible energy storage technologies (Deign 2020).

When it comes to energy consumption for countries with a high need for heating or cooling needs, the importance of tackling the peak load period becomes more pronounced. Countries in hot climates are mostly employing fossil fuel-based energy resources to meet the required energy for cooling. It is worth mentioning that the emitted carbon will cause more warming effects globally in a way that the current cooling systems will cost more than what they are doing now. This can be seen in the recent tries to limit the temperature increase by 1.5°, although realistic scenarios prove that this increase will be more than 2.5° if the current policies and trends continue. This also shows the importance of cold energy storage in limiting the carbon footprint.

Energy storage can be classified as Thermal energy storage, Electrical energy storage, Chemical energy storage, and Mechanical energy storage systems. Mechanical energy storages which consist of pumped hydro energy storage (PHES), Compressed air energy storage (CAES) and Flywheel energy storage are more dominant, which returns to the prevalent pumped hydro energy storage with more than 90% of all energy storage in the globe (Irany et al. 2019). Since this technology needs specific conditions, such as having access to water resources and uneven regions to have enough potential energy, other types of energy storage such as thermal energy storage are also of interest. The advantage of thermal energy storage systems, to be employed Furthermore; there is waste thermal energy in various industrial sections, which can be harvested.

An alternative to the conventional energy systems is District Energy (DE) systems in which biomass fuels or other renewable energy resources can be employed to decrease greenhouse gasses (GHGs) emissions (Nijjar et al. 2009). Another approach to mitigate the GHGs emission is to improve the efficiency of conventional heating and cooling systems by replacing them with district energy plants (Rezaie and Rosen 2012). Lake et al. (2017) reviewed district energy systems and their future projections and trends including environmental considerations and their shift away from fossil fuels to provide sustainable energy resources.

Thermal energy storage in the form of sensible energy storage is an acceptable methodology with a variety of applications ranging from small-scale residential buildings (Pomianowski et al. 2020) to sensible molten salt energy storage for solar tower power plant applications in high temperatures (Shaikh et al. 2018). There are three main thermal energy storage methods including sensible, latent and thermo-chemical TES systems. Thermal Energy Storage (TES), therefore, is a practical and more accessible method for energy storage purposes. In district Energy systems, TES systems provide an effective way to compensate for the mismatch issue between supply and demand by storing the extra energy as sensible or latent heat formats for later use. For example, in a sensible TES, the medium can be water. The main reasons for this selection are the abundance, non-toxicity, and having a higher thermal capacity and availability in a rather high range of temperatures compared to many other materials, or rock beds. Liquid water is commonly used for the sensible system. Cold energy storage systems can be used integrated with different power cycles such as carbon dioxide Brayton cycle, and thermal storage in low temperatures. For example, Zhang et al. (2020), proposed such a system in which water was used as thermal storage heat transfer fluid, and for cold energy storage, they considered ice slurry as the working medium. They established the thermodynamic model of this cycle and analyzed it in detail. Their sensitivity analysis showed the importance of heat exchangers on the system performance, which needs more attention in designing and application. Seasonal cold storage is studied by Li et al. (2020), using a passive heat transfer device with a two-phase closed thermosiphon effect and a theoretical energy conversion model. The effects of the ambient variables and the working period of a thermosiphon on the ice formation were identified, giving Practical guidance in the evaluation of passive cold storage system design.

Even in Compressed air energy storage systems and before injecting the pressurized air inside the cavern, the rock beds in the entrance of the cavern stores the heat in the charging period and release it in the discharge period as preheating. This, in turn, increases the roundtrip efficiency of the whole system. Such a model has been studied (Ozturk et al. 2020). The latent heat deals with phase changing materials (PCM) and possesses a larger energy density compared to sensible TES (Dincer and Rosen 2021) and their temperature is constant during the phase changing process, which is beneficial to extend the efficiency of energy storage systems. PCMs can be used for thermal management systems in buildings, such as PCM-embedded radiant wall heating systems in buildings (Oruc et al. 2019) or can be used for cold chain applications.

Thermochemical storage is somehow in the research phase and it needs more developments to be commercially feasible in large-scale energy storage systems. Normally, inorganic substances are used as storage mediums. A pair of chemical materials should be selected. When these two materials come together, through an exothermic reaction, heat is generated and can be used for the application in the discharge period. In the charging period, heat should be added to separate these two materials and they can be kept in separate mediums for later use again. The storage period, amount of the heat, operating conditions and abundancy among the parapets in selecting these materials (Dincer 2002a). Miro et al. (2016) have studied TES technology for harvesting waste heat in different industrial processes. They have assessed and evaluated industrial sectors in terms of their potential in using waste heat and employing TES. For a conventional energy system without TES, waste heat will not be easy to use due to its intermittent behavior. Li (2016) has evaluated sensible TES systems as a practical and highly efficient method for storing thermal energy. In his study, a major factor influencing the performance of sensible TES systems such as reservoir geometry and flow rate have been investigated.

When a TES system is studied thermodynamically, it can be viewed from the first and second laws of thermodynamic points of view. Of course, in such an evaluation, apart from the availability of waste heat, it is important to realize the environmental impact of the system. The maximum available work, which can be harvested from an energy source, such as a TES system, is described as the Exergy of that resource, which is affected by the ambient situation. Unlike the conservation of energy principle, exergy is not conserved and there is exergy destruction term in exergy balance of a system (Dincer and Rosen 2021) losses Exergy analysis based on the second law of thermodynamic, is a preferred approach for this purpose and it has a good potential to assess this characteristic of TES systems (Szargut et al. 1987). In recent years, thermodynamic analyses of TES systems have been increased, due to the importance of identifying the effectiveness of the considered energy storage system and the ways to increase their efficiency. The main advantage of exergy analyses is providing a device to measure the environmental impacts of any system components and the degree of irreversibility in each process. Therefore, there can be a linkage between exergy, energy and sustainable development (Dincer and Rosen 2005, 1998; Dincer 2002b).

The stratification effect on energy capacity and exergy capacity in TES systems have been studied in the literature, which shows that higher stratified storage systems are associated with higher exergy storage capacity and should be considered in designing sensible TES systems (Rezaie et al. 2012a, 2012b, 2015). In a cold thermal energy storage system, exergy analyses give the same results. Rosen et al. showed that intuitive advantages could be found for cold TES by conducting exergy analysis (Rosen et al. 1999). The efficiency of cold TES systems can reach up to 90%, with as low as 20% exergy efficiency. Based on their results, exergy efficiency can provide a realistic evaluation of the irreversibility in TES systems (Rismanchi et al. 2012).

In this Chapter, a cold TES system has been analyzed in detail. As a case study, the cold TES at the University of Idaho (UI), United States of America (USA), the Moscow campus is taken into consideration. The data acquisition process, modelling process and second law of thermodynamic analyses are described in this Chapter to show the applicability of exergy analyses and their benefits. The current TES system is replaced by a mathematical model and employed measurements are described. Considering the transient behavior of the cold TES, TRSNSYS is used for modelling purposes and to evaluate the exergy efficiency of the system. It is tried to evaluate incomplete cycles of charging and discharging of TES systems to give applicable and valuable information for the performance and exergy analysis of similar cold TES systems. Upon obtaining results and key information about the system, the analysis results can also be applied to the current cold TES system to improve its performance and efficiency. Decision-makers and engineers along with researchers will be able to modify the existing design procedures based on the exergy results. As mentioned before, there is a huge energy consumption due to the need for cooling loads in residential buildings and industrial applications. Therefore, chilled water systems will be also modified to use the minimum energy for the peak load periods by changing the operation time for charging and discharging the cold thermal energy storage.

Cold energy storage systems, such as ice storage, can be integrated with air conditioners in places where preparing cooling load is a major issue. Such a system has been studied for a hypermarket in Ankara, Turkey from thermodynamic and economic aspects (Erdemir et al. 2021). Results of their study show that during peak hours for electricity consumption, using ice-cold energy storage makes it possible to shut down the chillers. Based on four years of data collecting, the payback period was estimated to be three years for the considered system.

2 Methodology

2.1 Exergy Analysis

Exergy analysis, unlike energy analysis, is evaluated concerning the dead state to show how much useful work can be extracted before attaining equilibrium with its environment. There is normally an agreement to define this "dead" state before starting an analysis. Therefore, when there is a difference between properties of state property and dead state property, there will be exergy or the ability to do work (Gaggioli 2012). Contrasting the energy, there is always exergy destruction in a real process where there is irreversibility. A general formulation for the exergy balance can be written as:

$$\text{Exergy Input} - \text{Exergy output} - \text{Exergy destroyed} = \text{Exergy increase} \quad (1)$$

On a rate base, Eq. (1) can be formulated as Eq. (2), for a transient system.

$$\sum\left(\dot{X}_{Qin}-\dot{X}_{Qout}\right)+\sum\left(\dot{X}_{Win}-\dot{X}_{Wout}\right)+\sum\dot{m}(\Psi_{in}-\Psi_{out})-\dot{X}_d=\frac{d\dot{X}_{sys}}{dt} \tag{2}$$

Here, ($\dot{m}$) is the mass flow rate and (Ψ) is the specific exergy, entering and leaving the system boundary. The exergy destruction term ($\dot{X}_d$) is a positive quantity and $\frac{dX_{sys}}{dt}$ is exergy change within the considered system. The first term in the left hand of Eq. (2) represents [exergy rate ($\dot{X}$)] consists of exergy associated with heat rate ($\dot{X}_Q$) and work rate ($\dot{X}_W$), which are defined in Eqs. (3) and (4), respectively:

$$\dot{X}_Q=\mathrm{Q}\left(1-\frac{T_0}{T_b}\right) \tag{3}$$

The exergy associated with work ($\dot{W}$) is defined as:

$$\dot{X}_W=\dot{W} \tag{4}$$

Heat transfer occurs in the boundary of the system and temperature (absolute) in the system boundary is T_b. As stated before, the exergy for each flow state represents the maximum possible work to be extracted from the fluid. Let us look at the definition of specific exergy, which is:

$$\Psi=h_f-h_0-T_0(s_f-s_0) \tag{5}$$

In Eq. (5), T_0, h_0 and s_0 are temperature, enthalpy, and entropy in the dead state, respectively. (h_f-h_0) represents the enthalpy difference between the flow state (with subscript f) and dead state, from which, the entropy difference is deduced. This means that to extract the maximum enthalpy in the process, the system should come to equilibrium with a dead state (reference state) at the end of the process (Sciubba et al. 2008).

The exergy change between the inlet (a) and outlet (b) of TES, associated with the TES between the inlet (a) and outlet (b) is shown in Eq. (6).

$$\Delta\Psi_{b-a}=\dot{m}_aC[(T_b-T_a)-T_0\ln(T_b/T_a)] \tag{6}$$

The internal exergy change from the initial (i) to final (f) times of a TES system is given in Eq. (7).

$$\Delta X_{int}=m\left[\left(u_f-u_i\right)-T_0\left(s_f-s_i\right)\right] \tag{7}$$

If we define ΔXint, C as the internal changes in cold thermal storage during the charging (C) and ΔXint, D as the internal changes in cold thermal storage during the discharging (D), then, the exergy efficiencies for charging (ηx, C) and discharging (ηx, D) and consequently, the overall exergy efficiency, ηx, are shown below in Eqs. (8)–(10).

$$\eta_{x,C} = \frac{\Delta X_{int\,C}}{\Delta \Psi_C} \tag{8}$$

$$\eta_{x,D} = \frac{\Delta \Psi_D}{\Delta X_{int\,D}} \tag{9}$$

$$\eta_x = \frac{\Delta \Psi_D}{\Delta \Psi_C} \tag{10}$$

The main idea of TES analysis is to improve the thermal capacity (E) and consequently, the maximum thermal capacity (E_{max}) in a TES system. The thermal capacity of the tank can be obtained by the integration of cross-sectional circular elements normal to the vertical direction (z) of the tank from the bottom to the height H of the tank. For this purpose, as stated in Eq. (17), the energy capacity of the differential element is the multiplication of mass, heat capacity (C) and temperature difference. Mass is density multiplied by the cross-sectional area (A), and thickness of the differential element (dz). The temperature difference is the difference between the temperature at a vertical point [T(z)] and the maximum return temperature of the TES that is (T_{max}). The total heat capacity would be the integration of the specified integrant in the vertical direction concerning dz from the bottom, (0), to the top of the TES tank, (H).

$$\mathrm{E},\ \mathrm{E}_{max} = \int_0^H \rho \cdot C \cdot A \cdot (T(y) - T_{max})dz \tag{11}$$

When T(z) is set equal to the minimum supply temperature throughout the entire TES, the maximum capacity is obtained. Biot number can be used to validate the assumption that the temperature difference between the centerline and the wall is negligible.

2.2 TRNSYS Model

In order to modify and improve the performance of a system during a specified interval, one should know the nature of transient heat transfer in the system. Transient System Simulation Tool (TRNSYS) has such a capability (Klein 2014). It can model the performance of a given system in an interval and has a comprehensive components library. It can simulate the energy rate of the modeled system as a whole and all components. TRNSYS is a suitable tool for cooling and heating systems modeling and simulation (Klein 2014). Different "types" can be extracted and dragged from

TRNSYS library. Each “type” has a specific number, along with a brief description of each type application. Each type is assigned a number and contains a brief description and its intended application. Depending on the problem, one component can be used for different usages.

3 Case Study: University of Idaho Cold TES

A DE system for heating and cooling in the University of Idaho campus in Moscow, Idaho, USA is the case study. The biomass (wood chips) boiler is the main component for steam production in the DE system. A steam-driven lithium bromide (LiBr) absorption chiller provides the cooling load of the UI campus. The DE plant at UI generates 120 million kg of steam per year. The biomass boiler utilizes wood chips primarily western red cedar with a higher heating value of 19.92–22.56 MJ/kg on a dry basis (Wilson et al. 2010). 95% of the steam production is by the biomass boiler, with a thermal efficiency of 76% and with an exergy efficiency of 24% (Compton and Rezaie 2017).

During the main cooling season, the absorption chiller consumes 27% of this steam to produce chilled water for cooling purposes. Cold TES stores the cooling in off pick time and release it to the DE system to assist three electrical compression chillers during cooling load pick. Figure 1 shows the cold TES in the UI Moscow campus.

The considered TES is a sensible heat storage cylinder with a diameter of 20.4 m and a height of 27 m above the ground. The volume of the water is 8,780 m^3 with a total cooling capacity of 70,340 kW-hours. The peak discharge/recharge rate is 8230 kW at a flow rate of 0.25 m^3/s. During the night, the cold TES is charged and after reaching the peak demand during the day, TES is discharged to improve the

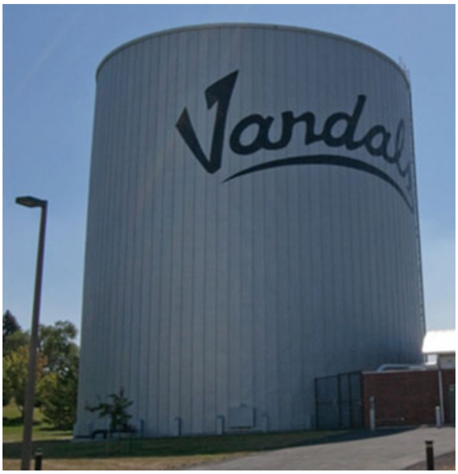

Fig. 1 Cold thermal energy storage in Moscow, Idaho, USA

overall efficiency of the system and compensate for the low efficient electric chillers. Absorption chillers are used during cold nights and early mornings to charge the cold TES. The outdoor, supply, return and mean temperatures of the cold TES for 17 days are presented in Fig. 2. The data is registered every 5 min days throughout the primary cooling season as well as data obtained during the cooler months. The registered data is used for comparison.

The return temperature changes substantially during a day as outdoor temperature damped version, while the supply temperature does not change. The mean line of the TES is a visual index for its capacity. Once the return temperature and mean temperature of the TES are almost identical, it can be concluded that the cold storage capacity of the TES has been exhausted. Figure 3 shows the TES design configuration

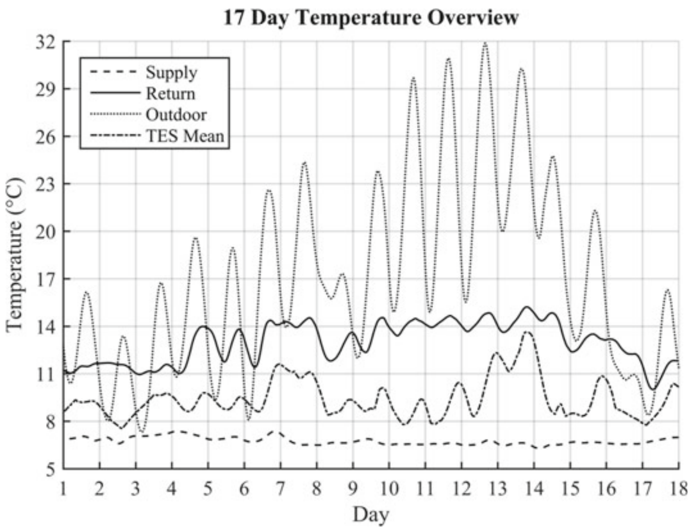

Fig. 2 Outdoor and various cold TES temperatures (Lake and Rezaie 2018) with permission

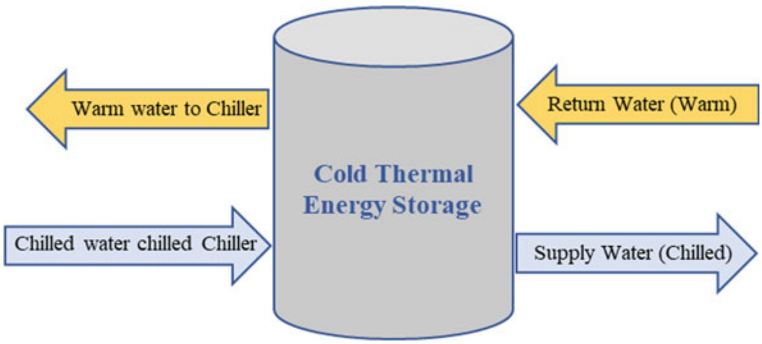

Fig. 3 Simplified cold TES flow diagram

where the outlet and inlet ports are placed in the tank centerline near the bottom and top of the tank. To slow the flow and decrease the mixing effects, diffusers are provided in the supply and return sides (Fig. 2). The warmer water is removed from the return side during the charging period and chilled water is fed to the supply line. The stored chilled water is then drawn from the supply side and is sent to the consumer. After the process, the created warm water returns to the tank for the top of the tank.

4 System Analysis

4.1 Empirical Model

The cooling load conditions vary from winter to summer, therefore, separate analyses are required for each season. In all conditions, the temperatures in different locations are measured and recorded.

The cold storage capacity of the TES in the summer season is around 60% of its maximum cold storage capacity, as can be seen from Fig. 4. Bases on the second data set in the cold season, which is during the late fall and winter months, the winter profile can be depicted (Fig. 4). The wavelength of the cold supply profile in the winter is longer, which implies that there is a lower demand for chillers in the charging period in the winter season. For the assessment of the TES environmental impacts and its performance, measured data in both the summer and winter is employed.

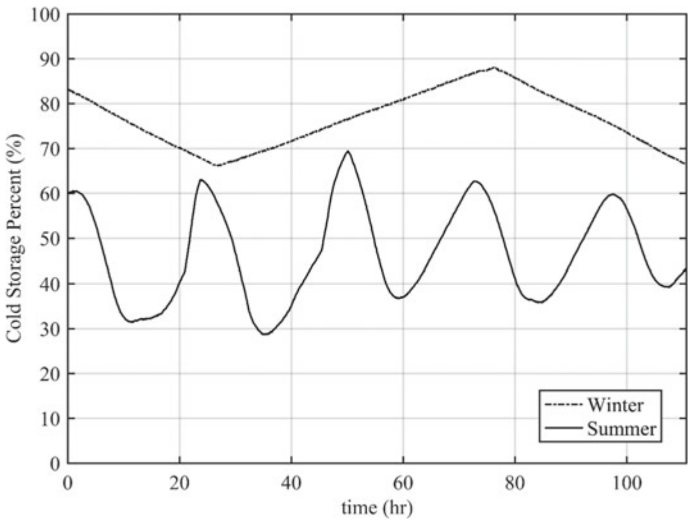

Fig. 4 Percent of total cold storage capacity in the summer and winter

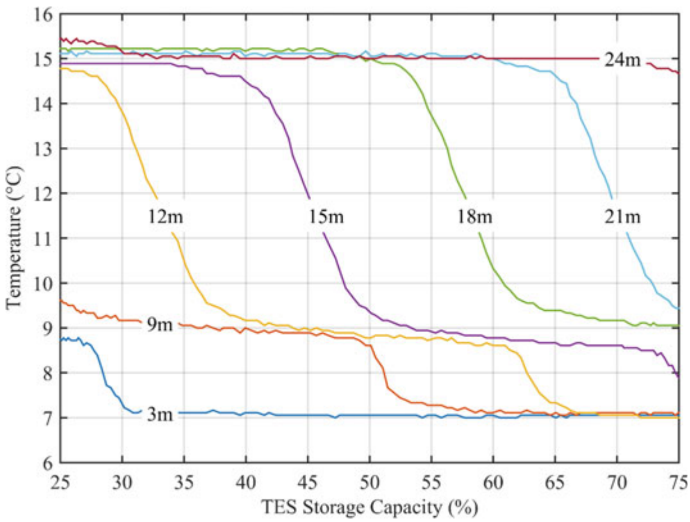

Fig. 5 Temperature profiles of TES during charging (Lake and Rezaie 2018) with permission

The profiles of the TES system for different locations are shown in Fig. 5, based on the total 3.131E8 kJ as its maximum capacity. The supply and return temperatures of 7 and 15.5 °C are used as designed temperatures of the TES system and using Eq. (11). For both charging and discharging periods, the measures temperatures give the required profiles. The distances are measured from the bottom of the tank. Various heights in the tank are considered in this assessment. The full load capacity of the chiller is used for each height and cycle. When it comes to the TES storage capacity, it is defined as the ratio of the current thermal capacity of the TES to the maximum thermal capacity of the tank. The capacity is then expressed as the percentage and Eq. (11) has been used for calculating purposes. Using percentage capacity in the figures gives a better idea about the effecting parameters. For the vertical lines, there is no change in the storage capacity storage, while there are temperature changes. In the case of horizontal lines, there is an ignorable change in temperature and an overall change in internal storage is observed. Once there is a horizontal trend for a specific depth, one would conclude that the related zone is passive during the charging or discharging cycles.

Considered temperature trends are depicted in Fig. 5 for the charging process. In the lower section of the TES tank, a secondary thermocline region has been created due to the located diffusers at the inlet ports of the tank bottom region. The charging cycle runs for a 12 h interval, starting around 9 P.M. to 9 A.M when the storage capacity of the TES reaches 75%. Once this capacity is obtained, the discharging cycle begins, as shown in Fig. 4.

Figure 6 shows the discharging cycle, during which temperature in all regions of the tank starts to increase. The reason for the temperature increase is the reduction in

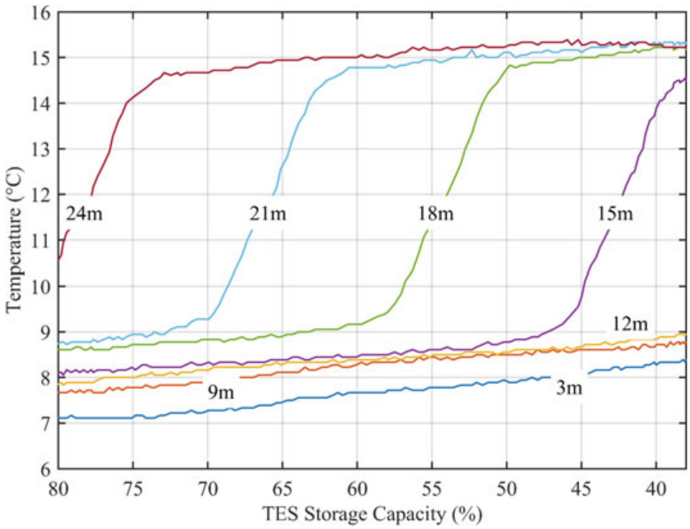

Fig. 6 Temperature profile of TES during discharging (Lake and Rezaie 2018) with permission

cold-water storage during this period and higher ambient temperatures, which cause heat losses in the tank.

4.2 TRNSYS Model

During the operation of the TES, the cycles can be incomplete, which makes it difficult to assess the TES full performance. The prediction of the full cycle can be conducted by establishing a TES model, using the collected real data for the validation of the model. TRNSYS is used for this purpose. The stratified TES models in TRNSYS take into account the input temperatures and mass flow coupled with the construction composition of the tank and initial temperatures for the simulation resolutions. In order to calculate the tank's external wall heat gain or heat losses, the model uses outdoor temperatures. Internal interactions among the stratified layers as well as modelling and simulation of the fully mixed model are possible through required adjustments to inversion characteristics. The advantages of the stratified storage tanks can be analyzed by using fully mixed models.

Initial conditions, obtained from the actual measurements are used to set up the TRNSYS model in the charging cycle. To create an effective model, similar to the actual TES system, accurate adjustments are required to be applied on the main parameters such as fluid properties, inversion characteristics and mean flow rate. Temperature profiles of the charging model are illustrated in Fig. 7. Temperature variations in different heights are potted versus the TES system total cold capacity. The same trends were shown for the real case in Fig. 6. Comparing the simulated and

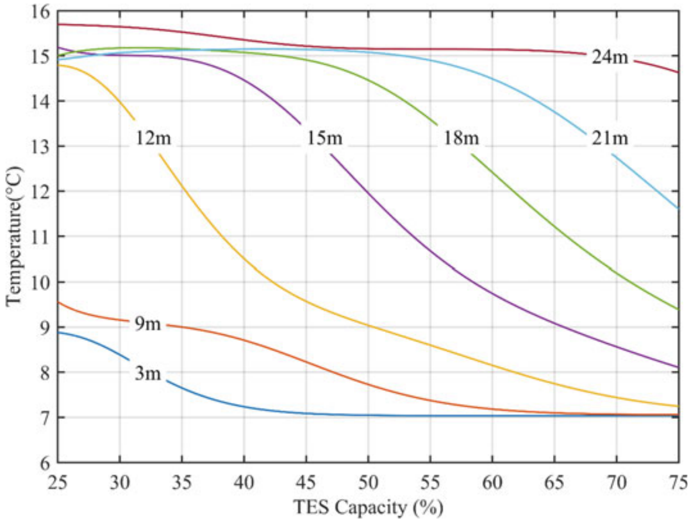

Fig. 7 Charging temperatures in the TRNSYS model (Lake and Rezaie 2018) with permission

real ones shows that the main deviation from the real data happens for the regions near the incoming diffuser side at the heights of 3 and 9 m lines.

During the charging period, in the entire height of the tank the stratification occurs, while the Richardson number values, which indicates that the effect of the inlet on the stratification is negligible. By paying attention to the temperature profiles in the discharging cycle, it can be seen that the profiles are much closer to each other and diffusers effect on the performance of the overall TES is not significant.

Initial conditions in discharging period, are set up based on the measured as shown in Fig. 8 data in the measurement. This means that the TES system is not starting from its full capacity and it starts at 80% capacity. In the considered model, the tank is discharged entirely and the same capacity range is calculated as the actual case. At the top region of the TES that inlet flow enters the tank as 21 m and 24 m, there will be more differences in the discharging cycles of the TES. The flow exits at the lower regions of the tank where the difference between the measurement data and modeled values are smaller than the top of the TES system.

The main idea of the modeling was to extend the available data to a full cycle and help to have a better understanding about the energy and exergy efficiencies of the TES. By plotting the efficiencies versus time and capacity, each layer efficiency would be evaluated. The TES efficiency can be improved by model evaluation and providing the necessary adjustments for the operating and effective parameters.

Figure 9 shows the modeling information for the charging cycle. Similar to the discharge cycle, the fully cold storage is used as a reference to give the capacity as a fraction of full cold storage in the TES system. It takes about 15 h for a typical charging cycle to reach 90% capacity, starting from 25% capacity. Once this capacity is grasped, a longer time is required to increase the capacity further. Once it takes 4%

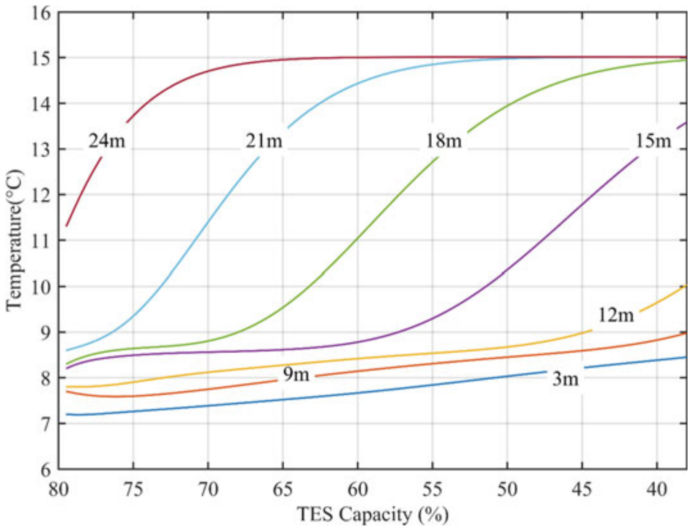

Fig. 8 Discharging temperatures in the TRNSYS model (Lake and Rezaie 2018) with permission

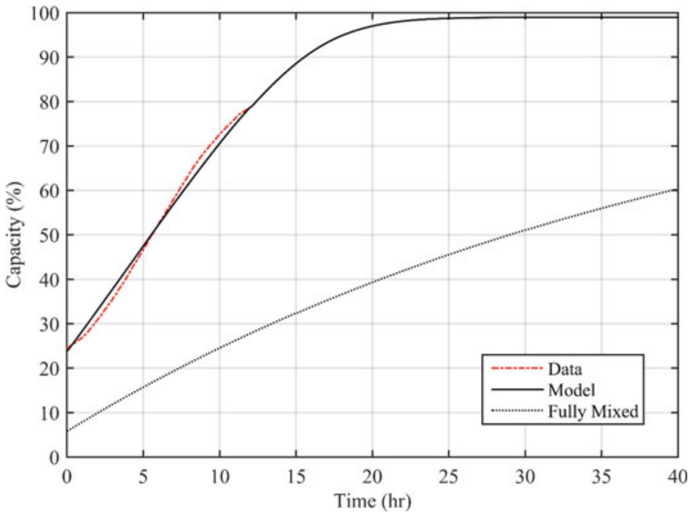

Fig. 9 Percent of full cold capacity vs time during a charging cycle and comparison to the measured data and fully mixed model (Lake and Rezaie 2018) with permission

per hour for the capacities below 90% to charge, it will take less than 2% charging capacity for over 90% capacities. The actual system cooling demands make the system more dynamic, which is turn, causes differences in the models. When the TES tank is in the charging process, still there is a high demand for cooling needs on the campus. Therefore, the created cooling load cannot be only stored in the TES system and has to be shared between the tank and the campus buildings. The cooling load continues to satisfy the building's needs until there will be no need for this load. After this set point, the cooling flow is guided to the TES system totally for 12 h of charging time. The stored load will be used for the cooling needs at 9 am again.

Figure 10 shows the discharging cycle, the same initial conditions are used for the TES set up based on the available data. When it gets closer to the end of the actual discharge cycle, the flow rate decreases to the designed values in the model. This is due to the complete discharging of the TES system. After 15 h, the change in the discharging capacity will decrease. The reason is the increased temperature of the exiting flow compared to the designed temperatures. Once the difference between the leaving flow and returning flow decreases, the capacity for supplying cooling load decreases effectively. A fully mixed model is shown in Fig. 11 for comparison purposes. The stratified TES value is understood qualitatively using a fully mixed model. From the energy point of view, a fully mixed model would give better results. When it turns to the temperature as the desired output, this will not necessarily be true. The specific supply temperature is used to design the equipment that uses the energy. A fully mixed TES system changes the output temperature gradient continually up to the point that will make it ineffective. Meanwhile, a stratified TES system provides the maximum storage regions in the tank under the desired temperatures.

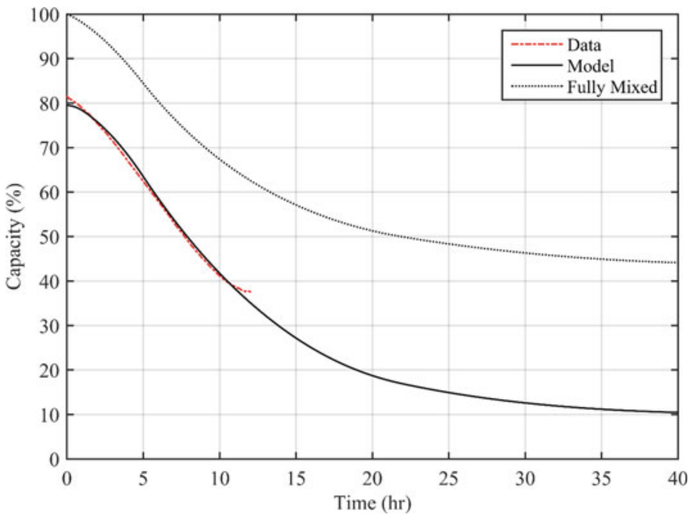

Fig. 10 Percent of full cold capacity vs time during a discharging cycle and comparison to the measured data and fully mixed model (Lake and Rezaie 2018) with permission

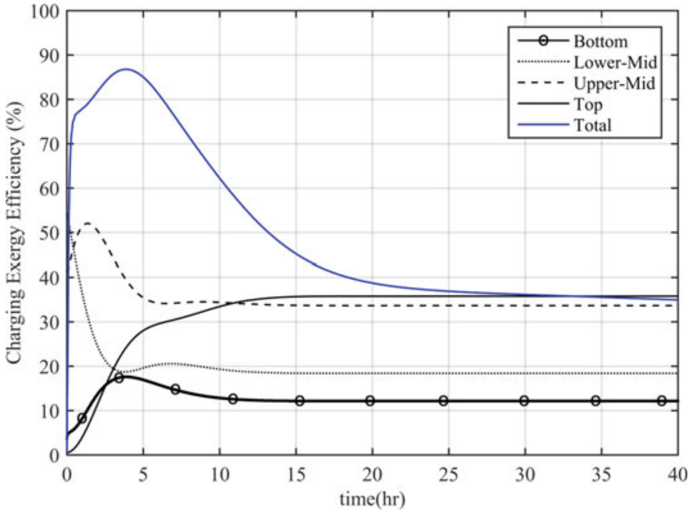

Fig. 11 Charging exergy efficiencies of the total TES and 4 sections of the TES vs time (Lake and Rezaie 2018) with permission

5 Results and Discussion

The exergy efficiency is calculated based on the TES system duration and capacity, through the created model and in a controlled manner. Figure 11 shows the charging cycle exergy efficiency. The TES highest exergy efficiency is obtained in the first 7 h of the charging cycle. Once the four sections of the TES are considered, the upper-middle and top of the TES have the highest exergy efficiencies. This is due to the very high internal exergy changes in these sections compared with the lower sections, which have no significant temperature gradients.

In the TES system, the lower middle and bottom zones have lower efficiencies when the charging process is marching, even for times exceeding 40 h. In a typical charging process of the TES, the overall efficiency is expected to be 55% after 12 h. Results show that the highest exergy efficiency of the TES system in the charging duration will be obtained when the charging takes 4–5 h. The effect of charging capacity on the exergy efficiency has been shown in Fig. 12. It is concluded that when the charging passes over 42% of the maximum capacity, there will be a decrease in the exergy efficiency. This is due to decreasing the temperature difference among the layers. In other words, in the limiting case, the TES system resembles a fully mixed tank, which has no storage benefit.

Therefore, the best efficiency in the charging period of the TES occurs for the 40% to 45% capacity of the tank, in which the stratification of the TES will have the most effective form. Furthermore, in this interval, the overall temperature difference between the bottom and top of the tank is in the optimum values. During the warm hours of the day and the need for higher cooling capacity, the low efficient tank and

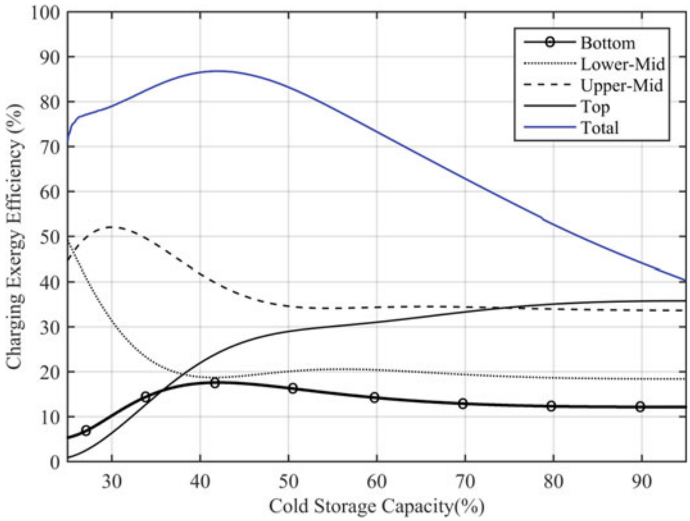

Fig. 12 Charging exergy efficiencies of the total TES and 4 sections of the TES versus capacity (Lake and Rezaie 2018) with permission

smaller capacity can be compensated by using complementary chillers to offset the peak loads. Another concluding remark is that the excessive cold storage in the TES for the next day is not reasonable, because the excessive charging is not effective and has lower efficiency.

Likewise, to understand to what extend the TES should be used in a discharging cycle, the exergy efficiency in this period is plotted in Fig. 13. Through the discharging time, the maximum overall exergy efficiency is reached at around 17 h when the stratification is at its highest degree. As the exergy efficiency is plotted versus time (Fig. 13), it can be seen that layers in the top and upper-mild zones have the highest performance, compared to a lower efficiency for the lower mild and bottom sections of the TES. The first layer that is affected by the stratification effect and temperature difference is the top layer. Figure 13 shows that top layer efficiency is increased. After 10–12 h, the top layer reaches its maximum efficiency. In the same way, layers towards the bottom regions are affected consequently with this difference that the effectiveness of bottom and lower-mild layers are reduced. After a rather long time of 30 h, the exergy efficiency decreases to its lowest values of 22–26%, therefore, further discharging will not be useful.

More information is obtained by comparing the effect of capacity on the exergy efficiency, as shown in Fig. 14. When 23% of the remaining storage capacity is reached, the discharging cycle can be stopped to get the maximum exergy efficiency in the TES system. Beyond this capacity, the inversion mixing starts in the tank, which will cause a substantial decrease in the efficiency, as is expected.

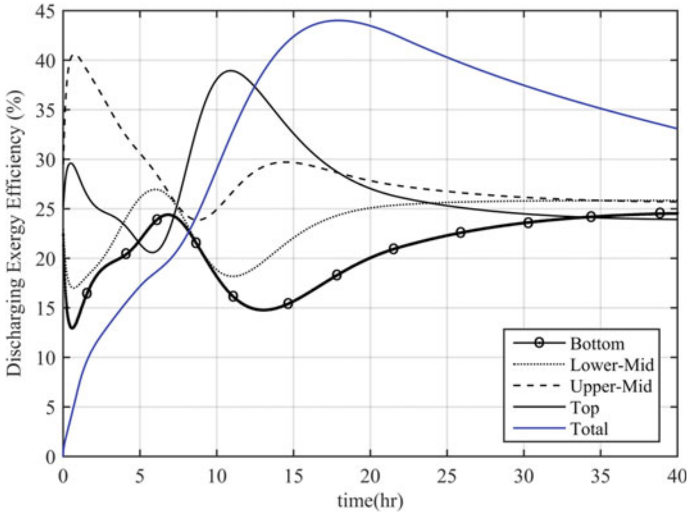

Fig. 13 Discharging exergy efficiencies of the total TES and 4 sections of the TES versus time (Lake and Rezaie 2018) with permission

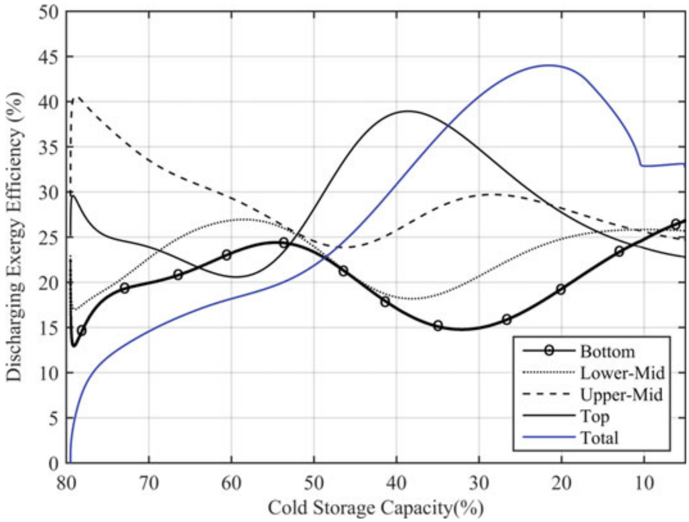

Fig. 14 Discharging exergy efficiencies of the total TES and 4 sections of the TES versus capacity (Lake and Rezaie 2018) with permission

For a majority of discharging times, the upper-middle zones result in higher exergy efficiencies. Just before reaching the maximum overall efficiency, lower-middle sections and bottom sections will have their lowest efficiency. In total, one can conclude that the available operational TES system at the University of Idaho

Table 1 Chillers operations in different scenarios

	Absorption chiller	NCCP chiller 1	SCCP chiller 1	SCCP chiller 2
Scenario 1	Always on	Always on	Always on	Always on
Scenario 2	Always on	15:00–17:00	1:00–20:00	10:00–19:00

has an energy efficiency of around 75% and an exergy efficiency of 20%. The chillers in the UI campus are full time during the hot season as introduced in scenario 1 in Table 1. By considering, the cold TES maximum effective capacity in charging and discharging the operation of the chiller can be modified as scenario 2 in Table 1.

Scenario 2 comes with some hours of setback for 3 chillers out of 4 chillers which means the cooling towers connected with chillers will not be in operations. Therefore, there will be hours of non-operation as are presenting in Table 2. These non-operation hours brings savings.

When scenarios 1 and 2 are compared to each other, it can be seen that in cost, electricity and CO2 emissions, there are savings and improvements.

The main idea of applying thermodynamic analysis for systems such as cold TES is to improve their efficiency and cut down costs. Once replacing the older devices with new ones can be expensive, but the way they are operating can easily decrease the costs and improve their efficiency. Table 3 lists the operation schedules for the current scenario (1) and suggested scenario (2) and their differences. The results show that there can be a significant energy saving of 592,200 kWh electricity energy consumption in the UI campus for the cooling load if the second scenario is followed. By considering the required electrical energy, monthly costs can be obtained for both of the scenarios. Given the electricity costs in UI as 0.059 $/kWh, the cost discrepancy between the two scenarios can be calculated. It shows that the suggested scenario, based on the modeling, saves $35,000 compared to the current system (scenario 1).

Table 2 Chillers operation hours changes

	Operation time (h/day)	Non-operating time (h/day)
Absorption chiller	24	0
NCCP	2	22
SCCP chiller 1	17	5
SCCP chiller 2	9	15

Table 3 Comparison of electricity, cost, and environmental impact of Scenarios 1 and 2

	Electricity (kWh)	Cost ($)	CO_2 (kg)
Scenario 1	945,700	55,800	171,200
Scenario 2	353,500	20,860	64,000
Saving in June	592,200	35,000	107,200
Saving for four cooling months	2,368,800	140,000	428,800

Another essential criterion to compare the scenarios is their environmental impacts. CO_2 emission reduction is a measure to show the sustainability of the campus and the amount of ecetricity consumption just a result of altering the operational schedules. In a natural gas power plant, around 0.181 kg-CO_2 kWh^{-1} is emitted based on the Energy Information Administration (EIA) of United States reports. Table 3 lists the CO_2 emission rate of each scenario, using the above-mentioned values. Again, it is shown that there is 107,200 kg less CO_2 in scenario 2, compared to scenario 1. This value is not fixed for all considered locations, since the electricity generation source varies for different locations. For the UI location, the annual saving of district cooling is 2,368 MWh of electricity for a four-month cooling season. The corresponding annual cost saving for these four months of cooling need is $140,000. In terms of environmental impacts, the offered scenario and applied operational changes for the chillers and cooling tower in the campus, 428,800 kg CO_2 emission will be reduced annually in the UI district cooling system, as can be seen in Table 3.

6 Validation

Energy and exergy efficiencies for charging and discharging cycles are compared with the results in the literature, as can be seen in Table 4. For this purpose, the results are compared with the outputs of a model developed by Rosen et al. for sensible heat storage and linearly stratified fluid (Rosen et al. 1999). TES model in UI is more realistic than this model. To control the experiments, their model was a cylindrical tank 5 m high and a diameter of 2 m. Measurable and predictable Environmental conditions could be imitated by their developed model, enabling more accurate energy and exergy control in the system and minimizing the associated errors. A linearly stratified storage fluid in a sensible heat format was compared with latent heat along with fully mixed storage tanks. The temperature difference between inlet and outlet flows in the TES system was near 17 °C, varying from 2 to 19 °C. The results of the presented case in this chapter are compared with Rosen et al. results (1999).

Table 4 Comparison of energy and exergy analysis of the TES system with Rosen et al. (1999)

Efficiencies (%)		Rosen et al. (1999)	Case study
Energy	Charging	100	92
	Storing	82	N/A
	Discharging	100	81
	Overall	82	75
Exergy	Charging	98	55
	Discharging	24	36
	Overall	20	20

The heat loss or gain at the walls affects the TES efficiency. Due to a short storage time, for the considered cases in the study, the storage effects are neglected. Looking at Table 4, there is a meaningful difference between the exergy efficiencies of Rosen et al. modelling and the results of our model. This is due to the considered assumptions in their study in which there is no heat gain in the charging and discharging periods. Therefore, their exergy efficiencies are higher than what is presented here. The reason is the higher internal temperature in nighttime periods, which are higher than the internal temperature of the TES, which causes heat gain in the system.

The comparison also shows a higher discharging exergy efficiency for our system than the literature as shown in Table 4. This can be justified based on the piping system on the campus. In the charging period, chilled water goes through a wide piping system in the campus before reaching the TES. The temperature of the pipes will be then lower in the discharging period and the pipes are already filled with the chilled water upon initiating of discharging period. This, in turn, the cooling capacity will be larger than conventional TES systems. The other reason for higher efficiency is due to the mass flow rate difference. In the literature case, constant inlet and outlet temperatures have been controlled by controlling the mass flow rate, while in the current study, we have enabled a dynamic flow rate that varies with the consumption changes throughout the university campus.

7 Conclusions

The cooling load can impose high costs for any residential or large-scale buildings. In order to decrease this cost, the University of Idaho has employed a TES system since 2010. The installed cold thermal energy storage had a limited controllable parameter. Previously, the operators' experience, the one-time guidelines at the installation time, and traditional guesswork were among the parameters to improve the efficiency of the system. Such a system needs to be analyzed based on the thermodynamic laws, especially exergy efficiency.

The present study provides such an analysis and a better understanding of the charging and discharging characteristics of the TES. It gives an idea about the idea operational range of the TES for full charging and discharging cycles. Dominant dimensionless parameters are used for the assessment of the tank. Measured data during the experiments along with the thermodynamic analyses shows which parameters have the most effect on the TES performance. For the considered TES system, the Richardson number is a valuable number for the stratification. Applying data of the current TES system to obtain this number reveals that the inlet flow has not a big impact on the stratification level of the tank. The results show that the biot number of the TES is significantly large which implies that there is almost a uniform temperature distribution from the centerline and the walls of the tank.

Thermal stratification prediction in the TES is possible through analyzing the Peclet and Fourier numbers. Based on these dimensionless numbers of analyses and the results of the current study, even if there is not enough experimental data and measurements, the stratification of TES can be predicted. In order to increase the overall performance of the system, it is important to identify which individual sections of the TES system have more effect on the performance. For the current study, exergy efficiency analysis is used to recognize the regions with a high potential to improve the overall efficiency of the system. For the current TES system, exergy analysis shows that the half-upper section has a higher efficiency than the half bottom section of the TES. Such results can be used in the operation of the cold storage tank to improve the efficiency of the tank. Second law analysis of the considered TES system recommends specific operational modifications should be followed in the system operation. When the depth of charge in the thermal capacity reaches 43%, the maximum efficiency will be maximized and once the charging process proceeds, the exergy efficiency reduces. It is concluded that the charging process can be continued until the stage that the next day demand is met. Through this approach, the overall exergy efficiency of the system increases. For the discharging period, the exergy efficiency will increase until the capacity reaches 23%. Further discharging will decrease the system exergy efficiency. The inversion process within the TES is the reason for this decrease. Therefore, the results of this study recommend that discharging of the TES should not exceed 25% of the thermal capacity.

A dynamic analysis of the exergy efficiency offers the operators a practical schedule for charging and discharging of the TES and their correct operation timetable. For further improvement of the system and to have a real-time idea about the TES system, a feedback control system is an effective methodology. TES technology is a practical way to use energy systems more wisely and efficiently. Moreover, the assessment of the TES performance itself results in a better performance. In this chapter, it is shown that thermodynamic modelling of the TES using TRNSYS and powerful assessments such as exergy efficiency are influential techniques to improve the design and performance of TES systems.

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A Wind Energy-Based Cogeneration System for Energy and Fresh Water Production

Ali Erdogan Karaca and Ibrahim Dincer

Nomenclature

A	Area, m^2
ex	Specific exergy, kJ/kg
$\dot{E}x_d$	Exergy destruction rate, kW
h	Specific enthalpy, kJ/kg
I_r	Solar irradiation, kW/m^2
$\dot{m}$	Mass flow rate, kg/s
$\dot{Q}$	Heat rate, kW
s	Specific entropy, kJ/kgK
$\dot{S}_{gen}$	Entropy generation rate, kW/K
$\dot{W}$	Work rate, kW
X	Salination, g/kg

Greek Letters

η	Energy efficiency
Ψ	Exergy efficiency
ρ	Density, kg/m^3
ϵ	Effectiveness

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Acronyms

CAES	Compressed air energy storage
EES	Engineering Equation Solver
HFO	Heavy fuel oil
GHG	Greenhouse gas
TES	Thermal energy storage

1 Introduction

Global warming and its associated impacts on nature, e.g. water scarcity, increasing fire threats, drought, salt level increase in soil, higher wildlife extinction rates and infectious diseases, is addressed as one of the primary threats to the existence of the living species by many authorities (https://www.un.org/en/chronicle/article/health-effects-global-warming-developing-countries-are-most-vulnerable, https://ec.europa.eu/clima/change/consequences_en, https://www.canada.ca/en/services/environment/weather/climatechange/causes-effects.html). The increase in the heat-trapping greenhouse gases in the atmosphere causes temperature rise and eventually change in climate pattern on a local and global level. Due to its long resistance in the atmosphere, carbon dioxide (CO_2) emissions primarily from human activities are known as the main driver of the on-going global warming and its side impacts on the planet earth. Since the industrial revolution, the energy needs of humankind to sustain the life and living standards have been increasing cumulatively. Fossil fuels were and still are the main source to meet this energy demand. Today, about 80% of the global energy supply is from fossil fuels (https://www.capp.ca/energy/world-energy-needs/). Figure 1 shows the ratios of the greenhouse gas emissions (GHGs) for different gases. Fossil fuels and its related activities, e.g. extraction, processing and burning, are responsible from 65% of global CO_2 emissions. Therefore, the primary objective for mitigation of global warming is to be the development of efficient and environmentally benign energy technologies.

Conventional fossil fuel-based energy technologies cause economic and ecological problems due to unstable fuel prices and emitting large amount of CO_2 when combusted. On the other hand, renewable resources, i.e. wind and solar, are more than enough to make the energy supply nature-friendly. However, intermittent characteristics of these resources raise concerns in terms of reliability. This can be mitigated/avoided by correct approaches to the renewable energy systems. The most common one is to store the obtained energy when it is abundant and offer to the service when it is needed. The selection of the correct energy storage system is also critical. For instance, pumped hydro is recognized as the most commonly used method for energy storage forming almost 95% of energy storage systems operating across the globe (https://www.hydropower.org/factsheets/pumped-storage). On the other hand, this approach may not be feasible in every cases due to geographical

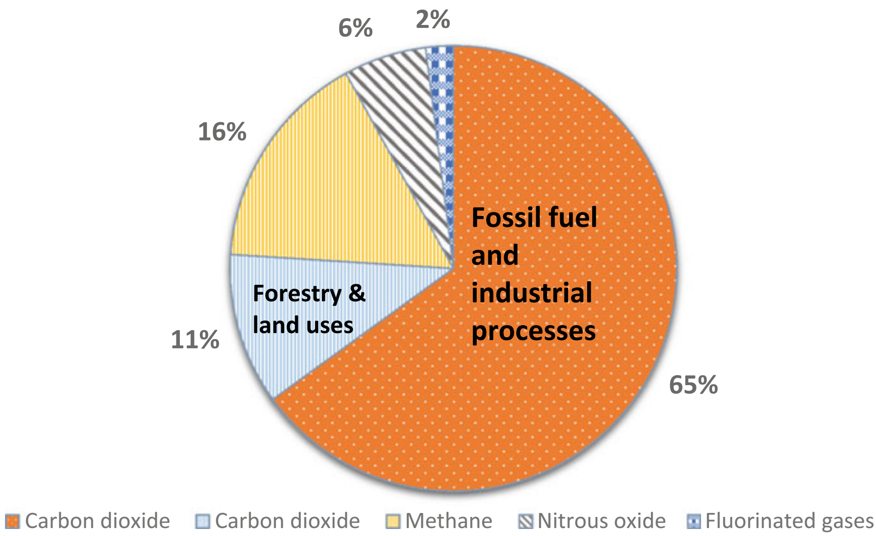

Fig. 1 Global greenhouse gas emissions ratios (Data from https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data)

and topographical restrictions. Chemical energy storage in the form of hydrogen is another promising method to store energy effectively and nature-friendly. In this case, the excess electricity can be used in the hydrogen production via electrolysis of water, and then the produced hydrogen can be converted back to electricity via fuel cells without any harm to the nature. As a mechanical energy storage method, compressed air energy storage systems (CAESs) is an alternative nature-friendly approach that is commonly investigated. In CAES, the excess energy is used to compress the air into a storage medium, which can be an underground cavern, or a balloon located under the surface of water. When it is needed, the energy is reproduced by the expansion of the compressed air through gas turbines. Use of underwater balloons may provide the advantage of utilizing from the hydrostatic pressure; thus, the instant pressure drops and decency of the storage medium can be achieved without any extra effort. Main drivers to consider renewable energy together with energy storage can be summarized as follows:

- To provide power on demand in case renewable resources are insufficient;
- To harness more energy from renewable resources;
- To decrease CO_2 emission rates of power sector by penetrating more clean energy to grid;
- To manage the problems associated with intermittency of the renewable resources.

In the scope of a more sustainable planet, the production of electricity from wind energy is one of the most promising and, consequently, one of the fastest growing renewable-based electricity generation methods. In 2000, the global installed wind capacity was 17.6 GW, and global electricity production from wind was about 30

GWh (https://www.nrel.gov/docs/fy01osti/29436.pdf). In 2020, these ratios reached to 743 GW of global wind capacity and global wind-based electricity production of 1590 GWh (https://ourworldindata.org/renewable-energy). Figure 2 shows the global renewable-based electricity generations trends with respect to sources from 2000 to 2020. Wind turbine can be located as on-shore and off-shore. Off-shore wind power generation plants can enjoy higher wind speeds and larger wind blades diameters that allows to generate electricity at higher rates compared to the on-shore applications. Nonetheless, off-shore wind-based electricity production has much higher capital and operational costs. Due to this, about 93% of the global installed wind capacity is on-shore. The energy in the form of kinetic energy from moving air is converted to mechanical energy via wind turbines and eventually to electricity via generator taking place in the body of the wind turbine set-up.

The selection of site with a favorable weather pattern is critical for effective operation of wind turbines. In this regard, the minimum wind speed of 12–14 km/h, which is also known as cut-in speed, is addressed to turn turbine blades to capture energy from blowing wind and produce the useful output of electricity (https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/canmetenergy/files/pubs/WindEnergy_buyersguide_ENG.pdf). The size of the wind turbine blades, wind speed and air density are some major parameters that define the amount of energy produced by wind turbines. Higher wind speeds mean to more energy available in the wind and electricity production via wind turbines at higher rates. However, wind turbines are designed to cope with certain wind speeds. In this regard, a cut-out wind speed is defined for safe operation of wind turbines that vary by turbine design (up to 80 km/h) (https://www.energy.gov/eere/articles/how-do-wind-turbines-survive-severe-storms). This is the maximum wind speed that wind turbines are capable of bearing if every single components in the system in cooperation, but in practice, wind turbines are stopped operating before reaching these ranges to remain in a safe zone.

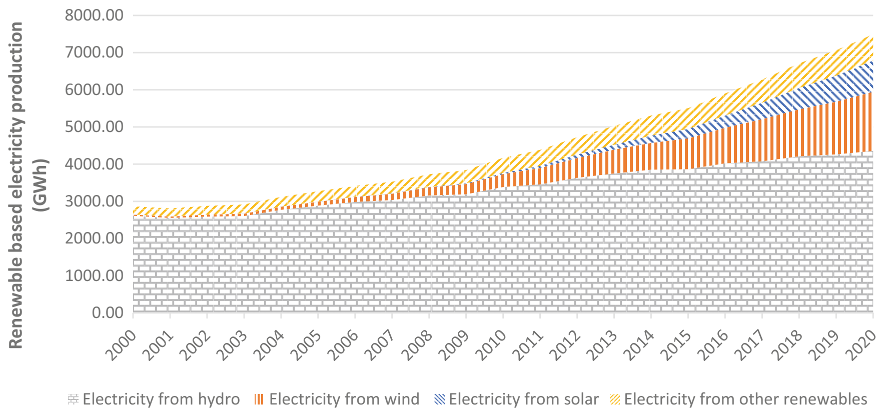

Fig. 2 Global renewable based electricity by sources from 2000 to 2020 (Data from https://ourworldindata.org/renewable-energy)

Another important parameter that defines the energy extraction ratio from wind is the Betz limit. Similar to Carnot cycle efficiency in thermodynamics, stating that all energy provided to a heat engine cannot be turned into useful output and partially must be rejected to the environment, Betz limit defines the limits of extracting energy from wind. According to Albert Betz, theoretical maximum efficiency of a wind turbine cannot exceed 59.3%; meaning that only 59.3% of the kinetic energy can be used for spinning wind turbines to generate electricity (Ragheb and Ragheb 2011). In practice, wind turbines cannot reach to this efficiency, and commonly practiced wind turbine efficiencies falls between 35 and 45% range (https://css.umich.edu/factsheets/wind-energy-factsheet). It should be noted that the Betz limit defines the maximum kinetic energy that can be turned into mechanical energy by a wind turbine. Since the desired useful output from wind power plants is electricity, the efficiency of other system components, i.e. gearbox and generator, must be considered while calculating the electrical output of wind turbines.

In this study, the system developed is evaluated within the scope of a case study for which Antigua and Barbuda is selected as the region for the potential implementation of the system. Antigua and Barbuda is an island nation with a total population of 96,286 (https://datacommons.org/place/country/ATG#Environment). The country consists of two main islands and several small islands covering an area of 443 square kilometers (km^2) in total (Vinet and Zhedanov 2011). For its energy, the country relies on imported fossil fuels, and heavy fuel oil is the main source used for the electricity production in the country. Due to this, the country struggles with unstable and high energy prices (0.4 US$/kWh) as well as high CO_2 emission rates (http://www.apua.ag/customer-service/rates/). The drinking water sector in Antigua and Barbuda is reliant on seawater desalination through reverse osmosis, and fresh water production consumes about 36 GWh of electricity annually, which corresponds to around 12% of the total electricity consumption in the country (https://www.worlddata.info/america/antigua-barbuda/energy-consumption.php). Hydropower, geothermal, and bioenergy resources are all said to be unavailable in the country. On the other hand, the country has a good solar insulation, and the capacity of power generation from wind is reported as 400 MW for the region (Samuel 2021). Figure 3 shows the average wind speed of Antigua and Barbuda for the corresponding months. The specific objectives of the study are listed as follows:

- To design and develop a wind-based multigeneration integrated energy system;
- To conduct a thermodynamic analysis on the system and determine energy and exergy efficiencies of the system;
- To evaluate the system performance through parametric studies by considering primary design and operational parameters;
- To conduct a case study for a potential implementation of the system in Antigua and Barbuda by considering regional parameters.

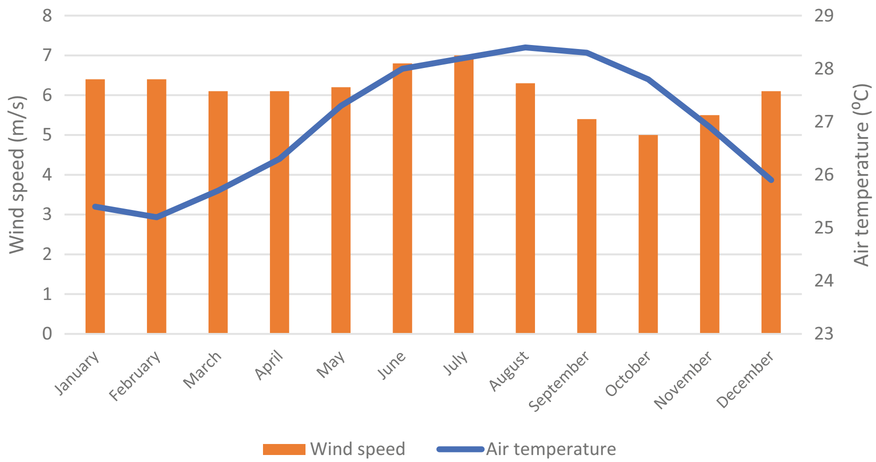

Fig. 3 Monthly average wind speed and air temperature of Antigua and Barbuda (https://www.weather-atlas.com/en/antigua-and-barbuda/codrington-climate#wind)

2 System Description

Within the scope of the current study, a wind based integrated energy systems is investigated through thermodynamic approaches. The developed system utilizes from wind as a primary energy source. The excess energy likely to occur during the off-peak time of the energy demand is stored via compressed air energy storage (CAES) system located underwater. Further, the waste heat occuring from the air compression process is stored in a thermal energy storage (TES) tank, and later introduced to the compressed air before the expansion through gas turbines. Lake/river water is utilized as a cooling agent to manage the temperature between the compression stages and store the thermal energy in the TES tank. After use in the interheaters to increase the carried energy within the compressed air before the expansion, the water is released back to its environment with acceptable temperatures to avoid any potential thermal pollution. The integrated system also comprises a thermal desalination system to produce fresh water from seawater, for which the required thermal energy is provided from the excess heat from the air compression process. The system consists of 100 wind turbines with a blade radius of 50 m. The energy analysis of the system is performed by considering an average wind speed of 8 m/s and a power coefficient of 49%. Figure 4 illustrates the system diagram. Antigua and Barbuda is selected as a region to evaluate the system as a case study. Table 1 presents the energy overview of the country. Table 2 presents the specifications considered in the analysis of the system.

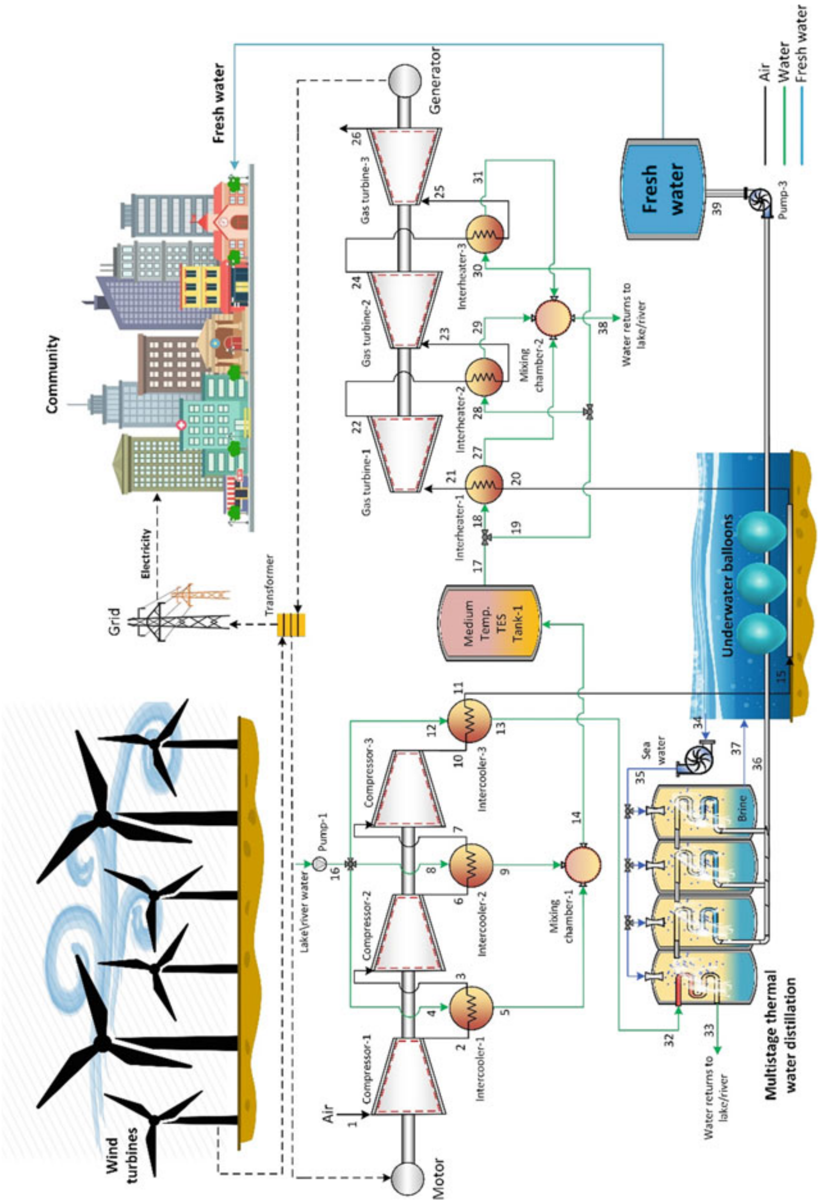

Fig. 4 A wind based integrated power system (Adapted from Karaca et al. (2021))

Table 1 Energy overview of Antigua and Barbuda (https://www.worlddata.info/america/antigua-barbuda/energy-consumption.php)

Parameters	Value
Electricity consumption (GWh/year)	308
Energy source	Fossil fuel (97%)
Electricity retail price (US$/kWh)	0.4
Main fresh water supply (HFO-powered)	Seawater reverse osmosis desalination
Fresh water electricity consumption (GWh/year)	36
CO_2 emission (tons/year)	557 million
CO_2 emission per capita (tons)	5.9

Table 2 Specifications of the facility

Parameters	Value
Region	Antigua and Barbuda
Wind speed	8 (m/s)
Power coefficient of wind turbine (C_p)	49%
Wind turbine efficiency (Generator (90%) and gearbox (80%))	72%
Wind turbine blade radius	50 m
Number of wind turbines required (1.5 MW/turbine)	100
Required area for wind turbines (1.8 acres/MW) (https://www.saskwind.ca/land-area)	270
Pressure ratio	$r_p = 6.7$

2.1 System Analysis

The proposed system is evaluated through energy and exergy approaches. Thermodynamic balance equations for corresponding sub-components are presented in Table 4 in accordance with the state points as illustrated in Fig. 4. The following assumptions are considered while conducting the thermodynamic analysis of the system:

- The steady state and adiabatic operations in the pumps, compressors and turbines.
- The reference temperature and pressure for air: 25 °C and 101.3 kPa.
- The reference temperature and pressure for water: 17 °C and 101.3 kPa.
- The reference state temperature and pressure for seawater: 20 °C and 101.3 kPa.
- The isentropic efficiency of 85% for pump, compressor and turbine operations.
- The potential pressure losses throughout the system are neglected.
- The potential and kinetic energy changes are neglected.

The specific exergy of a given state point can be calculated by

$$ex_i = h_i - h_0 - T_0(s_i - s_0) \tag{1}$$

Both compressor (including pump) and turbine isentropic efficiencies can be computed by

$$\eta_{s_{comp}} = \frac{h_{out,s} - h_{in}}{h_{out} - h_{in}} \tag{2}$$

$$\eta_{s_{turbine}} = \frac{h_{in} - h_{out}}{h_{in} - h_{out,s}} \tag{3}$$

The exit temperature for the isentropic compressor operation can be identified by (k = 1.4)

$$\frac{T_{out,s}}{T_{in}} = \left(\frac{P_{out}}{P_{in}}\right)^{\frac{(k-1)}{k}} \tag{4}$$

For the multistage water desalination unit, mass balance equation is as follows [e.g., Demir and Dincer 2017]:

$$\dot{m}_{sw} = \dot{m}_{b} + \dot{m}_{des} \tag{5}$$

$$\dot{m}_{sw} X_{sw} = \dot{m}_{b} X_{b} \tag{6}$$

where $\dot{m}_{sw}$, $\dot{m}_{b}$, $\dot{m}_{des}$, X_{sw}, X_{b} are fed seawater mass flow rate, brine mass flow rate, desalinated product mass flow rate, fed seawater salinity, and brine salinity, respectively. Table 3 presents the values of the variables used in the analysis of the multistage water desalination unit.

The temperature increase during the air compression process is managed by inter-coolers between the stages in which lake/river water is utilized as a cold stream fluid.

Table 3 Thermodynamic properties of desalination unit (Azhar et al. 2017)

Process	Temperature (K)	Pressure (kPa)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kgK)	Specific exergy (kJ/kg)	Salination (g/kg)
Hot water in	373.6	101.3	4.903	2572	7.07	522.8	–
Hot water out	305	101.3	4.903	133.6	0.462	1.537	–
Sea water in	293.15	101.3	65.21	78.19	0.2726	0.217	48
Brine out	304.2	4.495	61.42	120.8	0.4147	0.4812	50.96
Distilled product	304.2	4.495	3.79	2557	8.432	113	0

The thermal energy absorbed by the fluid is conveyed and stored into a thermal energy storage tank (TES). During the discharging period where wind speed is not high enough to produce enough power, the energy in the TES tank is utilized in interheaters to further increase the carried energy by the compressed air before expanding through gas turbines to generate power. The effectiveness of the heat exchangers taking place in the aforementioned cycle is written as

$$\epsilon = \frac{\dot{Q}_{actual}}{\dot{Q}_{max}} \tag{7}$$

where $\dot{Q}_{actual}$ is the actual heat transfer, and $\dot{Q}_{max}$ is the maximum possible heat transfer between hot and cold stream in the heat exchangers.

$$\dot{Q}_{actual} = \dot{m}_{hs} c_{p,hs} \left(T_{hs,in} - T_{hs,out} \right) = \dot{m}_{cs} c_{p,cs} \left(T_{cs,out} - T_{cs,in} \right) \tag{8}$$

where subscript of "hs" indicates the hot stream, and "cs" is for the cold stream. c_p is the specific heat capacity (kJ/kgK) of the corresponding fluid at the corresponding state properties.

$$\dot{Q}_{max} = \dot{m}_{hs} c_{p,hs} \left(T_{hs,in} - T_{cs,in} \right) \tag{9}$$

or

$$\dot{Q}_{max} = \dot{m}_{cs} c_{p,cs} \left(T_{hs,in} - T_{cs,in} \right) \tag{10}$$

Here, $\dot{Q}_{max}$ will be the minimum value obtained from these two equation. By employing the presented equations, the effectiveness of the heat exchangers operating in the compressed air cycle is evaluated as in a range between 0.612 and 0.955. The value of the 0.612 is obtained in the intercoolers, whereas the effectiveness of the interheaters is evaluated as 0.955.

Both energy and exergy efficiencies of the system are evaluated as charging phase and discharging phase. For the charging phase, in which the energy storage is implemented, the energy efficiency can be written as

$$\eta_{charging} = \frac{\dot{W}_{net} + \dot{Q}_{ca} + \dot{Q}_{Tes}}{\dot{W}_{wind}} \tag{11}$$

where $\dot{W}_{net}$ represents the net power output from the system, $\dot{Q}_{ca}$ is the energy storage in the form of compressed air, $\dot{Q}_{Tes}$ is the thermal energy storage in the TES tank and $\dot{W}_{wind}$ is the available wind power hitting the wind turbines. Table 4 shows thermodynamic balance equations written for the each sub-components taking place in the overall system.

Table 4 Thermodynamic balance equations of the corresponding sub-units

Component	Mass balance equation	Energy balance equation	Entropy balance equation	Exergy balance equation
Compressor-1	$\dot{m}_1 = \dot{m}_2$	$\dot{m}_1 h_1 + \dot{W}_{in} = \dot{m}_2 h_2$	$\dot{m}_1 s_1 + \dot{S}_{gen} = \dot{m}_2 s_2$	$\dot{m}_1 ex_1 + \dot{W}_{in} = \dot{m}_2 ex_2 + \dot{E}x_d$
Intercooler-1	$\dot{m}_2 = \dot{m}_3$ $\dot{m}_4 = \dot{m}_5$	$\dot{m}_2 h_2 + \dot{m}_4 h_4 = \dot{m}_3 h_3 + \dot{m}_5 h_5$	$\dot{m}_2 s_2 + \dot{m}_4 s_4 + \dot{S}_{gen} = \dot{m}_3 s_3 + \dot{m}_5 s_5$	$\dot{m}_2 ex_2 + \dot{m}_4 ex_4 = \dot{m}_3 ex_3 + \dot{m}_5 ex_5 + \dot{E}x_d$
Compressor-2	$\dot{m}_3 = \dot{m}_6$	$\dot{m}_3 h_3 + \dot{W}_{in} = \dot{m}_6 h_6$	$\dot{m}_3 s_3 + \dot{S}_{gen} = \dot{m}_6 s_6$	$\dot{m}_3 ex_3 + \dot{W}_{in} = \dot{m}_6 ex_6 + \dot{E}x_d$
Intercooler-2	$\dot{m}_6 = \dot{m}_7$ $\dot{m}_8 = \dot{m}_9$	$\dot{m}_6 h_6 + \dot{m}_8 h_8 = \dot{m}_7 h_7 + \dot{m}_9 h_9$	$\dot{m}_6 s_6 + \dot{m}_8 s_8 + \dot{S}_{gen} = \dot{m}_7 s_7 + \dot{m}_9 s_9$	$\dot{m}_6 ex_6 + \dot{m}_8 ex_8 = \dot{m}_7 ex_7 + \dot{m}_9 ex_9 + \dot{E}x_d$
Compressor-3	$\dot{m}_7 = \dot{m}_{10}$	$\dot{m}_7 h_7 + \dot{W}_{in} = \dot{m}_{10} h_{10}$	$\dot{m}_7 s_7 + \dot{S}_{gen} = \dot{m}_{10} s_{10}$	$\dot{m}_7 ex_7 + \dot{W}_{in} = \dot{m}_{10} ex_{10} + \dot{E}x_d$
Intercooler-3	$\dot{m}_{10} = \dot{m}_{11}$ $\dot{m}_{12} = \dot{m}_{13}$	$\dot{m}_{10} h_{10} + \dot{m}_{12} h_{12} = \dot{m}_{11} h_{11} + \dot{m}_{13} h_{13}$	$\dot{m}_{10} s_{10} + \dot{m}_{12} s_{12} + \dot{S}_{gen} = \dot{m}_{11} s_{11} + \dot{m}_{13} s_{13}$	$\dot{m}_{10} ex_{10} + \dot{m}_{12} ex_{12} = \dot{m}_{11} ex_{11} + \dot{m}_{13} ex_{13} + \dot{E}x_d$
Mixing chamber-1	$\dot{m}_5 + \dot{m}_9 + \dot{m}_{13} = \dot{m}_{14}$	$\dot{m}_5 h_5 + \dot{m}_9 h_9 + \dot{m}_{13} h_{13} = \dot{m}_{14} h_{14}$	$\dot{m}_5 s_5 + \dot{m}_9 s_9 + \dot{m}_{13} s_{13} + \dot{S}_{gen} = \dot{m}_{14} s_{14}$	$\dot{m}_5 ex_5 + \dot{m}_9 s_9 + \dot{m}_{13} ex_{13} = \dot{m}_{14} ex_{14} + \dot{E}x_d$
TES tank (charging)	$\dot{m}_{14} \times t = m_f$	$\dot{m}_{14} h_{14} \times t = m_f h_f$	$\dot{m}_{14} s_{14} \times t + S_{gen} = m_f s_f$	$\dot{m}_{14} ex_{14} \times t = m_f ex_f + Ex_d$
TES tank (discharging)	$m_i = \dot{m}_{17} \times t$	$m_i h_i = \dot{m}_{17} h_{17} \times t$	$m_i s_i + S_{gen} = \dot{m}_{17} s_{17} \times t$	$m_i ex_i = \dot{m}_{17} ex_{17} \times t + Ex_d$
Balloons (charging)	$\dot{m}_{15} \times t = m_f$	$\dot{m}_{15} h_{15} \times t = m_f h_f$	$\dot{m}_{15} s_{15} \times t + S_{gen} = m_f s_f$	$\dot{m}_{15} ex_{15} \times t = m_f ex_f + Ex_d$
Balloons (discharging)	$m_i = \dot{m}_{20} \times t$	$m_i h_i = \dot{m}_{20} h_{20} \times t$	$m_i s_i + S_{gen} = \dot{m}_{20} s_{20} \times t$	$m_i ex_i = \dot{m}_{20} ex_{20} \times t + Ex_d$
Interheater-1	$\dot{m}_{20} = \dot{m}_{21}$ $\dot{m}_{18} = \dot{m}_{27}$	$\dot{m}_{20} h_{20} + \dot{m}_{18} h_{18} = \dot{m}_{21} h_{21} + \dot{m}_{27} h_{27}$	$\dot{m}_{20} s_{20} + \dot{m}_{18} s_{18} + \dot{S}_{gen} = \dot{m}_{21} s_{21} + \dot{m}_{27} s_{27}$	$\dot{m}_{20} ex_{20} + \dot{m}_{18} ex_{18} = \dot{m}_{21} ex_{21} + \dot{m}_{27} ex_{27} + \dot{E}x_d$
Gas turbine-1	$\dot{m}_{21} = \dot{m}_{22}$	$\dot{m}_{21} h_{21} = \dot{m}_{22} h_{22} + \dot{W}_{out}$	$\dot{m}_{21} s_{21} + \dot{S}_{gen} = \dot{m}_{22} s_{22}$	$\dot{m}_{21} ex_{21} = \dot{m}_{22} ex_{22} + \dot{W}_{out} + \dot{E}x_d$
Interheater-2	$\dot{m}_{22} = \dot{m}_{23}$ $\dot{m}_{28} = \dot{m}_{29}$	$\dot{m}_{22} h_{22} + \dot{m}_{28} h_{28} = \dot{m}_{23} h_{23} + \dot{m}_{29} h_{29}$	$\dot{m}_{22} s_{22} + \dot{m}_{28} s_{28} + \dot{S}_{gen} = \dot{m}_{23} s_{23} + \dot{m}_{29} h_{29}$	$\dot{m}_{22} ex_{22} + \dot{m}_{28} ex_{28} = \dot{m}_{23} ex_{23} + \dot{m}_{29} ex_{29} + \dot{E}x_d$
Gas turbine-2	$\dot{m}_{23} = \dot{m}_{24}$	$\dot{m}_{23} h_{23} = \dot{m}_{24} h_{24} + \dot{W}_{out}$	$\dot{m}_{23} s_{23} + \dot{S}_{gen} = \dot{m}_{24} s_{24}$	$\dot{m}_{23} ex_{23} = \dot{m}_{24} ex_{24} + \dot{W}_{out} + \dot{E}x_d$

(continued)

Table 4 (continued)

Component	Mass balance equation	Energy balance equation	Entropy balance equation	Exergy balance equation
Interheater-3	$\dot{m}_{24} = \dot{m}_{25}$ $\dot{m}_{30} = \dot{m}_{31}$	$\dot{m}_{24}h_{24} + \dot{m}_{30}h_{30} = \dot{m}_{25}h_{25} + \dot{m}_{31}h_{31}$	$\dot{m}_{24}s_{24} + \dot{m}_{30}s_{30} + \dot{S}_{gen} = \dot{m}_{25}s_{25} + \dot{m}_{31}s_{31}$	$\dot{m}_{24}ex_{24} + \dot{m}_{30}ex_{30} = \dot{m}_{25}ex_{25} + \dot{m}_{31}ex_{31} + \dot{E}x_d$
Gas turbine-3	$\dot{m}_{25} = \dot{m}_{26}$	$\dot{m}_{25}h_{25} = \dot{m}_{26}h_{26} + \dot{W}_{out}$	$\dot{m}_{25}s_{25} + \dot{S}_{gen} = \dot{m}_{26}s_{26}$	$\dot{m}_{25}ex_{25} = \dot{m}_{26}ex_{26} + \dot{W}_{out} + \dot{E}x_d$
Mixing chamber-2	$\dot{m}_{27} + \dot{m}_{29} + \dot{m}_{31} = \dot{m}_{38}$	$\dot{m}_{27}h_{27} + \dot{m}_{29}h_{29} + \dot{m}_{31}h_{31} = \dot{m}_{38}h_{38}$	$\dot{m}_{27}s_{27} + \dot{m}_{29}s_{29} + \dot{m}_{31}s_{31} + \dot{S}_{gen} = \dot{m}_{38}s_{38}$	$\dot{m}_{27}ex_{27} + \dot{m}_{29}s_{29} + \dot{m}_{31}ex_{31} = \dot{m}_{38}ex_{38} + \dot{E}x_d$
Desalination unit	$\dot{m}_{35} = \dot{m}_{36} + \dot{m}_{37}$ $\dot{m}_{32} = \dot{m}_{33}$	$\dot{m}_{32}h_{32} + \dot{m}_{35}h_{35} = \dot{m}_{33}h_{33} + \dot{m}_{36}h_{36} + \dot{m}_{37}h_{37}$	$\dot{m}_{32}s_{32} + \dot{m}_{35}s_{35} + \dot{S}_{gen} = \dot{m}_{33}s_{33} + \dot{m}_{36}s_{36} + \dot{m}_{37}s_{37}$	$\dot{m}_{32}ex_{32} + \dot{m}_{35}ex_{35} = \dot{m}_{33}ex_{33} + \dot{m}_{36}ex_{36} + \dot{m}_{37}ex_{37} + \dot{E}x_d$

The net power of the system during the charging phase can be defined as

$$\dot{W}_{net} = \dot{W}_{wt} - \dot{W}_{comp1} - \dot{W}_{comp2} - \dot{W}_{comp3} \tag{12}$$

where $\dot{W}_{wt}$ represents the wind turbines' power output, and $\dot{W}_{comp}$ is for the compressor power input needed for the CAES. Power output from the wind turbine and total wind power crossing from the area swept by turbine blades can be determined by

$$\dot{W}_{wt} = \frac{1}{2} \times \pi \times r_d^2 \times C_{p_{wt}} \times N_{wt} \times V_{wt}^3 \times \rho_{air} \times \eta_{wt} \tag{13}$$

$$\dot{W}_{wind} = \frac{1}{2} \times \pi \times r_d^2 \times N_{wt} \times V_w^3 \times \rho_{air} \tag{14}$$

where N_{wt} represents the number of wind turbines, $C_{p_{wt}}$ is the power coefficient of the wind turbine and η_{wt} is the wind turbine efficiency regarding the gearbox and generator efficiencies. It is important to note that wind turbines operate with wind speed in certain ranges to provide an effective and safe operation. Therefore, turbine speed (V_{wt}) and wind speed (V_w) are defined separately. In the analysis of the system, the maximum wind speed that the turbine can cope with is assumed as 11 m/s. Beyond this value, the turbine operates at a constant speed up until 25 m/s. After this, wind turbine stops working to avoid potential damages. Table 5 presents the thermodynamic properties of each state points shown in Fig. 4.

The exergy efficiency of the charging phase can be defined as

Table 5 Thermodynamic properties of the corresponding state points depicted in Fig. 4

State point	Temperature (K)	Pressure (kPa)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kgK)	Specific exergy (kJ/kg)	Vapor quality
0 (air)	298.15	101.3	–	298.6	5.696	–	–
0 (water)	290.15	101.3	–	71.45	0.2534	–	–
0 (sea water)	298.15	101.3	–	97.79	0.3391	–	–
1	298.15	101.3	36.82	298.6	5.696	0	–
2	547.9	678.7	36.82	552.9	5.768	232.8	–
3	390	678.7	36.82	391.2	5.42	174.7	–
4	290	103	4.903	70.83	0.2512	0.002	0
5	373.6	103	4.903	1285	3.626	235.4	0.3862
6	708.2	4547	36.82	722.4	5.493	484.3	–
7	390	4547	36.82	391.2	4.874	337.5	–
8	290	103	4.903	70.83	0.2512	0.002	0
9	373.6	103	4.903	2552	7.034	519.8	0.954
10	708.2	30,467	36.82	722.4	4.947	647.1	–
11	390	30,467	36.82	391.2	4.328	500.2	–
12	290	103	4.903	70.83	0.2512	0.002	0
13	373.6	103	4.903	2559	7.034	519.8	0.954
14	373.6	103	9.806	1922	5.33	377.6	0.67
15	293.15	30,467	36.82	293.6	4.041	488.4	–
16	290.15	103	14.709	70.83	0.2512	0.002	0
17	373.6	101.3	9.806	1922	5.33	377.6	0.67
18	373.6	101.3	3.269	1922	5.33	377.6	0.67
19	373.6	101.3	6.538	1922	5.33	377.6	0.67
20	293	30,467	36.82	293.4	4.04	488.4	–
21	368	30,467	36.82	368.9	4.27	495.5	–
22	236.9	4547	36.82	237.1	4.373	332.9	–
23	368	4547	36.82	368.9	4.816	332.7	–
24	236.9	678.8	36.82	237.1	4.919	170.1	–
25	368	678.8	36.82	368.9	5.362	169.9	–
26	236.9	101.3	36.82	237.1	5.465	7.33	–
27	373.1	101.3	3.269	1071	3.055	187	0.2915
28	373.6	101.3	3.269	1922	5.33	377.6	0.67
29	373.1	101.3	3.269	437.4	1.356	46.02	0.009
30	373.6	101.3	3.269	1922	5.33	377.6	0.67

(continued)

Table 5 (continued)

State point	Temperature (K)	Pressure (kPa)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kgK)	Specific exergy (kJ/kg)	Vapor quality
31	373.1	101.3	3.269	437.4	1.356	46.02	0.009
32	373.6	101.3	4.903	2559	7.034	519.8	0.954
33	305	101.3	4.903	133.6	0.462	1.537	0
34	293.15	101.3	65.21	78.19	0.2726	0.217	0
35	293.15	101.3	65.21	78.19	0.2726	0.217	0
36	304.2	4.495	3.79	2557	8.432	113	1
37	304.2	4.495	61.42	120.8	0.4147	0.4812	0
38	373.6	101.3	9.806	648.7	1.923	93	0.1032
39	293.15	101.3	3.79	84.01	0.2965	0.065	0

$$\psi_{charging} = \frac{\dot{W}_{net} + \dot{E}x_{Q_{ca}} + \dot{E}x_{Q_{Tes}} + \dot{E}x_{Q_{des}}}{\dot{W}_{wind}} \tag{15}$$

For the discharging phase, energy and exergy efficiencies can be determined by

$$\eta_{discharging} = \frac{\dot{W}_w + \dot{W}_{gast}}{\dot{W}_{wind} + \dot{Q}_{ca} + \dot{Q}_{Tes}} \tag{16}$$

$$\psi_{discharging} = \frac{\dot{W}_w + \dot{W}_{gast} + \dot{E}x_{Q_{des}}}{\dot{W}_{wind} + \dot{E}x_{Q_{ca}} + \dot{E}x_{Q_{Tes}}} \tag{17}$$

The integrated system's overall energy and exergy efficiencies can be calculated by

$$\eta_{discharging} = \frac{\dot{W}_w + \dot{W}_{gast} + \dot{Q}_{des}}{\dot{W}_{wind} + \dot{Q}_{ca} + \dot{Q}_{Tes} + \dot{Q}_{dis}} \tag{18}$$

$$\psi_{discharging} = \frac{\dot{W}_w + \dot{W}_{gast} + \dot{E}x_{Q_{des}}}{\dot{W}_{wind} + \dot{E}x_{Q_{ca}} + \dot{E}x_{Q_{Tes}} + \dot{E}x_{Q_{dis}}} \tag{19}$$

Table 6 presents the variables taking place in the efficiency analysis. The purpose of using multiple sub-systems is to harvest more useful output from the overall energy input. Thus, the effectiveness of the renewable energy can be increased by utilizing more from abundant renewable resources. In this regard, energy efficiency of a conventional wind power plant is defined to provide a better picture of the benefit of the integrated renewable power systems. The energy efficiency for a conventional power plant can be defined as

Table 6 Variables used in the efficiency analysis of the system

Parameters	Definition
Energy rate carried by compressed air (kW)	$\dot{Q}_{ca} = \dot{m}_{15} \times h_{15}$
Thermal energy rate carried by hot water (kW)	$\dot{Q}_{Tes} = \dot{m}_{14} \times h_{14}$
Desalinated water in energy rate form (kW)	$\dot{Q}_{des} = \dot{m}_{36}h_{36} + \dot{m}_{37}h_{37} - \dot{m}_{35}h_{35}$
Thermal energy to desalination unit (kW)	$\dot{Q}_{dis} = \dot{m}_{32} \times (h_{32} - h_{33})$
Exergy rate of $\dot{Q}_{ca}$ (kW)	$\dot{E}x_{Q_{ca}} = \dot{m}_{15} \times ex_{15}$
Exergy rate of $\dot{Q}_{Tes}$ (kW)	$\dot{E}x_{Q_{Tes}} = \dot{m}_{14} \times ex_{14}$
Exergy rate of $\dot{Q}_{des}$ (kW)	$\dot{E}x_{Q_{des}} = \dot{m}_{36}ex_{36} + m_{37}ex_{37} - m_{35}ex_{35}$
Exergy rate of $\dot{Q}_{dis}$ (kW)	$\dot{E}x_{Q_{dis}} = \dot{Q}_{dis} \times \left(1 - \frac{T_0}{T_s}\right)$

$$\eta_{conventional} = \frac{\dot{W}_w}{\dot{W}_{wind}} \tag{20}$$

3 Results and Discussion

In this section, the results of the study are presented and discussed with figures. Engineering Equation Solver (EES) software has been used in the thermodynamic, energy and exergy analysis of the system. The system performance is evaluated through various parametric studies by considering primary design and operational parameters. Antigua and Barbuda is considered as potential region to implement the system; thus wind data from the region is considered in the monthly-based analysis of the system. In the current state, the country produces its electricity from heavy fuel oil (HFO). Potential impact and performance analysis for the replacement of the existing systems with the integrated system is discussed. The total power produced by 100 wind turbines is evaluated as 85.12 MW at a wind speed of 8 m/s. On a monthly basis, the system is capable of providing 9818 tons of fresh water. Overall energy and exergy efficiencies of the system are evaluated as 39.49% and 37.62%, respectively. Figure 5 shows the exergy destruction rates in the major system components. Total exergy destruction rate throughout the system is evaluated as 15,033 MW. According to the thermodynamic analysis results, the highest exergy destruction rates are observed in the interheaters 1 and 2 with a value of 2858 MW. Exergy destruction is the loss of work potential. Therefore, it is possible to extract more useful output by decreasing the exergy destruction rates. In this specific case, high exergy destruction in intercoolers can be mitigated by lowering the temperature difference between hot and cold stream. Table 7 presents the performance results of the developed integrated renewable energy system.

Figure 6 shows the monthly basis electricity production of the integrated system. July and January are evaluated as the most productive period of the year in this regard.

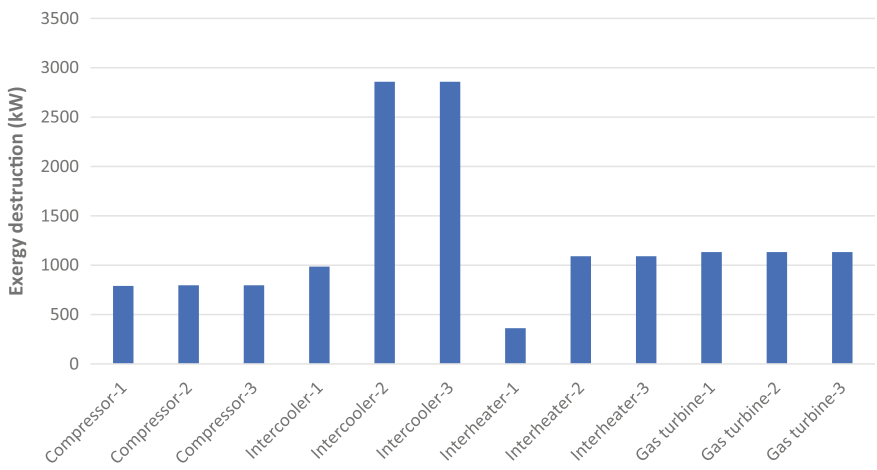

Fig. 5 Exergy destruction rates in the major system components

Table 7 The summary of the integrated system performance results

Parameters	Value
Number of wind turbines	100
Average wind speed	8 m/s
Power coefficient of wind turbine (C_p)	49%
Wind turbine efficiency (Generator (90%) and gearbox (80%))	72%
Wind turbine blade radius	50 m
Power capacity of the system (Wind)	85.12 MW
Power capacity of energy storage system	14.55 MW
Net power production of the system during charging phase	51.36 MW
Monthly fresh production	9818
Overall energy efficiency of the system	39.49%
Overall exergy efficiency of the system	37.62%

For the corresponding periods, the electricity productions become 48.9 MWh and 44.5 MWh per month, respectively. The similar result is expected for energy storage ratios since higher electricity production via wind may allow to dedicate higher portion of the produced electricity to energy storage via CAES. September, October and November are the least productive period of the year in the region.

Figure 7 presents the potable water production in accordance with monthly basis average wind speed (see Fig. 1). In this regard, the most productive period of the year is evaluated as July with a total fresh water production of 7833 tons, where the average wind speed of the region is reported as 7.42 m/s. The lowest fresh water production rates are obtained for October with a value of 3386 tons. It should be

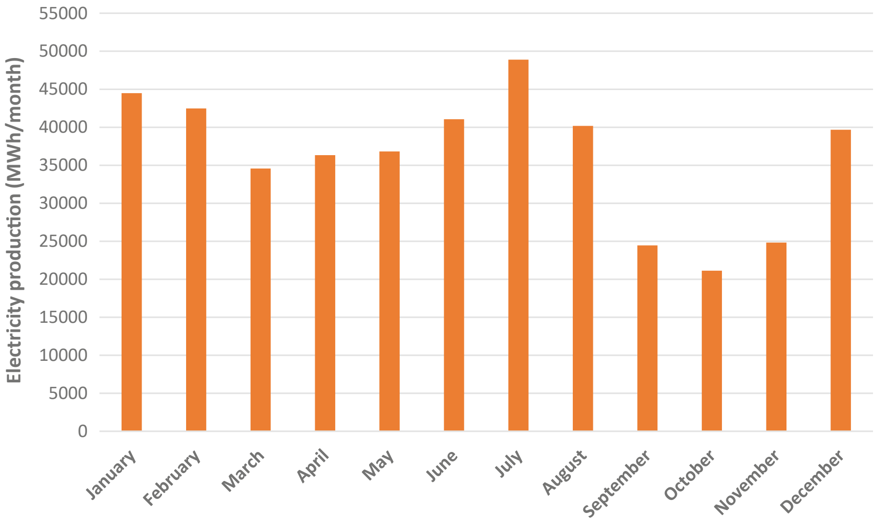

Fig. 6 Monthly-based electricity production

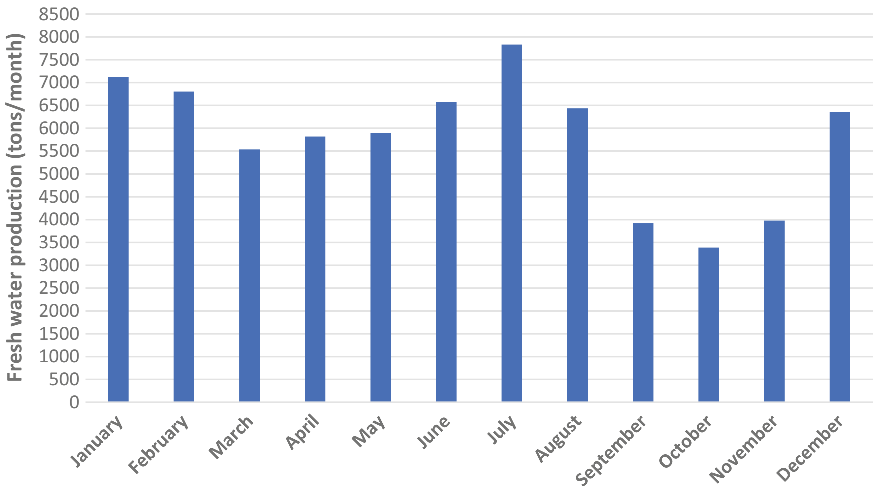

Fig. 7 Monthly potable water production rates

noted that thermal energy for water desalination process is from the excess heat occurring during the period of energy storage via CAES. For off-peak time, 60% of electricity produced by wind turbine is considered as excess power and utilized for the energy storage. Therefore, average wind speed for the corresponding periods of the year greatly impacts the freshwater production ratios.

Note that integrated systems allow to harness more energy from renewable resources. In this regard, comparative assessment of the integrated system with a

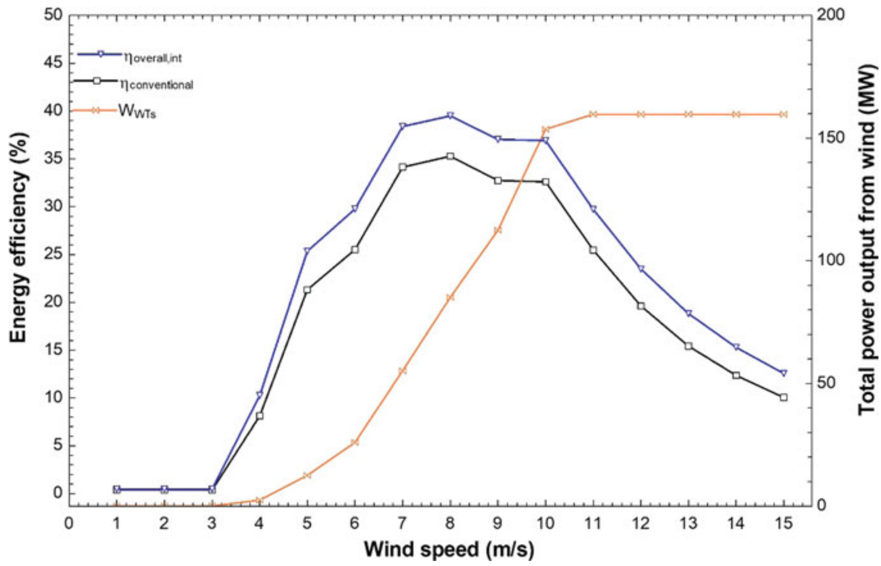

Fig. 8 Integrated system versus conventional wind power plant

conventional wind power plant is presented in Fig. 8 to provide a better understanding. Up to 11 m/s, it is considered that the wind turbine operates with the wind speed. Then, the turbine operates with a constant speed 11 m/s up until the wind speed 15 m/s. After this, the turbine stops working to avoid potential damages. The power coefficient factor is varied for different wind speeds, for which the C_p values provided in Neill and Hashemi (2018) for corresponding wind speeds are used. Due to the determined operational limit of the wind turbine, the power production becomes stable after the wind speed of 11 m/s. However, the efficiency of the plant decreases since the output from the system becomes stable while the wind energy increases with higher wind speeds. At a wind speed of 11 m/s, the system is capable of producing 156 MW of electrical power. On the other hand, it is found that integrated system performs higher energy efficiency (39.49%) than that of a conventional wind power plant (35.28%). According to this results, it is evaluated that the integrated system offers around 12% increase in the harnessing energy from the wind compared conventional wind power plant. Figure 9 presents the energy and exergy efficiencies of the integrated system for different operational phases with respect to wind speeds. Exergy efficiency of the discharging phase becomes slightly higher than the energy efficiency due to the decrease in the denominator of the exergy efficiency definition for the corresponding phase.

The annual electricity need of Antigua and Barbuda is reported as 308 GWh (See Table 1, which totally relies on imported heavy fuel oil. The country also produces its potable water from seawater via reverse osmosis where electricity required is from HFO-based power plants. The analysis of the proposed system indicates that the system is capable of 745.66 GWh clean energy production for the region, which is

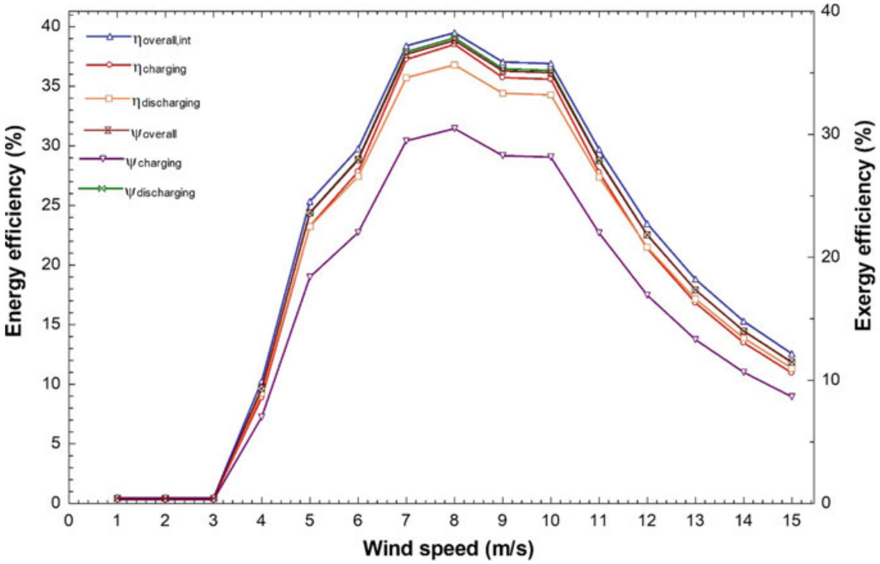

Fig. 9 Energy and exergy efficiencies of the system at various wind speeds

well above the country's annual electricity demand. Beyond making the country totally energy independent and consuming clean energy, the potential implementation of the proposed system may make Antigua and Barbuda an energy exported in the Caribbean region.

4 Conclusions

In the scope of the current study, thermodynamic analysis of a wind-based integrated energy system is conducted. The performance of the study is investigated through various parametric studies. The findings of the conducted study can be summarized with couple bulleted points as follows:

- At a wind speed of 11 m/s, the electrical power output of the system 156 MW;
- At an average wind speed of 8 m/s, the potable water production is about 9618 tons/month;
- Overall energy and exergy efficiencies of the system are evaluated as 39.49% and 37.62%, respectively;
- Compared to conventional wind power plant, the integrated system is capable of harnessing 12% more energy from wind.

In closing, conventional fossil fuel-based energy production and consumption activities are the primary contributors to global warming and its devastating impacts on the planet. Furthermore, having depleting sources and unstable prices make fossil fuel and energy relying on these sources even more problematic. Therefore, renewable-based effective and nature-friendly energy systems become a necessity for all if a cleaner, safer, and more stable environment is demanded.

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Investigation of a Solar Energy- Based Trigeneration System

Ugur Kahraman and Ibrahim Dincer

Nomenclature

ex	Specific exergy (kJ/kg)
$\dot{E}x_{dest}$	Exergy destruction rate (kW)
h	Specific enthalpy (kJ/kg)
$\dot{m}$	Mass flow rate (kg/s)
P	Power (kW)
Q	Heat transfer (kJ)
$\dot{Q}$	Heat transfer rate (kW)
$\dot{Q}_{gen}$	Heat transfer rate for the generator (kW)
s	Specific entropy (kJ/kg. K)
$\dot{S}_{gen}$	Entropy generation rate (kJ/K)
T	Temperature (°C)
T_0	Ambient temperature (°C)
T_b	Boundary temperature (°C)
T_s	Source temperature (°C)
$\dot{W}$	Work rate (kW)

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Greek Letters

η	Energy efficiency
ψ	Exergy efficiency

Subscripts

ABS	Absorber
ARC	Absorption refrigeration cycle
BC	Brayton cycle
CHP	Combined heat and power
COMP	Compressor
COND	Condenser
COP	Coefficient of performance
EBE	Entropy balance equation
EES	Engineering equation solver
EnBE	Energy balance equation
ExBE	Exergy balance equation
EXV	Expansion valve
EV	Evaporator
GEN	Generator
h	Higher temperature
HX	Heat exchanger
HTTS	Higher temperature thermal storage
HTST	Higher temperature storage tank
in	Inlet
l	Lower temperature
LTTS	Lower temperature thermal storage
LTST	Lower temperature storage tank
ms	Molten salt
MBE	Mass balance equation
NASA	National aeronautics and space administration
out	Outlet
Q_H	Heat rejected to high temperature medium
Q_L	Heat input from low temperature medium
P	Pump
REC	Rectifier
RRC	Reheat Rankine cycle

ST	Solar tower
T	Turbine
x	Ammonia-water mixture mass fraction

1 Introduction

Undoubtedly, one of the biggest problems of our time is recognized as global warming, which is affecting us more and more. The temperature increase has reached 1.18 degrees worldwide from 1880 to the present. Moreover, according to the National Aeronautics and Space Administration (NASA), the last 19 years after 2000 have been the hottest period in the world (NASA's Goddard Institute for Space Studies (GISS) 2021). According to a study, the global mean sea level has risen fairly steadily for most of the 24 years, at around 3 mm/year, although higher in the last few years (Beckley et al. 2017). The results show that the effects of global warming continue to increase dramatically. In addition to the relatively low efficiency of fossil fuel power systems compared to multi-generational systems, the global detrimental effects lead us to search for alternative technologies day by day because another issue that is at least as important as global warming is our dependence on energy and the necessity of using energy resources in one way or another.

It is indisputable that the energy demand has been the greatest need of humanity in the past and the cornerstone of development and will continue to be in the future. Along with technology, this demand increases with each passing day. Still, it should not be forgotten that the cleanliness and quality of this kind of energy are just as crucial for a sustainable environment and the world. The key reason why we have specifically mentioned the quality of energy here is that we want this energy to be not only environmentally friendly but also have high efficiency. Because only in this way can we obtain the relatively cheap energy as provided by fossil fuels and realistically abandon these energy sources as humanity in a realistic way only with low-cost methods.

Numerous studies on multigeneration systems, which produce many useful outputs and consist of many subsystems, are slowly but surely increasing. For instance, CHP systems in which heating and power generation are made together can be given as a good example. Another example is solar integrated gasification systems or numerous systems where geothermal energy and anaerobic digestion are used. Undoubtedly, innumerable examples of multigeneration types can be given, but another issue to be considered here is that these sorts of systems work in integration with renewable energy sources and offer clean and sustainable energy to the community with high efficiency. As an alternative to fossil fuels, the need for intensive research on multigenerational systems and hence intensification of studies are expected to further increase in the near future, as it offers a very satisfactory efficiency and multiple useful outputs.

Thanks to the numerous advantages and benefits it provides compared to traditional energy sources, multigeneration using renewable energy resources has attracted significant interest over the recent decades. These types of systems, which energy and exergy efficiency and sustainability are more reliable, provide better energy security and efficiency as well as being more environmentally friendly (Dincer and Bicer 2019). Moreover, unlike fossil fuels, they are more widely distributed around the world. For instance, some regions take advantage of geothermal resources or tidal energy; conversely, in other areas, energy resources such as biomass, wind power, or hydropower are utilized as primary energy resources. Solar radiation is the primary source of most common energy, even more shared around the earth than other green energy resources since it falls to its surface all over.

The continuously falling cost of renewable energy sources is one of the driving factors for their widespread adoption. The economics of renewable energy-based multigeneration systems are impacted by the demand for a relatively quick payback period. For this reason, the design should be optimized to maximize energy end exergy efficiencies wisely whereas minimizing the excess valuable energy. However, it should be noted that enlarging the system to increase its efficiency will bring additional operational and maintenance costs. Another difficulty of using systems integrated with renewable energy sources is the need for relatively larger areas to benefit from these energy sources, such as solar energy, which has low energy density. However, it should not be forgotten that such resources are freely available and will continue to exist as an endless energy source as long as the world exists.

Although much research on integrated combine cycles aims to generate power and produce valuable outputs, very few aim to convert inputs into the maximum number of useful outcomes. Furthermore, this research attempts to make more useful outputs with fewer inputs by utilizing entirely sustainable energy sources such as solar tower. In this study, a solar-based integrated multigeneration system is analyzed, developed, and evaluated in terms of its energy and exergy performances for heating, cooling, as well as electricity for a sustainable population. The main objectives of this study can be listed as follows: (1) to investigate a solar-based multigeneration system to generate power, heating, and cooling. (2) to perform parametric studies to analyze system outcomes, power generation, process heat production and overall system efficiencies depending on solar tower outlet temperature. (3) to calculate the proposed system's overall energy and exergy efficiencies, as well as exergy destructions by individual sub-systems. (4) to implement parametric studies to examine the total system energy and exergy efficiencies by lower temperature thermal storage tank (LTTS) temperature.

2 System Description

In Fig. 1, the solar-based multigeneration system is illustrated. The main objective of this system is to obtain heating and cooling and electricity generation for the desired community by using the solar tower to utilize from the sun. The higher and lower

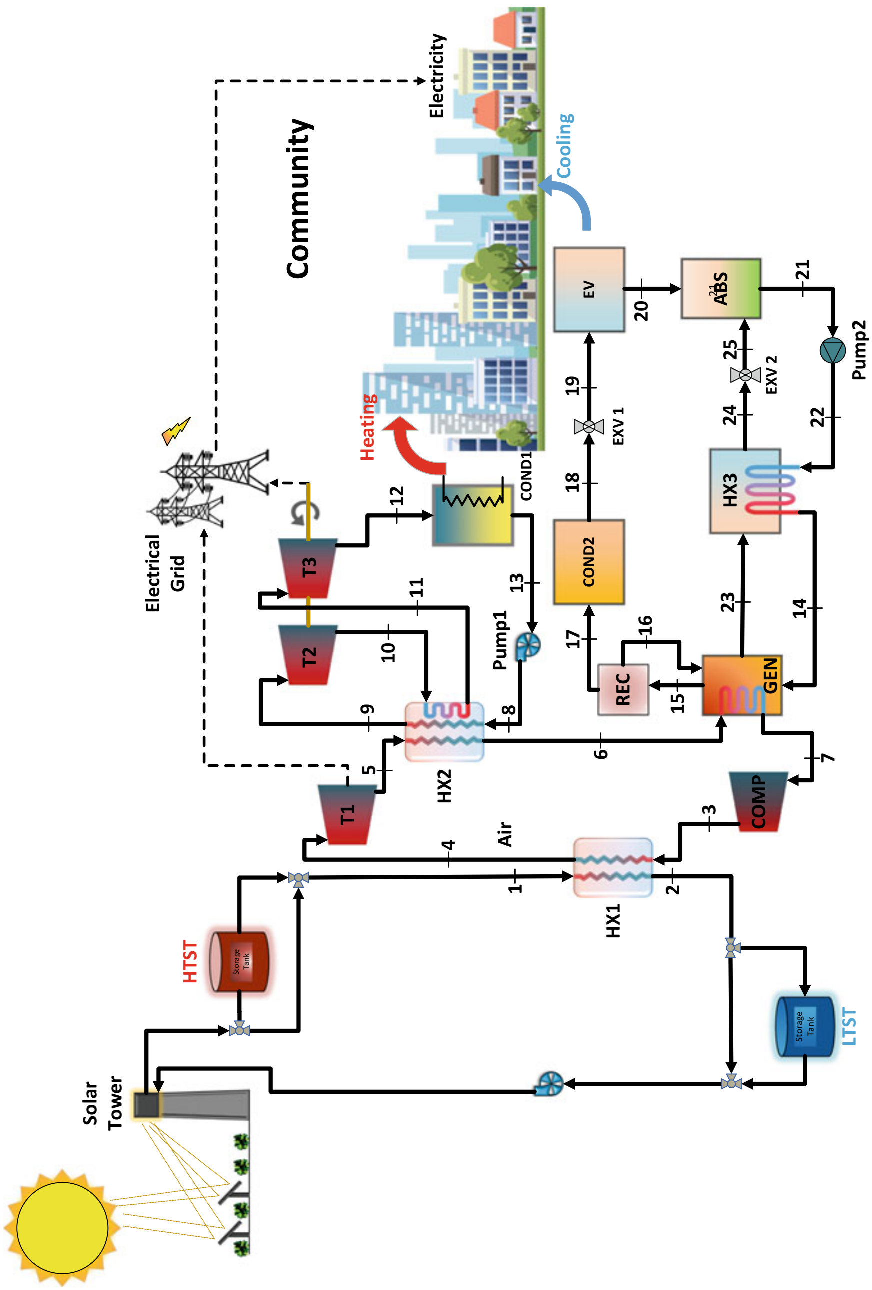

Fig. 1 Solar-based multigeneration system schematic

temperature molten salt storages are being used to minimize energy imbalances all day, especially for the lack of solar energy. The input heat, coming through heat exchanger 1, transfers the storage system's needed energy to the combined cycle. Thus, the power is produced by Brayton and reheat Rankine cycle, respectively. Moreover, the remaining heat feeds the absorption refrigeration system via HX3 to produce cooling as a valuable output for the community. This designed system consists of three sub-systems, respectively: (1) Brayton cycle, (2) reheat Rankine cycle, and (3) absorption refrigeration cycle.

2.1 Solar Tower (ST)

The total energy available in the incoming solar irradiance is calculated in the above formula:

$$\dot{Q}_{in} = SI.A_{heliostat} \tag{1}$$

The formula 2 is used to compute the total energy received by the heliostats in terms of heliostat area and efficiency:

$$\dot{Q}_{receiver} = SI.A_{heliostat}.\eta_{heliostat} \tag{2}$$

The total energy transmitted to the thermal fluid is determined by subtracting the radiation energy from the total energy received by the heliostats as follows:

$$\dot{Q}_{solar} = \dot{Q}_{receiver} - \dot{Q}_{radiation} \tag{3}$$

where $\dot{Q}_{radiation} = A_{receiver}.\eta_{reveiver}.\sigma.\left(T_0^4 - T_{receiver}^4\right)$.

2.2 Brayton Cycle (BC)

The solar tower and molten salt storage system are used to provide the energy needed by the Brayton cycle. In this sub-system, the air is utilized as a fluid. The solar tower outlet temperature in the system is determined as 900 °C, and the molten salt temperature reaching the solar tower is 445 °C. A thermal energy store system basically consists of a higher temperature thermal storage tank and a lower temperature thermal storage tank maintained at 800 °C and 445 °C, respectively. The energy absorbed by the thermal fluid is transported through heat exchanger 1 to the combined cycle for power production. Thus, the energy is transferred to the air, used as the thermal fluid in the Brayton cycle, at ambient conditions ($T_0 = 293$ K; $P_0 = 101:325$ kPa). Moreover, electrical power is generated in Turbine 1. In the further step, the reheat

Rankine cycle receives the excess heat from the Brayton cycle via heat exchanger 2, acting as a condenser.

2.3 Reheat Rankine Cycle (RRC)

In this sub-system, the water is utilized as a heat transfer fluid. The rejected heat, coming from the Brayton cycle, generate vapour at stage 9 through heat exchanger 2. After this steam is used in the high-pressure turbine, it is expanded again in the low-pressure turbine to generate shaft work one more time. As the water vapour leaving the low-pressure turbine at stage 12 passes through the condenser, it emits heat that can be utilized for the community. In addition, in this way, the water will pass into the liquid phase at stage 13 and become pressurized by the pump.

2.4 Absorption Refrigeration Cycle (ARC)

An absorption refrigeration cycle is included to achieve the desired cooling by utilizing the waste heat. Water-ammonia mixture is used as heat transfer fluid in this cycle. The hot air from heat exchanger 2 transfers the heat required for the ARC as it passes through the generator, which acts as a heat exchanger. At stage 15, while the water ammonia mixture to condenser 2 passes through the rectifier, most of the water returns to the generator. The remaining and very pure ammonia passes through the condenser and releases some heat to the environment. In the designed system, the ammonia-water mixture fraction rate is 0.99 at stage 17. At constant entropy between stages 18 and 19, the temperature of the ammonia passing through the throttling valve drops dramatically. Expansion valve outlet temperature is slightly below $-15°$ for the designed system. In the evaporator, ammonia, which draws heat from the environment, heats up and reaches the absorber. It combines with the hot water vapour from the generator and heat exchanger 3, respectively, and reaches pump 2. Pressurized water ammonia mixture passes through heat exchanger 3, recovering some of the waste heat and returns to the generator.

3 Modelling and Analysis

This study uses Engineering Equation Solver (EES) software (EES 2021) academic professional version 10.836-3D to complete parametric studies. The ambient (reference) temperature is taken as $T_0 = 293$ K, and the reference pressure is taken as $P_0 = 101.325$ kPa. The following assumptions were made to aid in the analysis:

- Both turbines and pumps have an isentropic efficiency of 80%.

- The turbines and pumps are adiabatic.
- The temperature increases in pumps is negligible.
- The changes in kinetic and potential energies and exergies are negligible.
- The temperature difference between solar tower and molten salt storage tanks is taken as 100 °C.

3.1 Brayton Cycle (BC)

This designed system utilizes the solar tower as a heat resource. The required heat for the Brayton cycle is transferred through heat exchanger 1. The amount of heat transferred via heat exchanger 1 is calculated as 9885 kW. The compressor of the Brayton cycle entails a pressure ratio of 8. The compressor inlet comprises an ambient air input at 25 °C. The heat exchanger efficiencies used for all processes are accepted as 100%. The mass, energy, entropy, and exergy balance equations can be represented for the Brayton cycle as follows:

Compressor

It is used to pressure the air from the generator to obtain the necessary pressurized air before expansion into the turbine. Here, the pressure ratio is chosen as 8. This means that the pressure, which is 101.325 kPa in stage 2, increases 8 times when leaving the compressor in stage 3 and becomes 810.60 kPa. The mass energy, entropy and exergy balance equations for compressor is written as:

$$\text{MBE: } \dot{m}_3 = \dot{m}_7 \tag{4}$$

$$\text{EBE: } \dot{m}_7.h_7 + \dot{W}_{Comp} = \dot{m}_3.h_3 \tag{5}$$

$$\text{EnBE: } \dot{m}_7.s_7 + \dot{S}_{gen,comp} = \dot{m}_3.s_3 \tag{6}$$

$$\text{ExBE: } \dot{m}_7.ex_7 + \dot{W}_{comp} = \dot{m}_3.ex_3 + \underset{dest,comp}{Ex} \tag{7}$$

Heat Exchanger 1

Here, heat exchanger 1 transfers the heat energy from the sun to the Brayton cycle and provides the necessary input energy for the system. The mass energy, entropy and exergy balance equations for heat exchanger 1 is written as:

$$\text{MBE: } \dot{m}_3 = \dot{m}_4 \text{ and } \dot{m}_{ms,h} = \dot{m}_{ms,l} \tag{8}$$

$$\text{EBE: } \dot{m}_3.h_3 + \dot{m}_{ms,h}.h_{ms,h} = \dot{m}_4.h_4 + \dot{m}_{ms,l}.h_{ms,l} \tag{9}$$

$$\text{EnBE: } \dot{m}_3.s_3 + \dot{m}_{ms,h}.s_{ms,h} + \dot{S}_{gen,HX1} = \dot{m}_4.s_4 + \dot{m}_{ms,l}.s_{ms,l} \quad (10)$$

$$\text{ExBE: } \dot{m}_2.ex_5 + \dot{m}_{ms,h}.ex_{ms,h} = \dot{m}_3.ex_3 + \dot{m}_{ms,l}.ex_{ms,l} + \underset{dest,HX1}{Ex} \quad (11)$$

Turbine 1

The heated air in heat exchanger 1 expands in turbine 1, and electricity is obtained. The mass energy, entropy and exergy balance equations for turbine 1 is written as:

$$\text{MBE: } \dot{m}_4 = \dot{m}_5 \quad (12)$$

$$\text{EBE: } \dot{m}_4.h_4 = \dot{m}_5.h_5 + \dot{W}_{T1} \quad (13)$$

$$\text{EnBE: } \dot{m}_4.s_4 + \dot{S}_{gen,ST1} = \dot{m}_5.s_5 \quad (14)$$

$$\text{ExBE: } \dot{m}_4.ex_4 = \dot{m}_5.ex_5 + \underset{dest,T1}{Ex} + \dot{W}_{T1} \quad (15)$$

Heat Exchanger 2

While the heat exchanger 2 acts as a kind of condenser for the Brayton cycle, it acts as a heat source for the reheat Rankine cycle. Thanks to heat exchanger 2, the heat released from the Brayton cycle is used in the reheat Rankine cycle. The mass energy, entropy and exergy balance equations for heat exchanger 2 is written as:

$$\text{MBE: } \dot{m}_5 = \dot{m}_6 \text{ and } \dot{m}_8 = \dot{m}_9 = \dot{m}_{10} = \dot{m}_{11} \quad (16)$$

$$\text{EBE: } \dot{m}_5.h_5 + \dot{m}_8.h_8 + \dot{m}_{10}.h_{10} = \dot{m}_6.h_6 + \dot{m}_9.h_9 + \dot{m}_{11}.h_{11} \quad (17)$$

$$\text{EnBE: } \dot{m}_5.s_5 + \dot{m}_8.s_8 + \dot{m}_{10}.s_{10} + \dot{S}_{gen,HX2} = \dot{m}_6.s_6 + \dot{m}_9.s_9 + \dot{m}_{11}.s_{11} \quad (18)$$

$$\text{ExBE: } \dot{m}_5.ex_5 + \dot{m}_8.ex_8 + \dot{m}_{10}.ex_{10} = \dot{m}_6.ex_6 + \dot{m}_9.ex_9 + \dot{m}_{11}.ex_{11} + \underset{dest,HX2}{Ex} \quad (19)$$

3.2 Reheat Rankine Cycle (RRC)

The steam Rankine cycle has a maximum cycle pressure of 5 MPa and a minimum cycle pressure of 101.325 kPa. The steam temperature at the high-pressure turbine's intake is 420 °C. The high-pressure turbine's steam outlet pressure is 1200 kPa, and the reheat temperature is 350 °C. Turbines, the compressor, and pumps are considered to have isentropic efficiencies of 80, 80, and 75%, respectively.

Pump 1

The low-pressure water leaving the condenser at stage 13 must be pressurized at pump 1 to generate power in turbines 2 and 3. As the pressure rises, the area in the T-S diagram will increase. Hence more work is produced in the turbines. While the pressure at the pump 1 inlet is 101.325 kPa, the pressure at the outlet is 5000 kPa. The mass energy, entropy and exergy balance equations for pump 1 is written as:

$$\text{MBE: } \dot{m}_{13} = \dot{m}_8 \tag{20}$$

$$\text{EBE: } \dot{m}_{13}.h_{13} + \dot{W}_{P1} = \dot{m}_8.h_8 \tag{21}$$

$$\text{EnBE: } \dot{m}_{13}.s_{13} + \dot{S}_{gen,P1} = \dot{m}_8.s_8 \tag{22}$$

$$\text{ExBE: } \dot{m}_{13}.ex_{13} + \dot{W}_{P1} = \dot{m}_8.ex_8 + \underset{dest,P1}{Ex} \tag{23}$$

Turbine 2

The water vapour, which is first pressurized in pump 1 and then brought to a high temperature by means of heat exchange 2, expands in turbine 2 and generates electrical energy. The mass energy, entropy and exergy balance equations for turbine 2 is written as:

$$\text{MBE: } \dot{m}_9 = \dot{m}_{10} \tag{24}$$

$$\text{EBE: } \dot{m}_9.h_9 = \dot{m}_{10}.h_{10} + \dot{W}_{T2} \tag{25}$$

$$\text{EnBE: } \dot{m}_9.s_9 + \dot{S}_{gen,T2} = \dot{m}_{10}.s_{10} \tag{26}$$

$$\text{ExBE: } \dot{m}_9.ex_9 = \dot{m}_{10}.ex_{10} + \underset{dest,T2}{Ex} + \dot{W}_{T2} \tag{27}$$

Turbine 3

The water vapour, whose pressure and temperature decrease by doing work in turbine 2, passes through the heat exchanger 2 one more time and its temperature increases again. Since a larger area in the T-S diagram will be obtained, the efficiencies will be higher as well as the more electricity to be produced. Here, the reheating temperature was determined as 350 °C. The mass energy, entropy and exergy balance equations for turbine 3 is written as:

$$\text{MBE: } \dot{m}_{11} = \dot{m}_{12} \tag{28}$$

$$\text{EBE: } , \dot{m}_{11}.h_{11} = \dot{m}_{12}.h_{12} + \dot{W}_{T3} \tag{29}$$

$$\text{EnBE: } \dot{m}_{11}.s_{11} + \dot{S}_{gen,T3} = \dot{m}_{12}.s_{12} \tag{30}$$

$$\text{ExBE: } \dot{m}_{11}.ex_{11} = \dot{m}_{12}.ex_{12} + \underset{dest,T3}{Ex} + \dot{W}_{T3} \tag{31}$$

Condenser 1

Relatively hot water vapour with a temperature of 126.4 °C coming out of Turbine 3 releases heat to the environment as it passes through condenser 1. In this way, both the necessary heating for the community is provided, and the water is entirely liquidized so that pump 1 can pressurize the fluid. The heating capacity of condenser 1 is calculated as 4507 kW. The mass energy, entropy and exergy balance equations for condenser 1 is written as:

$$\text{MBE: } \dot{m}_{12} = \dot{m}_{13} \tag{32}$$

$$\text{EBE: } \dot{m}_{12}.h_{12} = \dot{m}_{13}.h_{13} + \dot{Q}_{cond1} \tag{33}$$

$$\text{EnBE: } \dot{m}_{12}.s_{12} + \dot{S}_{gen,cond1} = \dot{m}_{13}.s_{13} + \dot{Q}_{cond1}/T_{b,cond1} \tag{34}$$

$$\text{ExBE: } \dot{m}_{12}.ex_{12} = \dot{m}_{13}.ex_{13} + \dot{Q}_{cond1}(1 - T_0/T_{b,cond1}) + \underset{dest,cond1}{Ex} \tag{35}$$

3.3 Absorption Refrigeration Cycle (ARC)

Generator

The residual heat from the Brayton cycle is transferred to the absorption refrigeration cycle with the aid of the generator. In this way, the necessary heat for the cooling process is obtained. There is a water-ammonia mixture in the generator. The water-ammonia mixture from state 14 is sent to the rectifier via stage 15. In Stage 16, the water leaving the mixture returns to the generator again. The balanced equation of the heat released from the Brayton cycle and sent to the generator is written as:

$$\dot{Q}_{gen} = \dot{m}_6.h_6 - \dot{m}_7.h_7 \tag{36}$$

The mass energy, entropy and exergy balance equations for generator is written as:

$$\text{MBE: } \dot{m}_{37} + \dot{m}_{39} = \dot{m}_{38} + \dot{m}_{46} \tag{37}$$

$$\text{EBE: } \dot{m}_{37}.h_{37} + \dot{m}_{39}.h_{39} + \dot{Q}_{gen} = \dot{m}_{38}.h_{38} + \dot{m}_{46}.h_{46} \tag{38}$$

$$\text{EnBE: } \dot{m}_{37}.s_{37} + \dot{m}_{39}.s_{39} + \dot{Q}_{gen}/T_s + \dot{S}_{gen,ge} = \dot{m}_{38}.s_{38} + \dot{m}_{46}.s_{46} \tag{39}$$

$$\text{ExBE: } \dot{m}_{37}.ex_{37} + \dot{m}_{39}.ex_{39} + \dot{Q}_{gen}(1 - T_0/T_s) = \dot{m}_{38}.ex_{38} + \dot{m}_{46}.ex_{46} + \underset{dest,G}{Ex} \tag{40}$$

Condenser 2

A tremendous amount of pure ammonia from the rectifier passes through condenser 2 and loses heat by dissipating some of its energy. In stage 18, the ammonia percentage of the mixture is 99.99%. The mass energy, entropy and exergy balance equations for condenser 2 is written as:

$$\text{MBE: } \dot{m}_{17} = \dot{m}_{18} \tag{41}$$

$$\text{EBE: } \dot{m}_{17}.h_{17} = \dot{m}_{18}.h_{18} + \dot{Q}_{cond2} \tag{42}$$

$$\text{EnBE: } \dot{m}_{17}.s_{17} + \dot{S}_{gen,cond2} = \dot{m}_{18}.s_{18} + \dot{Q}_{cond2}/T_{b,cond2} \tag{43}$$

$$\text{ExBE: } \dot{m}_{17}.ex_{17} = \dot{m}_{18}.ex_{18} + \dot{Q}_{cond2}(1 - T_0/T_{b,cond2}) + \underset{dest,cond2}{Ex} \tag{44}$$

Expansion Valve 1

The ammonia-water mixture is throttled in expansion valve 1 at steady enthalpy. In this way, the temperature is reduced from 40 °C to −15.13 °C. Ammonia-water mixture with decreasing temperature is sent to the evaporator. The mass energy, entropy and exergy balance equations for expansion valve 1 is written as:

$$\text{MBE: } \dot{m}_{18} = \dot{m}_{19} \tag{45}$$

$$\text{EBE: } \dot{m}_{18}.h_{18} = \dot{m}_{19}.h_{19} \tag{46}$$

$$\text{EnBE: } \dot{m}_{18}.s_{18} + \dot{S}_{gen,exv1} = \dot{m}_{19}.s_{19} \tag{47}$$

$$\text{ExBE: } \dot{m}_{18}.ex_{18} = \dot{m}_{19}.ex_{19} + \underset{dest,exv1}{Ex} \tag{48}$$

Evaporator

The cold ammonia-water mixture coming to the evaporator draws heat from the environment and provides the necessary cooling for the community. The mass energy, entropy and exergy balance equations for expansion evaporator is written as:

$$\text{MBE: } \dot{m}_{19} = \dot{m}_{20} \tag{49}$$

$$\text{EBE: } \dot{m}_{19}.h_{19} + \dot{Q}_{eva} = \dot{m}_{20}.h_{20} \tag{50}$$

$$\text{EnBE: } \dot{m}_{19}.s_{19} + \dot{Q}_{ev}/T_{s,ev} + \dot{S}_{gen,ev} = \dot{m}_{20}.s_{20} \tag{51}$$

$$\text{ExBE: } \dot{m}_{19}.ex_{19} + \dot{Q}_{ev}(T_0/T_{s,ev} - 1) = \dot{m}_{20}.ex_{20} + \underset{dest,ev}{Ex} \tag{52}$$

Absorber

The mixture, which is mostly ammonia at −11 °C from the evaporator, is mixed with the ammonia water mixture at 40.2 °C from the state 25 in the absorber. The mass energy, entropy and exergy balance equations for expansion absorber is written as:

$$\text{MBE: } \dot{m}_{20} + \dot{m}_{25} = \dot{m}_{21} \tag{53}$$

$$\text{EBE: } \dot{m}_{20}.h_{20} + \dot{m}_{25}.h_{25} = \dot{m}_{21}.h_{21} + \dot{Q}_{abs} \tag{54}$$

$$\text{EnBE: } \dot{m}_{20}.s_{20} + \dot{m}_{25}.s_{25} + \dot{S}_{gen,abs} = \dot{m}_{21}.s_{21} + \dot{Q}_{abs}/T_{b,abs} \tag{55}$$

$$\text{ExBE: } \dot{m}_{20}.ex_{20} + \dot{m}_{25}.ex_{25} = \dot{m}_{21}.ex_{21} + \dot{Q}_{abs}(1 - T_0/T_{b,abs}) + \underset{dest,abs}{Ex} \tag{56}$$

Pump 2

Ammonia-water mixture from the absorber is sent to heat exchanger 3 through pump 2. The mass energy, entropy and exergy balance equations for pump 2 absorber is written as:

$$\text{MBE: } \dot{m}_{21} = \dot{m}_{22} \tag{57}$$

$$\text{EBE: } dotm_{21}.h_{21} + \dot{W}_{P2} = \dot{m}_{22}.h_{22} \tag{58}$$

$$\text{EnBE: } \dot{m}_{21}.s_{21} + \dot{S}_{gen,P2} = \dot{m}_{22}.s_{22} \tag{59}$$

$$\text{ExBE: } \dot{m}_{21}.ex_{21} + \dot{W}_{P2} = \dot{m}_{22}.ex_{22} + \underset{dest,P1}{Ex} \tag{60}$$

Heat Exchanger 3

Ammonia-water mixture with a mass fraction of 0.3644 from pump 2 absorbs heat while passing through heat exchanger 3. At the same time, the ammonia-water mixture with a temperature of 131.9 °C coming from stage 23 also loses its heat in heat exchanger 3, reducing its temperature. The balance equations for heat exchanger 3 are written as follows:

$$\text{MBE: } \dot{m}_{22} + \dot{m}_{23} = \dot{m}_{24} + \dot{m}_{14} \tag{61}$$

$$\text{EBE: } \dot{m}_{22}.h_{22} + \dot{m}_{23}.h_{23} = \dot{m}_{24}.h_{24} + \dot{m}_{14}.h_{14} \tag{62}$$

$$\text{EnBE: } \dot{m}_{22}.s_{22} + \dot{m}_{23}.s_{23} + \dot{S}_{gen,HX3} = \dot{m}_{24}.s_{24} + \dot{m}_{14}.s_{14} \tag{63}$$

$$\text{ExBE: } \dot{m}_{22}.ex_{22} + \dot{m}_{23}.ex_{23} = \dot{m}_{24}.ex_{24} + \dot{m}_{14}.ex_{14} + \underset{dest,HX3}{Ex} \tag{64}$$

Expansion Valve 2

Ammonia-water mixture with a mass fraction of 0.2644 from heat exchanger 3 is throttled while passing through is throttled in expansion valve 2 at steady enthalpy. The mass energy, entropy and exergy balance equations for expansion valve 2 is written as:

$$\text{MBE: } \dot{m}_{24} = \dot{m}_{25} \tag{65}$$

$$\text{EBE: } \dot{m}_{24}.h_{24} = \dot{m}_{25}.h_{25} \tag{66}$$

$$\text{EnBE: } \dot{m}_{24}.s_{24} + \dot{S}_{gen,exv2} = \dot{m}_{25}.s_{25} \tag{67}$$

$$\text{ExBE: } \dot{m}_{24}.ex_{24} = \dot{m}_{25}.ex_{25} + \underset{dest,exv2}{Ex} \tag{68}$$

While Table 1 shows the state points of the system, Table 2 illustrates the primary system components' heat and power inputs and outputs.

3.4 Overall System Energy and Exergy Efficiencies

The valuable outputs of the overall system include electric power, heating, and cooling. In addition to the heat and work equations for the general design, the energy and exergy equations are represented as:

$$\Sigma \dot{Q}_{in} = \dot{Q}_{Solar} \tag{69}$$

$$\Sigma \dot{W}_{in} = \dot{W}_{P_1} + \dot{W}_{P_2} + \dot{W}_{C} \tag{70}$$

$$\Sigma \dot{Q}_{useful\_out} = \dot{Q}_{cond_1} + \dot{Q}_{cond_2} + \dot{Q}_{ev} \tag{71}$$

$$\Sigma \dot{W}_{useful\_out} = \dot{W}_{T_1} + \dot{W}_{T_2} + \dot{W}_{T_3} \tag{72}$$

$$\Sigma \dot{W}_{net} = \Sigma \dot{W}_{useful\_out} - \Sigma \dot{W}_{in} \tag{73}$$

$$\Sigma \underset{in}{Ex} = \dot{Q}_{Solar}\left(1 - \frac{T_0}{T_{sun}}\right) \tag{74}$$

$$\Sigma \underset{useful\_out}{Ex} = \dot{Q}_{cond_1}\left(1 - \frac{T_0}{T_{b,cond_1}}\right) + \dot{Q}_{CON_2}\left(1 - \frac{T_0}{T_{b,cond_2}}\right) + \dot{Q}_{EV}\left(\frac{T_0}{T_{s,ev}} - 1\right) \tag{75}$$

The overall system energy efficiency is determined as:

$$\eta_{overall} = \frac{\Sigma \dot{Q}_{useful\_out} + \Sigma \dot{W}_{net}}{\Sigma \dot{Q}_{in}} \tag{76}$$

The overall system exergy efficiency is calculated as:

Table 1 State point table for the system

State No.	Fluid	Temperature (°C)	Pressure (kPa)	Mass flow rate (kg/s)	h (kJ/kg)	s (kJ/kgK)	ex (kJ/kg)
1	Molten salt	800.00	101.33	30.00	383.7	0.43	1628.00
2	Molten salt	495.00	101.33	30.00	54.23	0.073	1404.00
3	Air	321.89	810.60	19.50	602.13	5.80	273.30
4	Air	781.56	810.60	19.50	1109.07	6.43	596.10
5	Air	431.60	101.33	19.50	718.80	6.58	162.30
6	Air	150.00	101.33	19.50	424.78	6.05	22.48
7	Air	25.00	101.33	19.50	298.60	5.70	0.02
8	Water	25.00	5000.00	2.26	109.40	0.37	5.07
9	Water	420.00	5000.00	2.26	3245.00	6.72	1364.19
10	Water	257.20	1200.00	2.26	2952.00	6.86	2313.00
11	Water	350.00	1200.00	2.26	3154.00	7.21	2412.00
12	Water	126.40	101.33	2.26	2729.00	7.49	1905.00
13	Water	25.00	101.33	2.26	104.90	0.37	0.18
14	Ammonia + Water	111.40	1556.00	9.38	310.10	1.47	−118.32
15	Ammonia + Water	108.70	1556.00	1.40	1552.00	4.90	118.88
16	Ammonia + Water	108.70	1556.00	0.13	267.80	1.36	−128.39
17	Ammonia + Water	44.70	1556.00	1.28	1309.00	4.22	76.00
18	Ammonia + Water	40.00	1556.00	1.28	190.80	0.66	0.29
19	Ammonia + Water	−15.13	234.80	1.28	190.80	0.76	−29.01
20	Ammonia + Water	−11.00	234.80	1.28	1257.00	4.88	−169.97
21	Ammonia + Water	40.00	234.80	9.38	−41.33	0.48	−179.10
22	Ammonia + Water	40.13	1556.00	9.38	−39.63	0.48	−177.40
23	Ammonia + Water	131.90	1556.00	8.11	406.00	1.66	−77.51
24	Ammonia + Water	40.13	1556.00	8.11	1.23	0.53	−151.19
25	Ammonia + Water	40.20	234.80	8.11	1.23	0.53	−151.19

Table 2 Heat and power inputs and outputs of the primary system components

System component	Capacity (kW)
$\dot{W}_{P_1}$	10.23
$\dot{W}_{P_2}$	15.94
$\dot{Q}_{Solar}$	22,679.00
$\dot{W}_{C}$	8716.00
$\dot{W}_{T_1}$	14,554.00
$\dot{W}_{T_2}$	827.00
$\dot{W}_{T_3}$	1134.00
$\dot{Q}_{COND_1}$	5901.00
$\dot{Q}_{COND_2}$	1427.00
$\dot{Q}_{EV}$	1361.00
$\dot{Q}_{ABS}$	2002.00

$$\psi_{overall} = \frac{\Sigma \underset{useful\_out}{Ex} + \Sigma \dot{W}_{net}}{\Sigma \underset{in}{Ex}} \tag{77}$$

4 Results and Discussion

The thermodynamics properties were calculated and analyzed parametrically using EES. According to the results obtained in line with the parametric studies, the energy production and consumption of the primary system components are shown in Table 2. While the system's overall energy efficiency is calculated as 69.33%, the overall exergy efficiency is found to be 41.81%. Exergy destructions of system foundation elements are calculated and illustrated in Fig. 2. According to these data, the most exergy destructions occur in heat exchanger1, compressor and heat exchanger 3, respectively.

Moreover, the energy and exergy efficiencies of the system and sub-systems are shown in Fig. 3. In contrast, the energy and exergy efficiencies of the Brayton cycle are calculated as 36.01% and 44.95%, respectively. The exact values for Reheat Rankine are found as 12.03% and 39.34%, respectively. For the absorption refrigeration cooling cycle, the COP value is determined as 0.5359. As a result, it is clearly seen that integrated systems are more advantageous than single systems in terms of energy and exergy efficiency as well as multiple useful outputs. Furthermore, the overall system's net-work generation is calculated as 16478 kW.

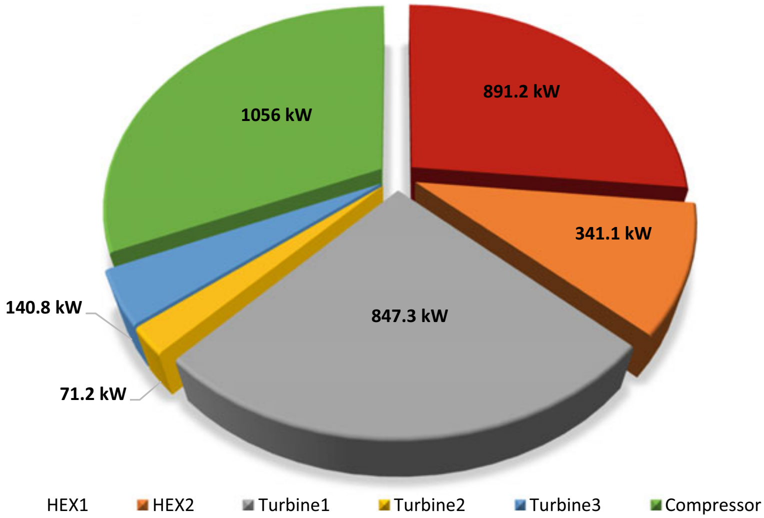

Fig. 2 Exergy destruction rates of main system components

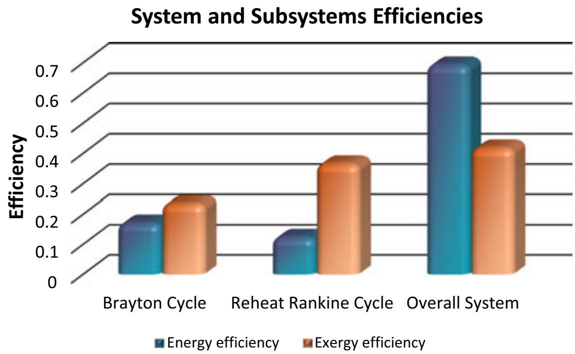

Fig. 3 Energy and exergy efficiencies of sub-systems

4.1 System and Sub-system Useful Outputs

The solar power's thermal energy supplied to the system is calculated using the energy equation stated for heat exchanger 1. The total useful heating amount produced in the system is obtained from condenser 1 and condenser 2, and this amount is 7328 kW. The total amount of cooling received with the evaporator is calculated as 1361 kW. Finally, the net amount of work produced from the turbines is 7789 kW when the electricity for the compressors and pumps is subtracted. The required energy transferred from the solar tower to keep this system running is calculated as 14,731 kW.

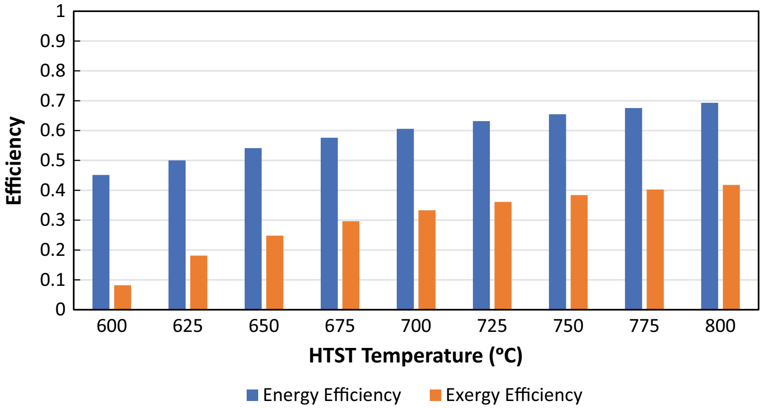

Fig. 4 The effect of inlet temperature on system efficiencies

4.2 The Effect of Inlet Temperature on System Efficiencies

In Fig. 4, the energy and exergy performance of the system is shown according to the higher temperature thermal storage tank temperature level. The data clearly shows that as the inlet temperature increases, the efficiency of the system gradually increases. While the system was being designed, molten salt NaCl-MgCl2 was chosen as a thermal fluid to be used in thermal storage tanks, and the allowable range is 450–800 °C for it because this temperature range is the conditions where our thermal fluid is in the liquid phase (Xu et al. 2018). The system constraint here is the operating temperature range of molten salt. For this reason, we cannot go above 800 °C as the inlet temperature because the operating range of the molten salt we have used here does not allow this. However, it should not be forgotten that the input temperatures should be as high as possible so that our system efficiency can be as high as possible. Therefore, it would be logical to feed our system at a high temperature as our thermal fluid allows.

4.3 The Effect of Outlet Temperature on System Efficiencies

In Fig. 5, similar to the previous figure, the energy and exergy performance of the system is illustrated according to the lower temperature thermal storage tank temperature level. The data clearly shows that as the outlet temperature decreases, the system's efficiency will increase inversely. The system constraint here is the operating temperature range of molten salt. For this reason, we cannot go under 450 °C as the outlet temperature indicated in 4.2 because the molten salt can be considered of fully melted at the temperature of 450 °C. As can be seen from Figs. 4 and 5, the increase in the inlet temperature of the source feeding the system and the lower

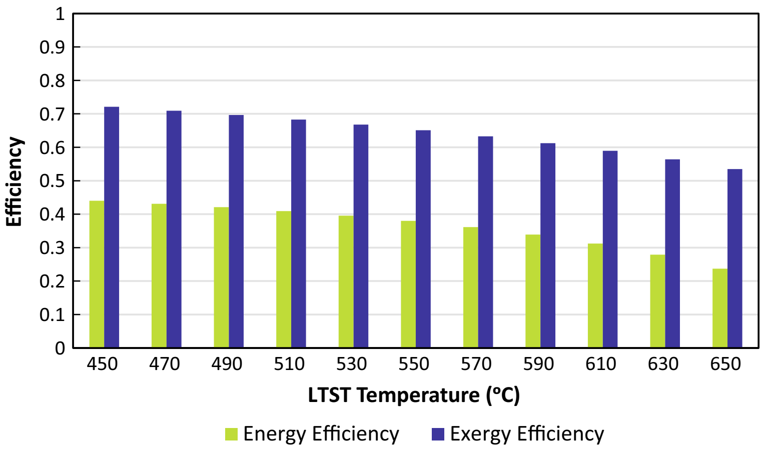

Fig. 5 The effect of outlet temperature on system efficiencies

leaving temperature from the system have a significant positive effect on the system efficiencies.

5 Conclusions

In the designed trigenerational system, the effect of operational modifications such as inlet temperature on the system is analyzed to assess production as well as the performance of the solar-based integrated system. Furthermore, parametric studies are performed to determine the overall energy and exergy efficiencies. Consequently, a system is built that uses only renewable energy and produces various valuable outputs such as heating, cooling, and electricity generation. Some of the findings of this study are listed as follows:

- The system's net electricity production, heating, and cooling capacity is observed to be 2918 kW, 4507 kW, and 1361 kW, respectively.
- The designed system's total energy and exergy efficiencies are calculated as 69.33% and 41.81%, in this order.
- The energy and exergy efficiency for the Brayton cycle are calculated as 17.1% and 23.6%, respectively. For the reheat Rankine combined process, these values are found as 12.4% and 36.6%, respectively.
- The compressor has the greatest exergy destruction rate, 891 kW, followed by the heat exchanger 1 and turbine 1 at 1056 kW and 847 kW, in this order.
- The coefficient of performance for the absorption refrigeration cycle is found to be 0.5359.

One of the essential conclusions we can draw from this study is the high energy conversion rates provided by such systems, where many valuable outputs are produced instead of focusing on only one useful output. No one denies that multigeneration energy system's efficiencies are much higher compared to traditional energy conversions. Another important conclusion to be drawn is that system efficiency is highly dependent on supply temperatures. Naturally, the idea of feeding the system with as high a temperature as possible may come to mind, but as in everything else, certain factors limit the design. For instance, the molten salt operating range is the main constrain for this system.

In addition to the high energy and exergy efficiencies obtained in this case study, multiple production systems are promising due to the combination of many valuable products. Since increased efficiency means more useful output with the same amount of energy input, we can easily conclude that these systems are worth considering for a sustainable environment and society, especially considering the world's increasing energy needs. According to the report published in 2010 (U. S. Oak Ridge National Laboratory 2010), while the efficiencies of the current passenger vehicle engines are slightly above 40%, it can be clearly seen that the energy efficiency of this system we designed is 69.33%. Although the design of large systems to increase efficiency brought additional operating and maintenance costs, it is apparent that it is a subject that needs to be developed and thought on it.

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A Comprehensive Exergy-Based Outlook of Renewable Technology Integration for the Fifth Generation District Energy Systems

Birol Kilkis

List of Symbols

A_p	Solar panel irradiation area, m^2
a, b	Constants of the heat pump *COP* versus temperature function. Also, see Eq. 41
ALT	Residence time in the atmosphere years
c	Exergy-based unit CO_2 content of fossil fuel, kg CO_2/kW-h of fuel exergy
c‘(LHV)	Lower-heating value-based unit CO_2 content of fossil fuel, kg CO_2/kW-h of fuel exergy
c_K	Direct CO_2 responsibility factor in the district energy system (depending upon whether thermal or power exergy is lost upstream or downstream of an energy conversion system, respectively, kg CO_2/kW-h
C_{eq}	Equipment Life-Cycle Cost-Design Temperature Difference Factor, €·K/kW h
C_{hp}	Heat Pump Life-Cycle Cost-Design Temperature Difference Factor, €/K·kW h
C_i	Curie
COP	Coefficient of performance
COPEX	Exergy-based coefficient of performance
CO_2	Carbon dioxide emission, kg of CO_2
CO_{2base}	Base (Reference) emission, kg of CO_2
CR_{EX}	Exergy-based compactness ratio
DU	Dobson unit
E	Electrical energy (load), kW-h

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E_x	Exergy, kW
EDR	Ratio of carbon CO_2 emissions difference to the base emission, dimensionless
ELC	Exergy-Levelized Unit Cost, €/m^2 (Based on REMM)
EM	Composite embodiment cost, €
EMR	Exergy embodiment recovery, years
FC	Selling price of the solar panel, €
GWP	Global warming potential
H	Well depth, m
ID	District Pipe Inner Diameter, m
I_n	Total solar insolation normal to solar receiver surface, kW/m^2
I_{UVB}	Solar UVB radiation
K	Ratio of solid fuels in power generation
L	One-way District circuit distance, km
n	Number of heat pumps in cascade
ODI	Composite Ozone Depletion Index
ODP	Ozone Depleting Potential
OF	Equipment oversizing ratio
P	Power demand for pump stations, kW
P_a	Auxiliary thermal power exergy demand, kW
PC	Unit power cost of a solar energy system, €
PEF	Primary energy factor
Q, Q_H	Thermal energy (load), kW-h
R_X	Renewable energy ratio in the exergy mix
RHC	Renewable Heating and Cooling
S_c	Solar constant, 1.3661 kW/m^2
T	Temperature, K
T_D	District supply temperature, K
T_E	Solar panel temperature, K
$\dot{V}$	Volume flow rate, m^3/h
W_p	Weight of a solar panel, kg
W_k	Weight of each material used in a panel, kg
X	Flow Split

Greek Symbols

η_B	First-Law boiler efficiency
η	First-Law efficiency
η_T	Power transmission and distribution efficiency
η_W	Wind turbine-to-electricity First-Law efficiency
Ψ_R	Rational exergy management efficiency
ε	Unit exergy, kW/kW
ΔCO_2	Avoidable CO_2 emissions, kg CO_2/kW-h heat
$\sum CO_2$	Total CO_2 emissions (Direct and avoidable), kg CO_2/kW-h heat

Superscripts

‘	Modified (after over insulation)
n	Equipment capacity power (Eq. 21)

Subscripts

a	Indoor air
app	Useful application (Temperature)
base	Base
BE	Electric boiler
c	Cooling
D	Design condition
dem	Demand
des	Destroyed
E	Electric
e	Break-even
eq	Equipment (heating or cooling)
X, EX	Exergy, exergetic
F	Fan
f	Energy source, fuel
g	Geothermal
H	Thermal (Heat)
hp	Heat pump
in	Input, return
m	Mean, average
min, max	Minimum, maximum
NG	Natural gas
o	Original
opt	Optimum
out	Output, supply
P	Pump
R	Reservoir, return
ref	Reference environment (Temperature)
ret	Return
sup	Supply
s, solar	Solar
T	Power transmission, total, overall
test	The test conditions
wind, wt	Wind, Wind Turbine

Acronyms

ABS, ADS	Absorption, Adsorption Cooling Machine
API	American Petroleum Institute
CHP	Combined heat and power (Cogeneration)
DE	District Energy System, 5th Generation District Energy System
5DE	5Th Generation District Energy System
DHW	Domestic Hot Water
EIA	Energy Information Administration (US)
EEA	European Environment Agency
EPA	Environmental Protection Agency
EU	European Union
ESP	Electrical submersible pump
FC	Fuel Cell
FPC	Flt-Plate Solar Collector
GSHP	Ground-source heat pump
HE	Heat exchanger, or Hydrogen Economy
IAQ	Indoor Air Quality
IEA	International Energy Agency
HVAC	Heating, Ventilating and Air-Conditioning (of Buildings)
LowEx	Low Exergy (Building)
nZEXB	Near-Zero Exergy Building
nZCB	Near-zero Carbon Building
ORC	Organic Rankine Cycle
PCM	Phase-Changing Material
PV, PVT	Photo Voltaic, Photo-Voltaic- Heat
REMM	Rational Exergy Management Model
TES	Thermal Energy Storage

1 Introduction

EU countries have developed roadmaps about 100% renewable energy utilization (100%RHC) and total electrification with renewable energy sources for building heating and cooling services using heat pumps. Based on the First Law of Thermodynamics, it is claimed that heat pumps running on 100% renewable electricity are not responsible for CO_2 emissions (Blum et al. 2010). According to the Second Law of Thermodynamics, this is not the case because the 1st Law does not recognize that energy sources have different qualities (Exergy) regarding the large exergy mismatch between high-exergy electric power and low-exergy thermal power generated. Exergy is the useful work potential of a given quantity or flow of energy. Especially with low-temperature systems, the quality of a given renewable energy source becomes particularly important.

1.1 Quality of Renewable Energy

Electricity, whether generated from renewable energy sources or fossil fuels, has high exergy of 0.95 kW/W, which means that 95% of the energy quantity may be utilized in a wide range of useful applications besides heating or cooling. Exergy is defined by the ideal Carnot Cycle (Kılkış 2014; Kilkis 2012):

$$\text{Exergy (Quality)} = \left(1 - T_{ref}/T_{\text{sup}}\right) \times \text{ Energy (Quantity)} \tag{1}$$

Here, T_{ref} is the reference environment temperature, and T_{sup} is the supply temperature in a district heating system. For example, if T_{ref} is chosen to be 283 K (Winter ground temperature) and a ground-source heat pump system provides heat at 320 K to the district, exergy will be only 0.115 of the quantity of the heat supplied. Because heat pumps use electrical power, their coefficient of performance, *COP* must be sufficiently high to match the electrical power exergy and the thermal exergy of the heat supplied:

$$COP \geq 0.95/0.115 = 8.3$$

If *COP* is less than 8.3, part of the electrical power exergy will be irreversibly destroyed, which has to be offset by someone, somewhere, sometimes by some type of fuels, causing additional CO_2 emissions responsibility. This emission is called nearly-avoidable emissions, ΔCO_2, because it may be largely avoided by minimizing the exergy destructions. On the contrary, if only the 1st Law would be considered, any *COP* greater than one would be acceptable as a green application as long as renewable energy systems drive it.

1.2 Wide Availability of Low-Exergy Heat Sources

Low-temperature renewable and waste heat sources from different sectors below 100 °C are abundant worldwide, corresponding to 63% of all the available waste heat sources. Unit exergy, ε of any waste heat below 100 °C may be quite low ($\varepsilon < 0.24$ kW/kW at a source temperature of 100 °C, and a reference temperature of 283 K). About 50% of them have temperatures below 50 °C. However, this is not a critical problem. Instead, today's major problem is the significant mismatch between the low Carnot exergy of the widely available low-temperature sources and the existing indoor heating equipment.

1.3 The Conflict Between the Existing Building Stock and Low-Temperature Heating

In many EU countries, half of the residential stock comprises buildings, which were built before 1970, when the first thermal efficiency regulations were not in place yet (EC 2014). Most of these buildings are energy-inefficient; despite some thermal insulation retrofits are in place, their thermal loads are high. They run on old heating equipment like steel or even cast-iron radiators or natural-convection coils, which were designed for high supply temperatures. Therefore, there is a significant conflict between the many old buildings in existence, which demand high supply temperatures, and the new EU roadmap of utilizing low-temperature thermal sources. Old hydronic heating equipment was designed for at least 70 °C of supply design temperature (T_{eq}). EU is moving towards ultra-low temperature district energy systems, namely the Fifth-Generation DE (5DE) systems supplying temperatures as low as 35 °C (T_{sup}) (van Dijk et al. 1998; Hesaraki et al. 2015). In the Framework of IEA Annex 37, a comprehensive compilation of research was carried out on low-temperature heating and its potential implications and the so-called side effects (IEA 2000). They argued that adding passive building systems for better retaining of solar gains and other internal sources with continuous but lower thermostat settings shave off the peak loads and somehow enhance the utilization of low-temperature heat supplies. They further considered floor heating, wall heating, oversized radiators and convectors, and air heating. Their studies were not too conclusive about energy performance, which were limited to the 1st Law of Thermodynamics only, and they did not investigate the effect of district piping and pumping on energy benefits or disadvantages.

The potential impacts of low-temperature heating from the perspective of buildings about indoor air quality (IAQ), comfort, and energy have been further investigated by Eijdems, Boerstra, and Veld, without considering the conflict between energy supply temperature and the equipment demand temperature (Eijdems et al. 2000). For public understanding and acceptance, they termed the low-exergy (Temperature) energy as 'low valued' energy. They overviewed the impact of low-temperature supply to heating equipment for several types of equipment, including radiant floor and wall panels, low-temperature air heating. They qualitatively claimed that IAQ and sensation of comfort improve mainly by using radiant panels, which already permit low temperatures for operation. However, they did not study how low-temperature heating may be accomplished by innovative equipment and oversizing the existing equipment, except noting that heat pump *COP* values may increase due to reduced temperature deficit between the supply and demand. Figure 1 models this conflict. When the low-temperature source is provided at T_{sup}, over insulation of the old buildings may reduce the deficit. However, additional thermal exergy must still be provided by temperature-peaking units at the expense of additional fuel, which defeats the purpose of decarbonization. Over insulation of the buildings may be a weak option because of embodiments and thermo-physical constraints. Even if over insulation will be possible to a certain extent, then the building heat loads may be

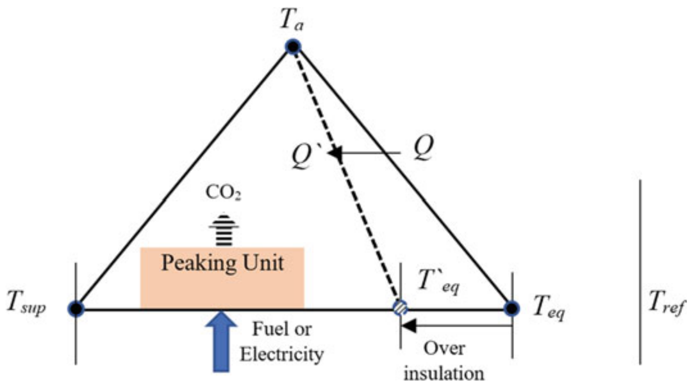


Fig. 1 Conflict between low-temperature district heating and buildings (Kilkis 2021a)

somehow decreased, which will reduce the supply temperature requirement of the equipment, T_{eq} to T'_{eq}. In the same token, any temperature peaking unit may increase the design supply temperature to T'_{eq}. It is possible to determine an optimum relation between the over-insulation process and equipment oversizing regarding the Rational Exergy Management Efficiency (REMM), ψ_R, given in Eq. 2 (Kılkış and Kılkış 2018). T'_{eq} is the supply temperature required by the heating equipment after optimally oversizing it for minimizing the need for temperature peaking. T_a is the indoor design temperature. In cooling applications, where $T_a < T_{ref}$, the same equation may be used, provided that parentheses are replaced by absolute-value bars (Jansen and Woudstra 2010).

$$\psi_R = \frac{\varepsilon_{dem}}{\varepsilon_{\text{sup}}} = \frac{\left(1 - \frac{T_{ref}}{T_a}\right)}{\left(1 - \frac{T_{ref}}{T_{\text{sup}}}\right) + \left(1 - \frac{T_{\text{sup}}}{T`_{eq}}\right)} \quad \{\text{Maximize}\} \tag{2}$$

1.4 *Fifth Generation District Heating (5DE) Challenges*

Despite challenges for 5DE systems, an important asset for decarbonization is the widely but sparsely available low-exergy renewable energy sources and waste heat. The main challenges are:

1. Low-exergy and exergy-incompatibility challenge. Low-exergy resources have been ignored so far primarily because the building heating and cooling systems are not compatible yet with low temperatures in heating and high temperatures in cooling. This challenge requires an optimum mix of temperature peaking and conventional equipment oversizing. The ultimate solution will be low-exergy heating and cooling equipment.

2. Temperature peaking challenge. As mentioned in previous sections of this chapter, the low-exergy thermal supply of renewables may be problematic when temperature adjustments are necessary with heat pumps or other conventional energy conversion systems like boilers in temperature peaking. Temperature peaking means exergy destructions. This challenge needs carefully designed and operated temperature peaking (in heating) systems with minimum exergy destructions.
3. Colocation challenge. Renewable energy sources are sparsely distributed over a wide range, which requires an infrastructure of a network of district pipelines. Beyond embodiments and additional costs, pumping power demand exergy may exceed the thermal power circulated in the district.
4. Co-existence challenge. Peak supply periods between wind and solar energy resources are generally not co-existent on the time scale. Generally, there are about six hours of the time difference between solar energy and wind energy peaks during a typical day. Such a time co-existence challenge requires energy and power storage systems.

Therefore, it becomes necessary to collect different renewable energy sources available from several points, store them as necessary, and then distribute heat and cold to the buildings through a carefully sized district energy system, with on-site prosumers. All of these functions call for district energy systems. Therefore, low-exergy district heating and cooling systems are attracting more attention than before.

1.5 Centralized or De-centralized Peaking

Temperature peaking may be applied either at the central plant (Centralized) or at the district prosumers at an individual building level (Decentralized). A third option may be a hybrid of them. Figures 2 and 3 show the basics of these two alternatives. Each alternative has advantages and disadvantages. The centralized system houses large and preferably cascaded heat pumps in tandem for higher *COP* values for heating and cooling. The advantages are centrally manageable thermal energy storage, savings

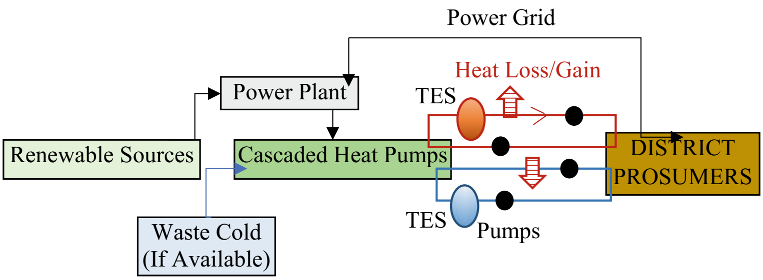


Fig. 2 Centralized temperature peaking in a district energy system

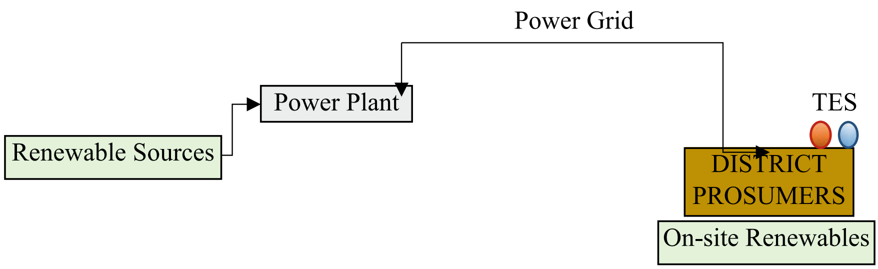


Fig. 3 De-centralized temperature peaking in a district energy system

from grid losses corresponding to power transmission to the district to satisfy individual heat pumps there, easier and better maintenance, proximity to renewable energy systems and ability to centrally utilize district wastes for biogas and biomass, better power balancing, and acting as central power storage for prosumer-generated electricity. The main disadvantages are heavy infrastructure, piping network both for heat and cold supply, distribution and metering problems among individual prosumers, higher heat losses because the transfer of heat from the central plant to the district is already peaked. Higher heat losses require more pipe insulation. In turn, high temperatures permit a higher temperature difference between the supply and return so that pumping power demand (lower fluid flow rates) may be reduced. For the cooling circuit, the same applies. The cold waste source must be closer to the district, which might require the placement of heat pumps somewhere in between the plant and the district.

Figure 3 corresponds to a de-centralized peaking alternative, where each prosumer has their heat pumps on-site (some neighboring buildings may share). The main advantage is the total elimination of the district piping system and the pumps, which may consume large amounts of electrical energy, especially if the distance is large. In this case, thermal metering and distribution of heat are easier and simpler. Each building may have its on-board and on-site solar, wind, and geothermal energy sources. A minor disadvantage is the increased grid load of individual heat pumps, cascading problems, and maintenance problems. Individual TES units may not be shared with neighbors easily. Heat losses or gain in the district piping is eliminated.

1.6 Quality or Quantity of Renewable Energy Sources

Any exergy mismatch among supply and demand points causes nearly-avoidable CO_2 emissions, which are as large as direct emissions in magnitude, and solar energy is not an exception. However, there have been few studies about solar energy and solar districts (EBC 2018). Science Europe Scientists also issued a memorandum on the critical need to consider the quality of energy, particularly in the built environment (SE, Science Europe 2016).

Solar Energy: The maximum quality of solar energy is derived by relating the solar constant, S_c outside the atmosphere (1.3661 kW/m^2), to the sun's surface temperature, 5778 K (Kilkis 2020a). 0.95 kW/kW is the maximum unit electrical exergy that a PV cell may generate under such conditions if Q_{solar} is taken to be the solar insolation over 1 m^2 PV area facing the sun, at a global reference temperature of 283 K. Some Authors round it to 1 kW/kW but this is impossible in our universe because the reference temperature may not be 0 K and the source temperature may not be infinity.

$$\varepsilon_{solar} = \left(\frac{E_{Xsolar}}{Q_{solar}}\right) \leq \frac{(1 - 283\,K/5778\,\mathrm{K})\ \mathrm{kW/kW}}{\left(1.3661\,\mathrm{kW/m^2} \times 1\,\mathrm{m^2}\right)}$$
$$= \frac{0.95\ \mathrm{kW/kW}}{\left(1.3661\ \mathrm{kW/m^2} \times 1\,\mathrm{m^2}\right)} 0.695\ \mathrm{kW/kW} \tag{3}$$

Therefore, the maximum *quality* of solar energy, $E_{Xsolar,}$ is 69.5% of the *quantity* of solar energy received i, Q_{solar} in space. On earth, the unit solar exergy will be lower because the total solar insolation on a solar panel on earth, I_n, [kW/m^2] will be less than S_c:

$$\varepsilon_{solar} = (0.95 \times I_n)/1.3661 \quad \{I_n < S_c\} \tag{4}$$

For example, if I_n is 0.757 kW/m^2 and the solar insolation surface area, A_p, is 1 m^2, the maximum useful work potential that any solar panel, irrespective of its type, may supply on earth is given below. The actual amount depends on the solar system, i.e., flat-plate collector (FPC), photo-voltaic panel (PV), or photo-voltaic-thermal panel (PVT).

$$E_{Xsolar} \leq 0.695 \times Q_{solar} = 0.695 \times I_n \times A_p = 0.695 \times 0.757\ \mathrm{kW/m^2} \times\ 1\ \mathrm{m^2}$$
$$= 0.526\ \mathrm{kW}.$$

Although none of the solar systems use fossil fuels, they are responsible for nearly avoidable (indirect) CO_2 emissions resulting from the quality of solar energy that they reject upstream or downstream the electrical or thermal power, or both that they generate.

An FPC system shown in Fig. 4-a supplies only thermal power and rejects the major portion of E_{Xsolar}, upstream instead of generating electrical power (Kilkis 2021b). The loss of electric power generating opportunity needs to be offset somewhere, by some other technology, possibly by a mix of fossil fuels and renewables with a ratio of R_X. This additional fuel spending causes indirect CO_2 emissions responsibility in a district, which is now expressed in terms of the REMM efficiency, ψ_R.

$$CO_{2responsible} = c_K(1 - \psi_R)(1 - R_X) = c_K\left(1 - E_{X\,\mathrm{sup}}/E_{Xsolar}\right)(1 - R_X) \tag{5}$$

The factor (c_K) depends on the average direct CO_2 emissions of the energy sector, attributable either to electrical power generation and transmission over a typical grid (0.63 kg CO_2/kW-h, from fuel to plug) or on-site thermal power generation (0.27 kg CO_2/kW-h: natural-gas boiler). These values are based on the exergy of the lower-heating value of fossil fuels (Reference: natural gas with $c = 0.2$ kg CO_2/kW-h/0.87 [kW/kW]). In turn, the same FPC avoids direct CO_2 emissions from the grid in proportion to the amount of thermal power it supplies. Table 1 gives sample data and the results both in terms of quality and quantity.

$$CO_{2avoided} = c_K E_{X\,\mathrm{sup}}(1 - R_X) \tag{6}$$

Therefore, for any solar energy system, the net CO_2 avoidance, ΔCO_2 will be the difference:

$$\Delta CO_2 = CO_{2avoided} - CO_{2responsible} \tag{7}$$

For a typical FPC (Fig. 4a), if R_X is 0.1 (10% renewables in the energy mix), T_1 is 340 K, and T_2 is 320 K (solar hot water supply and return temperatures, respectively, and η_{FPC} is 0.7, then per unit Q_{solar};

$$\begin{aligned} CO_{2responsible} &= 0.63\left(1 - \left(1 - \frac{320\ \mathrm{K}}{340\ \mathrm{K}}\right) \times 0.7/0.695\right)(1 - 0.1) \\ &= 0.533\ \mathrm{kg\ CO_2/kW\text{ - }h} \end{aligned}$$

$$CO_{2avoided} = 0.27 \times \left(1 - \frac{320\ \mathrm{K}}{340\ \mathrm{K}}\right) \times 0.7 \times (1 - 0.1) = 0.010\ \mathrm{kg\ CO_2/kW\text{ - }h}$$

$\Delta CO_2 = 0.010 - 0.533 = -0.433$ kg CO_2/kW - h ($-\Delta CO_2$: positive carbon).

A PV cell generates electric power, upstream but misses the thermal power generation opportunity.

$\psi_R = E_{Xsup}/0.695 = (0.95 \times \eta_{PV} + 0.035 \times \eta_c)/\ 0.695 = 0.246$.

$CO_{2avoided} = 0.63 \times \eta_{PV} \times 0.95$ x (1-R_X) = 0.097 kg CO_2/kW-h.

$CO_{2responsible} = 0.27$ x (0.695–0.18 × 0.95) x (1–0.1) = 0.127 kg CO_2/kW-h.

ΔCO_2 = -0.030 kg CO_2/kW-h (almost carbon neutral).

A PVT system combines both FPC and PV functions and thus minimizes quality rejections. A heat exchanging system cools the PV cells so that their power efficiency is maintained at high temperatures. $\psi_R = 0.225/0.695 = 0.246$.

$$\begin{aligned} CO_{2avoided} &= 0.63 \times \eta_{PVT} \times 0.95 \times (1 - 0.1) \\ &= 0.108\ \mathrm{kg\ CO_2/kW\text{ - }h\ (With\ electrical\ power\ generated)} \end{aligned}$$

Table 1 $E_{Xsolar} = 0.695$ kW, $R_X = 0.1$

Solar system	Solar energy quantity, $Q_{solar} = 1$ kW				Solar energy quality, $E_{Xsolar} = 0.695$ kW					
	Power generated	Energy quantity efficiency	T_1	T_2	E_{Xsup} [kW]		ψ_R	$CO_{2avoided}$	$CO_{2responsible}$	ΔCO_2
			[K]		Power	Heat		[kg CO_2/kW-h of solar energy]		
FPC	Thermal	$\eta_{FPC} = 0.7$	340 K	320 K	n/a	0.041	0.059	0.010	0.333	−0.433
PV	Electric	$\eta_{PV} = 0.18$	n/a	n/a	0.171	n/a	0.246	0.097	0.127	−0.030
PVT	Electric	$\eta_{PV} = 0.20$	n/a	n/a	0.190	n/a	0.324	0.108	~ 0	+0.108
	Thermal	$\eta_c = 0.55$	330 K	300 K	n/a	0.035		0.008	0.114	−0.034
	Totals for PVT				0.225			0.116	0.114	+0.006

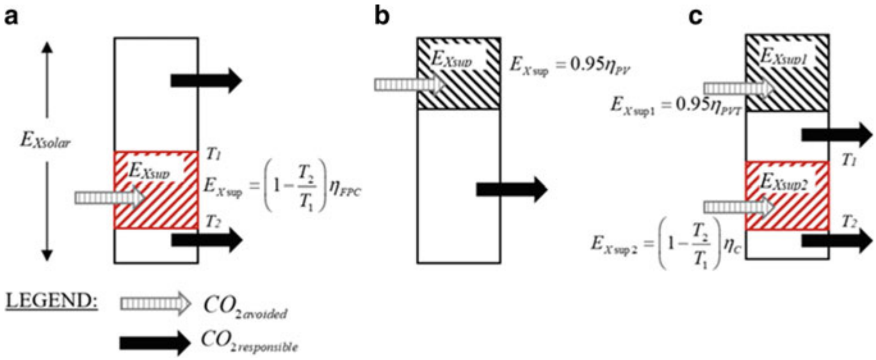


Fig. 4 **a** FPC panel**, b** PV panel, **c** PVT panel

$$CO_{2avoided} = 0.27 \times \left(1 - \frac{300\ \text{K}}{330\ \text{K}}\right) \times \eta_c \times (1 - 0.1)$$
$$= 0.012\ \text{kg CO}_2/\text{kW - h (With thermal power generated)}$$

Total $CO_{2avoided} = 0.12$ kg CO_2/kW-h.
$CO_{2responsible} = 0.27 \times 0.695$ (1- ψ_R) x (1–0.1) = 0.114.
$\Delta CO_2 = 0.12–0.114 = +\ 0.006$ kg CO_2/kW-h (Carbon negative).

These results, presented in Table 1, show the essence of considering the quality of energy in solar projects of any size and application. Table 1 also shows that energy quantity may sometimes mislead the designer or practitioner. For example, solar FPC has high energy quantity efficiency (0.70) but a very low output of solar quality (0.041 kW). Conversely, the PV panel has the lowest efficiency (0.18) but more than four times more solar quality output than FPC (0.171 W).

1.7 CO_2 Emission Responsibility of not Utilizing Available Solar Insolation Areas

The above discussion may be extended further by questioning what happens if freely available areas for solar energy utilization are not used. If solar insolation surfaces are freely available, like building roofs, without much shading obstructions from the vicinity and do not have any other potentially more value-adding function options, this area is available for solar energy utilization. If not utilized, then this means that this surface has a CO_2 emissions responsibility, which is also an indicator for other greenhouse emissions. Three scenarios are identified:

- Photo-Voltaic (PV) System
- Flat-Plate Collectors (FPC)
- Photo-Voltaic-Thermal (PVT) Panels.

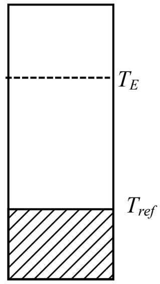


Fig. 5 Exergy flow bar for the waste of solar area by PV panel installation

1.7.1 Scenario 1: PV Panel

This scenario corresponds to installing PV panels if feasible at a given location and expected demand (Only power). Until PV panels are installed, any unit area ($A_p = 1\ m^2$) of available space for solar utilization will be responsible for direct emissions because no power is generated; thus, no CO_2 emissions are reduced from the stock. If PV panels are installed, then electrical power will be generated upstream, and the corresponding amount of CO_2 emissions from the stock would be avoided in the power grid. However, the thermal power potential is lost downstream. This loss causes indirect (nearly-avoidable) emissions responsibility, namely ΔCO_2 (due to exergy loss) responsibility of installing PV panels (except embodiments). According to Fig. 5, the empty section represents the emissions responsibility of not installing PV panels. The dashed section is the ΔCO_2 responsibility that PV panels come with because they only generate electrical power and destroy the rest of the solar exergy.

Then the net emissions responsibility of *not* installing PV panels will be the difference between grid emissions responsibility and the ΔCO_2 when PV panels are installed.

$$\sum_{PV} CO_2 = [c \times PEF - 0.27\varepsilon_{des}] \times (1 - R_X) \tag{8}$$

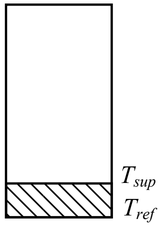
$$\varepsilon_{des} = \left(1 - \frac{T_{ref}}{T_E}\right) \tag{9}$$

T_E is the PV panel temperature under design conditions without any cooling. T_{ref} is the reference environment temperature. For GSHP-based (ground-source heat pump) analyses provided in this chapter, a stable reference temperature has been selected to an average ground temperature of 283 K.

1.7.2 Scenario 2: FPC Panel

If only FPC panel installation is feasible at a given location and expected demand (only Heat). According to Fig. 6, the empty section represents the emissions responsi-

Fig. 6 Exergy Flow Bar Showing the Waste of Solar Area by FPC Panel Installation



bility of not installing FPC panels, and the dashed section is the ΔCO_2 responsibility if FPC panels are installed just for hot water supply. The rest of the solar exergy is destroyed in the FPC system.

$$\sum_{FPC} CO_2 = \left(\frac{c}{\eta_B}\right) - 0.63\varepsilon_{des} \tag{10}$$

$$\varepsilon_{des} = 0.95 - \left(1 - \frac{T_{ref}}{T_{\text{sup}}}\right) \tag{11}$$

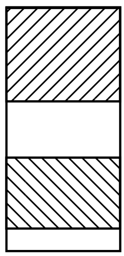
Here 0.95 kW/kW is the unit exergy of electric power. Usually, the net balance is negative. FPC systems come with more ΔCO_2 responsibility, economic and environmental footprints exceed potential benefits.

1.7.3 Case 3: PVT Panel

If PVT panel installation is feasible (Climate, demand profiles, temperature peaking requirements, etc.) at a given location and expected function (Power and Heat Generation).

According to Fig. 7, empty sections representing the ΔCO_2 responsibility are limited because both electrical and thermal powers are generated at the same unit panel area.

Fig. 7 Exergy flow bar showing the waste of solar area by PVT panel installation



$$\sum_{PVT} CO_2 = \sum_{PV} CO_2 + \sum_{FPC} CO_2 \tag{12}$$

A_p is the same (1 m^2) because a PVT system overlays PV and FPC on almost a single area. These equations show that a building owner is responsible for not utilizing the free solar area (except heat island effects, shading effects), if not useful for other purposes, and if the PVT system is feasible. Therefore, FPC systems are not useful at all. For example, roof areas must be allocated to more useful applications like green roofs.

Summary of Unit Exergy of Renewable Energy Sources

Solar Energy:

$$\varepsilon_{solar} = \frac{0.95 \times I_n}{S_c} \tag{13}$$

{see also Eq. 3}.

Wind Energy:

$$\varepsilon_{wind} = \left(1 - \frac{T_{ref}}{T_{wind}}\right); \tag{14}$$

$$T_{wind} = \frac{T_{ref}}{(1 - 0.95\eta_{Iw})}. \tag{15}$$

Therefore,

$$\varepsilon_{wind} = 0.95\eta_{Iw} \tag{16}$$

The efficiency of a wind turbine is limited by the Betz Law, which is 0.593. Therefore, the maximum unit exergy of a wind turbine is 0.56 kW/kW, which is less than the unit solar exergy of 0.62 kW/kW at $I_n = 0.85$ kW/m^2. Wind energy may compete with solar energy for I_n values less than 0.765 kW/m^2.

Geothermal Energy:

$$\varepsilon_{geothermal} = \left(1 - \frac{T_{ref}}{T_f}\right) \tag{17}$$

For example, if T_{ref} is 283 K and the wellhead temperature is 343 K (70 °C), the unit exergy will be only 0.175 kW/kW. This equation also holds for all forms of waste heat sources.

2 Primary Metrics

Five metrics were developed to facilitate the minimization of CO_2 emissions during the design and operation phases of renewable technologies, their penetration into practice, and energy policies about 5DE systems. These metrics encompass the entire model given in the next section. These metrics may be treated as general constraints for renewable energy systems. These metrics expand the concept of the standard levelized cost concept by including embodiments, supply exergy, 1st Law efficiencies, and the panel area. First, costs must be levelized according to the exergy output. *ELC* also includes exergy rationality, thus, environmental cost. Exergy-Levelized Cost,

$$ELC = \left(\frac{PC + EM \times W_p}{I_{test} A_p \psi_R \left[\varepsilon_{\sup E} \eta_E + \varepsilon_{\sup H} \eta_H \right]} \right) \{ EUR/\mathrm{kW_{EX\,peak}}/\mathrm{m}^2 \} \tag{18}$$

W_p is panel weight, thus also represents embodiments, *PC* is in Euro. *EM* is in Euro/kg. *ELC* is at design (Test Conditions), which excludes energy and CO_2 embodiments.

- Exergy-Levelized Emissions

  A similar equation may also be derived for CO_2 embodiments plus due to exergy destructions during operation at a given renewable ratio, R_X:

$$ELC_{CO_2} = \left(\frac{EM_{CO_2} \times W_p + 0.27(1 - R_X) I_{test} A_p (1 - \psi_R)}{I_{test} A_p \psi_R \left[\varepsilon_{\sup E} \eta_E + \varepsilon_{\sup H} \eta_H \right]} \right) \{ \mathrm{kg\ CO_2/kW_{EX\,peak}/m^2} \} \tag{19}$$

- Equation 19 may be extrapolated to *EMR*, which is the exergy recovery period in years by dividing ELC_{CO2} by the net CO_2 savings per year.
- Exergy-Based Compactness Ratio

  CR_{EX} evaluates the total exergy output of a solar panel for given solar supply exergy at design conditions per unit weight, defining the rational exergy management performance intensity of a solar panel. The panel weight, $W_{p,}$ is also an indicator of energy, exergy, and CO_2 embodiments. The ideal panel is rational and light (High CR_{EX}).

$$CR_{EX} = \left(\frac{A_p}{W_p} \right) \left[\frac{\varepsilon_{\sup E} \eta_E + \varepsilon_{\sup H} \eta_H}{(0.95 \times I_n / 1.3661)} \right] = \left(\frac{A_p \psi_R}{W_p} \right) \tag{20}$$

- The Ratio of Operational Emissions to Embodied Emissions, R_{CO2}

This metric is the ratio of the nearly-avoidable CO_2 emissions to the embodied CO_2 emissions due to oversizing ratio, *OF*. Figure 8 is a sample plot for different

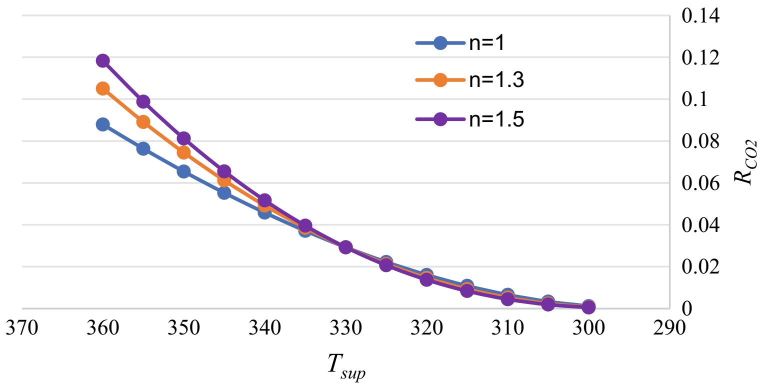


Fig. 8 Variation of R_{CO2} with T_{sup}

(n) values, showing the decrease in R_{CO2} with decreasing T_{sup}. Another advantage of low T_{sup} is that R_{CO2} becomes independent of (n). Three curves intersect at $T_{sup} =$ 330 K, where the oversizing was arbitrarily equated to one. The advantage of lower supply temperatures supports the EU roadmap of low and ultra-low heating districts.

Here (n) is the heating equipment performance exponent. For example, for a carefully optimized heat pipe radiator, n maybe 0.88, where for a conventional fan-coil, it may be 1.4. Figure 8 shows that innovative equipment must carry low n values (Kılkış et al. 2021).

$$R_{CO_2} = \frac{\Delta CO_2}{OF} = 0.27\varepsilon_{\text{sup}}\frac{(1-\psi_R)}{OF}$$
$$= 0.27 \times \left(\frac{T_{ref}}{T_{\text{sup}}}\right)\left(1-\frac{T_a}{T_{\text{sup}}}\right) / \left(\frac{(T_D - T_a)}{(T_{\text{sup}} - T_a)}\right)^n \tag{21}$$

3 Development of the Model

Figure 9 shows how complicated its connections and the district background of a prosumer solar building with a central plant, possibly including fossil fuel use. This system is responsible for five different CO_2 emission sources. In addition to the direct and nearly-avoidable CO_2 emissions responsibility during operation and embodied CO_2 emissions during manufacture of the systems, CO_{2em}, there are two additional components of CO_2 emissions equivalencies, which remain unaccounted. These are health-equivalent CO_2 emissions from coal and lignite power plants, converted from radioactive emissions from the stack and I_{UVB}, CO_{2N+UV}. Ozone depletion effect from cooling towers and refrigerant leakages from chillers, adsorption/absorption cooling machines, and heat pumps are combined in GWP equivalent emissions,

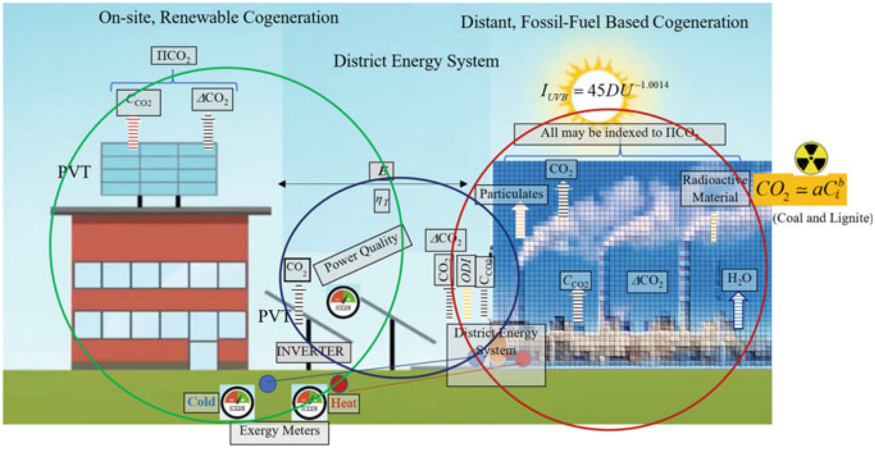


Fig. 9 Background of a net-zero prosumer building in the built environment

CO_{2GWP}. These are five components of $CO_{2\ \text{that}}$ also apply for temperature peaking and equipment oversizing.

$$\Pi CO_2 = \underset{1+}{CO_2} + \underset{2+}{\Delta CO_2} + \underset{3+}{CO_{2em}} + \underset{4+}{CO_{2GWP}} + \underset{5}{CO_{2N+UV}} \quad (22)$$

1. Direct Emissions Responsibility for the power (grid) and local thermal back-up, CO_2.

$$CO_2 = cPEF \times X_E \times (1 - R_X) + c(X_H/\eta_B) \times (1 - R_X) \quad (23)$$

- X_E: Annual ratio of electrical power backup from the grid (net after prosumer supply to the grid).
- X_H: Annual ratio of local thermal power backup.
  X_E and X_H are the ratios of annual-average backup demand (net after supply to the power grid).
- R_{EX}: Exergy-based ratio of the average renewable energy mix in the 5DE.
- c: Exergy-based average unit CO_2 content of fossil fuels, kg CO_2/kW-h of fuel exergy:

$$c = c'(\text{LHV})/\varepsilon_F \quad (24)$$

For example, c'(LHV) of natural gas is 0.2 kg CO_2/kW-h. $\varepsilon_F = 0.87$ kW/kW. Then c is 0.2/0.87 = 0.2298 kg CO_2/kW-h of fuel exergy. Normally, in district energy systems, fossil fuels are spent in non-condensing thermal energy conversion systems. The same also holds for cogeneration systems. This model uses the lower heating value (LHV) of fossil fuels.

2. Nearly-avoidable CO_2 emissions due to exergy destructions, ΔCO_2. See Eqs. 4a, 4b, 4c. Embodied CO_2 emissions, CO_{2em}. Koroneos and Kalemakis, for example, give embodied CO_2 as well as energy and cost values for different materials in their paper (Koroneos and Kalemakis 2012). These values can be used to determine embodiments of different systems. For any given system, composed of m number of major components, each having a different material weight of W_k where EM_{CO2} is the CO_2 embodiment per kg of used material weight during manufacturing.

$$CO_{2em} = \sum_{k=1}^{m} W_k \times EM_{CO_2} \tag{25}$$

3. This is a combined emissions component due to the radioactive particulate release when ash meets with humid air at the exit of a power plant's stack using coal and lignite. The water vapor released from open cooling towers is also taken into account.

$$CO_{2N+UV} = aC_i^b + d(I_{UVB})^e \tag{26}$$

$$I_{UVB} = 45DU^{-1.0014} \tag{27}$$

C_i is the curie unit of radioactive emissions from the stack of a thermal power plant using solid fossil fuels (Except biomass). DU is the Dobson Unit equivalence of emissions. The coefficients a, b, d, and e depend upon solid fuel properties, type, and power plant efficiency.

4. Greenhouse effect equivalent CO_2 of Refrigerant Leakages (Heat Pumps or adsorption cooling machines), CO_{2GWP}. It must be kept in mind that beyond their CO_2 emissions responsibility, heat pumps come with ozone-depleting potential, even with the recent F-gas refrigerants and even better refrigerants in the market. Although the newest commercial refrigerants are claimed to have zero ozone-depletion potential (*ODP*), their global-warming potential (*GWP*) values are high, which can be translated to equivalent ΔCO_2 emissions in terms of the global warming effect. Usually, they have zero *ODP* but still have non-zero *GWP*. Equation 28 is a combination of them (Kılkış 2019). *ALT* is the average residence years of a refrigerant in the atmosphere. Interestingly, CO_2 is gaining popularity as a refrigerant gas to minimize the *ODI* and CO_2 emissions equivalency.

$$ODI = \frac{0.1GWP^{0.03}}{(1 - ODP)} \left(\frac{ALT}{1} \right)^{0.01} \quad \{ODP < 1\}. \tag{28}$$

CO_2 has the lowest *GWP* (1: By definition) and *ODP* (0) but long *ALT* (100 years). For example, R-507 has zero *ODP* but 3300 *GWP* (ETB 2021). Therefore, R-507 seems to be a safe refrigerant but a high CO_2 emission equivalency of leakages due to its high *GWP* value, often neglected in industry. Additional CO_2 emissions responsibility of Leakage is given below. The first term is the emissions responsibility of the refrigerant leakage. The second term concerns the heat pump exergy destructions. The third positive term represents the savings of electrical power from the grid by eliminating a conventional chiller.

$$CO_{2\,GWP} = \Delta CO_{2_1} + \Delta CO_{2_2} - \Delta CO_{2_3} = \left(\frac{CDH}{CDH + HDH}\right) \times HLR \times ODI + 0.63 \times \left(\frac{0.95}{COP_c}\right) - \frac{c_k PEF}{COP_{ch}} \{\text{Cooling mode}\}. \quad (29)$$

$$HLR = LR \times (CH/5780\,\text{h}) \quad CH = \text{Annual Charge of Refrigerant [kg]} \quad (30)$$

3.1 *Temperature Peaking with Heat Pumps*

3.1.1 Oversizing Versus Temperature Peaking with Heat Pumps

A solar PVT system trying to satisfy the heating load, Q of a building, has a limited capacity of heating the fluid from T_{in} to T_{out} in its hydronic circuitry to maintain the PV cells sufficiently cool for maximum power generating efficiency. Both the return and the supply temperatures need to be low. However, neither of these temperatures fit the supply and return temperature requirements of standard heating equipment, like a radiator. Therefore, the heating equipment must be oversized, or the supply temperature must be peaked. On the other hand, an oversized heat pump compensating its lowered *COP* due to the lower supply temperature available from the PVT system (with or without temperature cascading) means more cost, ozone depletion potential (*ODP*), and more ΔCO_2 emissions responsibility.

Economy-Based Optimum

Figure 10 shows the temperature conflict concerning the rated operating temperatures between the design supply temperature, T_{fhp} to meet a given thermal load, Q at Point A, and the design supply temperature, T_{feq} required by standard heating equipment to deliver the same thermal load at point B (Kilkis 2000).

Either the heat pump has to be oversized and, or the equipment must be oversized. From a cost perspective only, the following equation provides the optimum solution for T_{fopt}, according to which both the heat pump and the equipment must be partially oversized for minimum cost. In Eq. 31, C_{hp} and C_{eq} are the life-cycle cost factors for the heat pump and the equipment, respectively[$/kW-h].

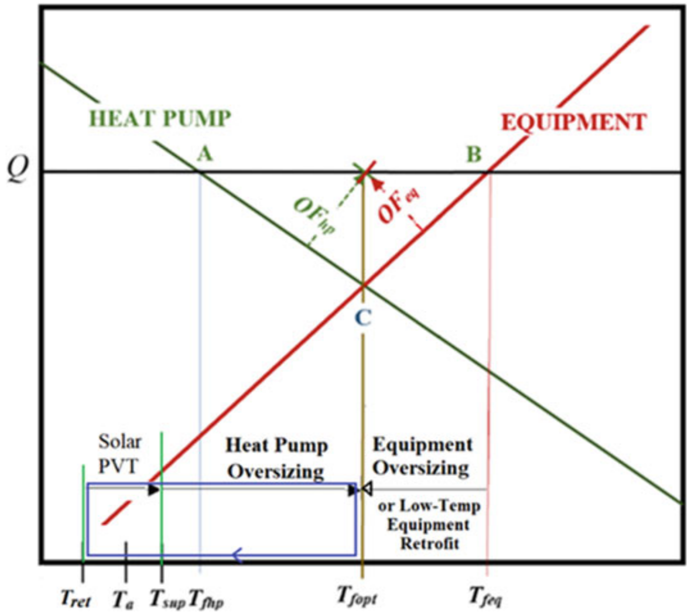


Fig. 10 Optimum resolution of the temperature conflict between heat pumps and the heating equipment (Kilkis 2000).

$$T_{fopt} = \sqrt[n]{\frac{nC_{eq}C_2}{C_{hp}/C_1}} + T_a \tag{31}$$

T_a is the design indoor comfort temperature, and the factor (n) is the power of the heating capacity equation of the equipment. (n) depends on the type of the equipment and varies between heat-piped radiators and 1.5 (convectors) (Kılkış et al. 2021; Kilkis 2000). Similar derivations may be made for minimum emissions responsibility, embodied costs, material, and energy quality spent.

$$C_1 = T_{fhp} - T_{\text{sup}};\ C_2 = \left(T_{feq} - T_a\right)^n \tag{32}$$

Exergy-Based Optimum for Minimum Emissions

$$CO_2 = OF_{HP} \times \left(\frac{c_K PEF}{COP} + EM_{CO_2} + CO_{2GWP} + 0.63 \times 0.95\right)$$
$$\{COP \propto 1/OF_{HP};\ \varepsilon_{dem} \text{assumed constant}\} \tag{33}$$

Here, CO_{2n+UV} component is neglected. For CO_{2GWP} see Eq. 29. The refrigerant leakage rate (*LR*) is assumed to be constant with the heat pump size. The last term represents unit exergy destruction with OF_{HP}.

3.1.2 Cascading of Heat Pumps for Higher *COP* Values

Smaller heat pumps in series may be arranged such that each heat pump operates at small temperature lifts, thus increase the total *COP* (Kilkis 2021a, c).

$$COP = a + b(n/\Delta T_o) \tag{34}$$

COP increases with lower ΔT in each heat pump by using multiple heat pumps (n) in series to cover the total temperature peaking required, ΔT_o. However, to accommodate for n values greater than two, where each ΔT must be at least 2 K, ΔT needs to be increased proportionately, which is bounded by indoor comfort requirements. The following rule is applied:

$$\Delta T = [5\text{ K} + (n - 1) \times 1.2\text{ K}]\ \{\ \Delta T \geq +2\text{ K}\} \tag{35}$$

$$\varepsilon_{des} = 0.95 - COP \times (1 - T_{out}/T_{in}) \tag{36}$$

For zero exergy destruction leading to zero carbon condition ($\varepsilon_{des} = 0$), *COP* from the above expression must be 54.15 in a standard indoor space application with 7 °C/12 °C regime. This *COP* value is impossible, and there will always exergy destructions, causing ΔCO_2 emissions responsibility.

The *COP* value may be increased using two heat pumps in series, which share the 5 K of ΔT_o equally (2.5 K for each heat pump). Then the *COP* value of each heat pump increases from 5.5 ($n = 1$, $\Delta T = 5$ K) to 9.06 ($n = 2$, $\Delta T = 2.5$ K), if the coefficients a and b are 0.5 and 25 K^{-1}, respectively, for a typical heat pump. This value is the upper limit because, for the higher number of series-connected heat pumps ($n > 2$), ΔT decreases below 2 K, and it is not economically feasible to have more and smaller heat pumps. Moreover, the reliability of a series heat pump connection, R_{total} decreases according to the $R_{total} = R_1$ x R_2 x R_3… reliability rule. If the reliability is not a concern, and the total ΔT may be increased from 5 K to 9.8 K, n may be increased up to five ($n = 5$), which increases the *COP* of each heat pump to 15.25 from 9.06 ($n = 2$). This is still a far lower value for the condition $\varepsilon_{des} = 0$. There is a diminishing return of using more heat pumps in series, as shown in Fig. 11. The reliability of the heat pump agglomeration may be split into an optimum set of series and parallel connections at the cost of reduced *COP*. CO_2 is gaining popularity as a refrigerant. CO_2 has the lowest *GWP* (1: By definition) and zero *ODP* but long *ALT* (100 years). For example, R-507 has zero *ODP* but 3300 *GWP* (ETB 2021).

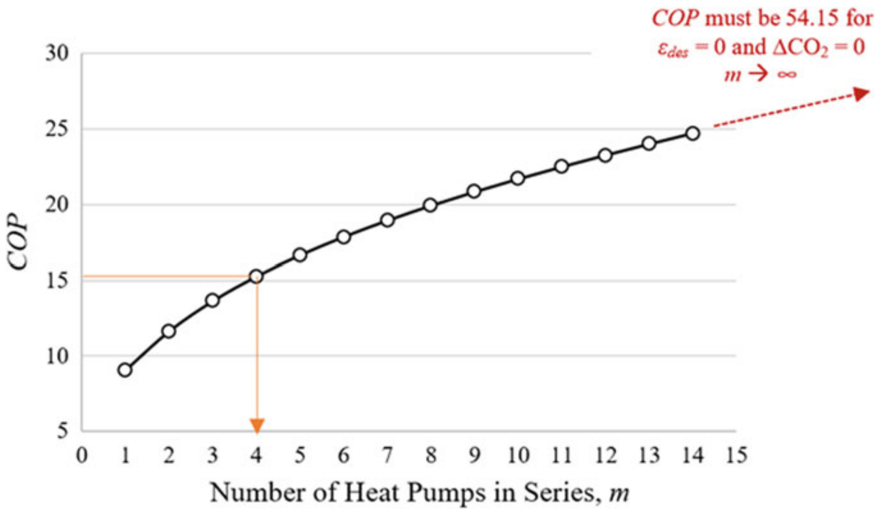


Fig. 11 Diminishing *COP* return of (m) number of temperature-peaking heat pumps in series (Kilkis 2021a)

Therefore, R-507 seems to be a safe refrigerant but has a high CO_2 emission equivalency of leakages due to its high *GWP* value, often neglected in industry.

3.2 Equipment Oversizing

Due to refrigerant leakages and cost concerns, oversizing (or adding) existing equipment is in order in many cases to keep the heat pump oversizing minimal (Kilkis 2000). As a better solution, low-temperature heating equipment must be installed or retrofitted in an existing building. Retrofitting with low-temperature systems, like floor heating, may not be easy. Another solution is the heat pipe-radiators (HPR), which already can operate at low temperatures with less oversizing and require less pumping energy. Next to the radiant panel systems, if practical (ASHRAE 2020), is to use heat pipes in radiators and PVT systems to minimize pump (or fan) power demand (Kılkış et al. 2021). Figure 12 compares hydro-dynamic properties of standard and heat-pipe radiators.

3.2.1 Exergy-Based CO_2 Emissions Responsibility of Equipment Oversizing

$$CO_{2eq} = OF_{eq} \times OF_{eq} \tag{37a}$$

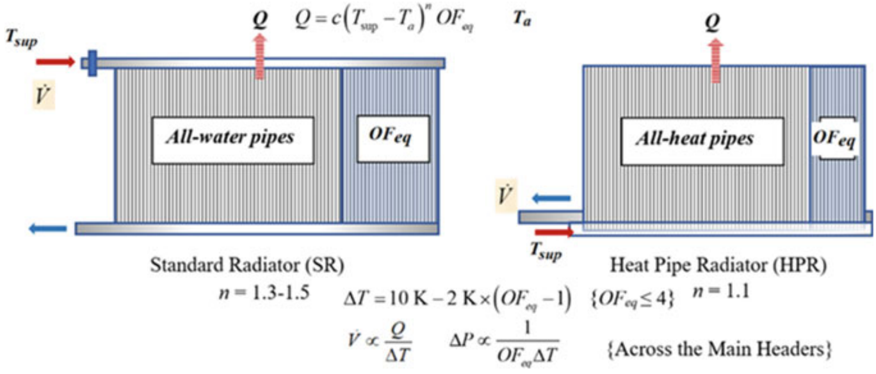


Fig. 12 Oversizing requirements of standard hydronic radiator (SR) and heat-pipe radiator (HPR)

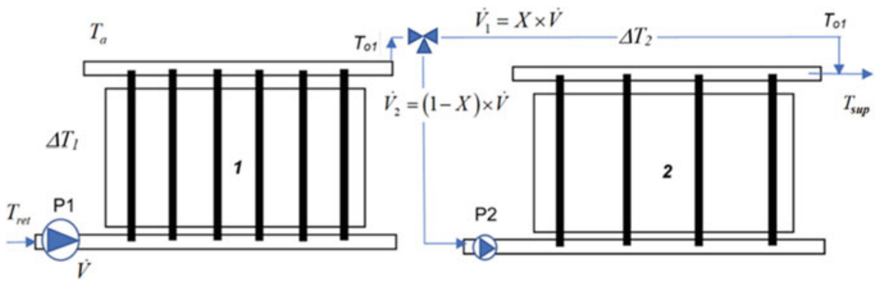


Fig. 13 Hydronic temperature cascading with series solar PVT panels

3.2.2 Tandem Solar PVT Panels for Temperature Peaking

Temperature Cascading of PVT Systems

For effective cooling of the PV panels, there is an optimum average temperature, $T_{m,}$ while thermal quality output is reasonable. The optimum temperature T_m for maximum ΣE_X is lower than what many useful thermal applications require. T_m also is not a match for the Legionella risk abatement requirements of about 65 °C supply temperature, T_{sup}, necessary for an open circuitry of domestic use. This condition often requires temperature peaking with a heat pump, electric, or fuel boiler, all of which defeats the purpose of utilizing solar energy. In Fig. 13, a second PVT panel with less electrical power efficiency but high thermal power efficiency is added in series to the first one shown on the left-hand side with the primary objective of peaking the temperature from T_{O1} to T_{O2}.

A flow-control valve optimally splits the flow for maximum quality gain. A flow-controlling valve optimally splits the flow for maximum quality gain.

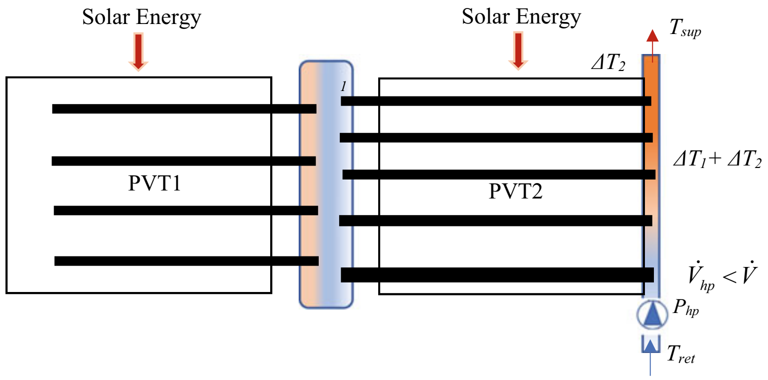


Fig. 14 Cascading with series solar PVT panels with heat pipes

PVT System with Heat Pipes

A better way is to eliminate onboard pumping, P_1, and P_2, replacing them with heat pipes. Figure 14 shows a pumpless cascading arrangement of two tandem PVT panels with heat pipes. Here, PVT1 generates electric power at high efficiency because coarse heat pipe layout does not collect much heat, thus permitting cooler mean fluid temperature, T_m. There is an interim thermal tank, which serves the moderate heat collected to the second PVT with variable heat pipe arrangement for maximum thermal output with less electrical output, thus permitting optimal temperature peaking.

$$CO_{2PVT} = OF_{PVT} \times EM_{CO2PVT} \quad \{OF_{PVT} \text{is approximately } 2\} \tag{37b}$$

Solar Panel Area Limitations in the Building

While we are trying to peak the temperature in solar energy systems, we must also be aware of space limitations. Solar PV panels do not recover heat unless a PVT system is used. Therefore, a flat-plate collector system (FPC) must complement the PV panels in tandem to offset the thermal loss unless a PVT alternative is employed. The necessity for sustainability means additional solar panel area requirements, like on the roof of a house. This addition, in turn, rejects the power generation opportunity because FPC generates only thermal power. This time another PV panel needs to be added to offset the power generation opportunity loss. Mathematically speaking, this loss-offset chain alternatively continues. At the same time, material, energy quality, and quantity embodiments build-up, even there is sufficient solar area available, which is not the case. The solar area is quite limited and at a premium, especially in urban areas. The following equation represents the geometric series concerning the CO_2 responsibility that never becomes exactly zero. Figure 15 and Eq. 38 depict this

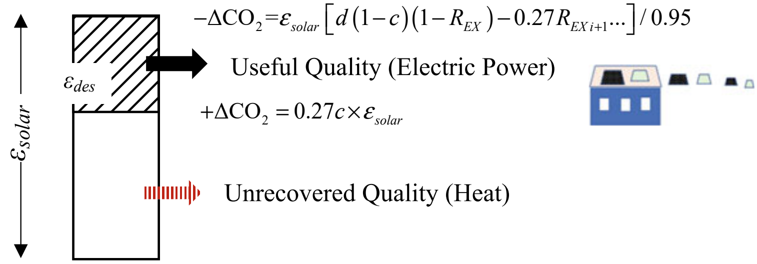


Fig. 15 If thermal exergy is destroyed downstream (PV panel)

condition.

$$\sum \Delta CO_2 = \varepsilon_{solar}\left[0.27c - \frac{d(1-c)(1-R_X) - 0.27c_{i+1}R_{X\,i+1}\ldots}{0.95}\right] \quad \{\text{With second - order cut - off}\} \tag{38}$$

Here, the term (d) is the average CO_2 content of the fuel mix for thermal power generation, and c is the ratio of destroyed quality, ε_{des} to the solar supply quality, ε_{solar}: $c = \varepsilon_{des} / \varepsilon_{solar}$. R_X is the exergy-based mix of renewables in the energy budget. The series shown in Eq. 38 cuts off at the second term.

3.3 Exergy-Based Limits on Deep Geothermal Technology

Temperature peaking by drilling deeper wells is possible for temperature peaking with an environmental cost. Drilling costs, embodiments, and operational emission responsibilities are a few of them. Pumping exergy and radiation content indicated by Gamma Ray (GR) also increase. There are four prongs of this model as shown in Fig. 16, namely: 1—The deep production well and ESP pump, 2—The wellhead to be exergy-rational for utilizing the geothermal exergy, 3—Application markets, 4—Reinjection well(s). The overall system is treated as a heat pump (*COP*), with optimum building insulation. If reinjection wells and the district are nearby, P_2 and P_3 may be ignored, and the source temperature, $T_{H,}$ is related to H by Eq. 39. Figure 16 shows the model developed for optimum well depth for minimizing CO_2 emissions responsibility. Larger ESP requires more unit electrical exergy. Assuming that an on-site natural-gas generator destroys exergy while supplies the additional electrical power, ΔCO_2 emissions responsibility arises.

$$T_H(H) = T_o + mH^c; \Delta T(H) = T_H(H) - T_o = mH^c, \tag{39}$$

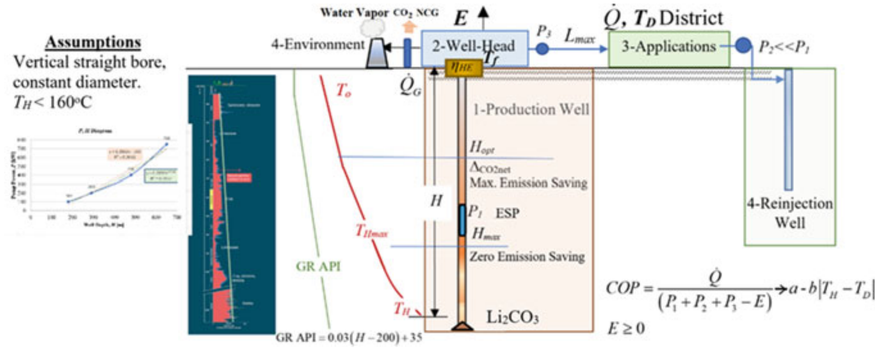


Fig. 16 Four prongs of deep geothermal energy for resource temperature peaking

Thermal exergy increase obtained by increasing H replaces unit exergy destruction of a boiler, ΔCO_{2G}:

$$\Delta CO_{2G}(H) = -0.63 \times \left(1 - \frac{T_o}{T_o + mH^c}\right) \quad (40)$$

$$\begin{aligned}\Delta CO_{2P}(H) &= +(0.27 \times 0.95)P_1 + |2.3 - R_{CO2}| \\ &\simeq +0.26aH^b + |2.3 - R_{CO2}| \text{ \{Emissions due to pump demand\}}\end{aligned} \quad (41)$$

P_1 is approximated by a power function, namely aH^b, where a and b represent the ESP characteristics. Borehole diameter may be increased to reduce P_1 at the expense of embodiments for the borehole and the pump with less operating and CO_2 costs. The net reduction in ΔCO_2, namely ΔCO_{2net} for each kW of ESP, is the difference between Eqs. 40 and 41, which must be maximized.

Direct CO_2 emission savings due to the replaced natural gas boiler and the on-site generator are equal when ($\Delta Q/\Delta P_1$) ratio is 2.43 (geothermal heat gain for 1 kW pump power increase), leaving only the ΔCO_{2net} term.

Otherwise, a remainder, R_{CO2}, which depends on geothermal enthalpy, borehole, etc., must be added. The optimum depth, $H_{opt,}$ is found by differentiating ΔCO_{2net} concerning H and then solving iteratively either from Eqs. 42 or 43 for a linear temperature profile, $c = 1$).

$$D\left(\frac{T_o H_{opt}^{c-1}}{\left(T_o + mH_{opt}^c\right)^2}\right) = H_{opt}^{b-1} \text{ \{Maximize, } R_{CO2} = 0\text{\}} \quad (42)$$

$$D\left(\frac{T_o}{\left(T_o + mH_{opt}\right)^2}\right) = H_{opt}^{b-1} \text{ \{Linear temperature profile\}} \quad (43)$$

$$D = \frac{0.63c \times m}{(0.26 \times a \times b)} = \frac{2.42c \times m}{a \times b} R_{CO2} = 0.2\left(\frac{1}{0.35} - \frac{1}{0.85}\frac{\dot{Q}}{P_1}\right) \quad (44)$$

Once H_{opt} is determined, the maximum temperature, T_{Hmax} obtainable at H_{opt} for maximum emissions sequestration, is calculated from Eq. 39. H_{max} may be iteratively found at $\Delta CO_{2net} = 0$:

$$\Delta CO_{2net} = 0 = 0.26aH^{b}_{\max} - 0.63\left(1 - \frac{T_o}{T_o + mH^{c}_{\max}}\right)\{H_{max} > H_{opt}\} \quad (45)$$

3.4 *Wind Energy and Heat Pumps*

Figure 17 shows a wind energy-driven heat pump system that provides low-exergy cold for comfort cooling. The wind turbine has zero CO_2 emission at the wind input as long as the grid power backup is not present. If power is exchanged with the grid, the net CO_2 emissions responsibility from the power plant periodically backing up the system must also be considered. The heat pump generates cold at a supply temperature of 287 K (14 °C) for a LowEx building that may be cooled at high temperatures. The return temperature is 292 K (14 °C). Such high temperatures raise the *COP* of the heat pump by ΔCOP. In turn, the heat pump destroys a large amount of unit exergy of [0.95–0.017] kW/kW, which will be responsible for ΔCO_{22}. Furthermore, refrigerant leakage and water vapor released from the cooling towers are responsible for ΔCO_{21}.

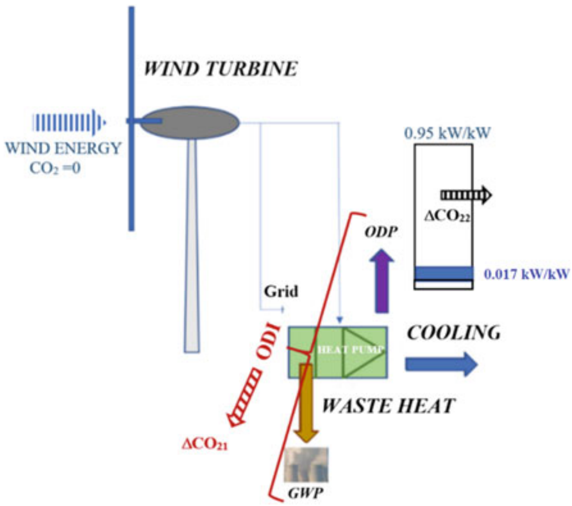


Fig. 17 The combination of a wind turbine and a heat pump is not carbon free

This system may be environmentally rational by reducing CO_2 emissions at the power plant due to increased ΔCOP, according to the condition in Eq. 46, which is quite difficult to satisfy.

$$\frac{c \times PEF}{\Delta COP} > \frac{[\Delta CO_{21} + \Delta CO_{22}]}{K \times (1 - R_X)} \tag{46}$$

Instead of a heat pump with the above problems, a hybrid wind turbine and solar PVT system have been designed, as shown in Fig. 18. This system is an on-shore version of a hydrogen harvesting ship for the Black Sea H_2S gas (Kılkış and Taseli 2021; Uyar 2019). This version employs the towers of existing or new wind turbines in close vicinity of district energy systems, which eliminates the heat pumps. If a geothermal reservoir is also in the vicinity, it is used for power generation with an ORC system. Part of the power generated is used to separate H2S gas to hydrogen and sulfur. In a water nexus cycle, hydrogen is generated and stored. The stored hydrogen drives the fuel cell on demand. All waste heat from the fuel cell, ORC, and adsorption cooler is also utilized as a low-exergy heat source like in greenhouses in the open farmland. Solar PVT panels, which can track the sun, are mounted on the turbine towers. Mechanical energy storage is possible in compressed air (in the tower cavity) and thermal energy in TES desirably with PCM content. Cooling by adsorption chillers has less carbon footprint than a heat pump.

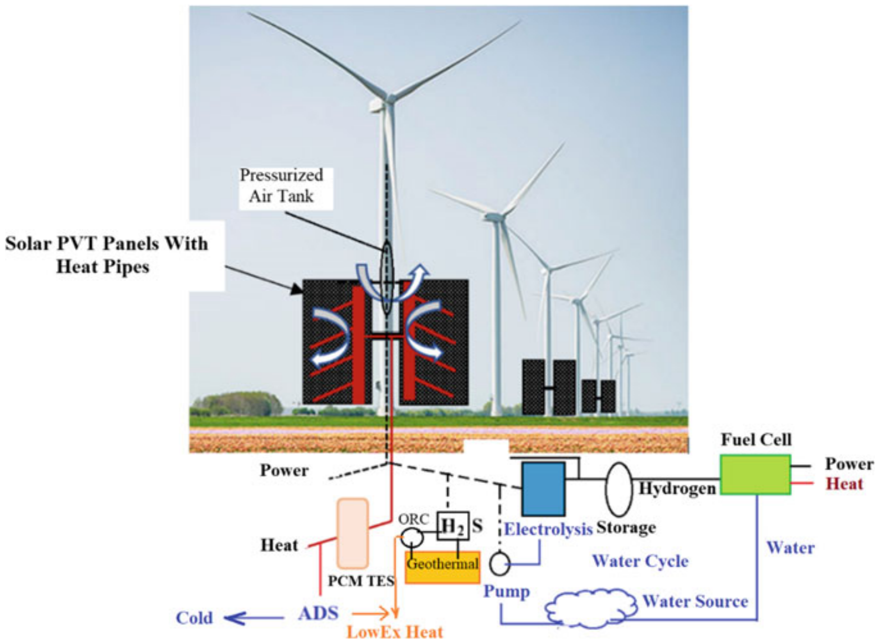


Fig. 18 Hybrid colocation of wind turbine, solar PVT and geothermal (if available) (Kılkış and Taseli 2021)

3.5 Renewable District Energy Systems and the Maximum Distance

Within the scope of 100% Renewable Heating and Cooling target for 2050 (RHC-ETIP 2019), Low-temperature solar heat finds wide demand in low-temperature district energy systems (Gawer and Cezarz 2016). Recently, large-scale solar thermal systems are installed worldwide. The largest plant is in the Danish city of Aabybro, which was built in 2008. The installed capacity of the system is 18.3 MWth (26,195 m^2 collector area). Another large solar heating plant was built in Langkazi, Tibet, at high elevation and high solar insolation. Since December 2018, the 15.6 MWth (22,275 m^2 collector area) solar collectors satisfy above 90% of Langkazi's heating demand. The system involves a 15,000 m^3 seasonal storage in a pit (PTES) and about 11 km of one-way district heating piping (SDH 2018). The supply and return temperatures at design conditions are 65 °C (338 K) and 35 °C (308 K), respectively. It covers 100,000 m^2 of residential floor area. There is a 3 MWth electric boiler for backup purposes (Efficiency, $\eta_B = 90\%$). Although such a large solar district heating system seems economical with dropping collector prices and almost carbon-free operation, the latter is not the case. In this respect, two equations are very critical for sustainability and true decarbonization. The first critical equation is the maximum one-way district piping distance, L_{max}, corresponding to a given amount of solar thermal quality circulated in the district (Kilkis 2020b).

$$L_{\max} \leq C\left[Q\left(1 - \frac{T_{ret}}{T_{\sup}}\right)\right]^{1.5} \tag{47}$$

C is a coefficient, which considers all design specifics for a given project, like pipe diameter, material, motor efficiencies, fluid properties, etc.

If C is 10^{-3} km/kW$^{1/1.5}$, Q is 10000 kW, T_{sup} and T_{ret} are 320 K and 300 K, then L_{max} will be about 15 km, excluding singular pressure losses in district piping.

As shown in Fig. 19, for a given district thermal power, T_{sup} is important in determining L_{max} for a given pipe *ID*. The pipe friction, *f*, and *w* are dominant factors to

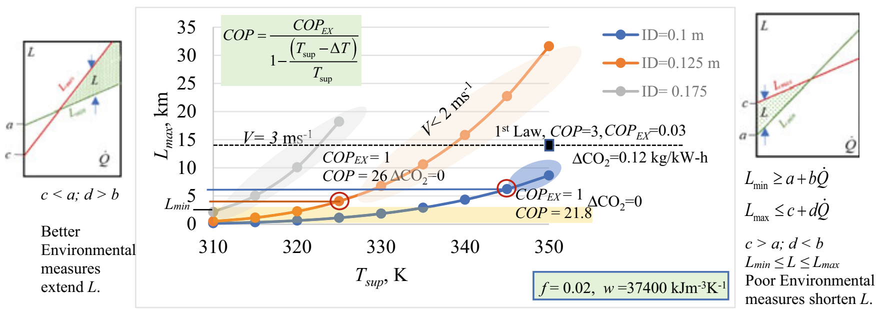


Fig. 19 Maximum district circuit lengths for 1000 kW heat supply at different pipe *ID*

limit L_{max} because the flow velocity, V, must correspond to a valid Reynolds number, which is also a function of ID. If the lower limit of V is 2 m s^{-1}, and ID is 0.1 m, then any district supply temperature lower than 345 K may be accommodated up to 6 km. If the pipe ID is 0.125 m, this distance slightly decreases to about 4 km. Any larger $ID > 0.175$ m is not feasible because V is always less than 2 m s^{-1}. Therefore, a careful analysis of the complex relationships among many variables is necessary for exergy rationality. If only the 1st Law is applied, then 14 km is permissible for $ID = 0.10$ m, with a COP of 3, irrespective of T_{sup}, causing ΔCO_2, while COP_{EX} is only 0.03. According to the 2nd Law, shorter L_{max} values mean zero ΔCO_2 (Ideal $COP_{EX} = 1$) and much higher COP values. L_{min} is another environmental safety limit, which must be satisfied. In this respect, $ID = 0.175$ m is not applicable.

The second equation is about the ΔCO_2 emissions responsibility, which compares the total electrical power quality demanded by the district pumps, P, and the auxiliary thermal power exergy demand, P_a, and the quality of solar thermal power, Q, distributed in the district. P_a may be supplied either by electric or fossil fuel boilers.

$$\left(P + \frac{P_a}{\eta_{BE}}\right) \times 0.95 << Q \times \left(1 - T_{ret}/T_{\mathrm{sup}}\right) \{\text{Electric Boiler}\} \tag{48}$$

$$\left(P \times 0.95 + \frac{P_a}{\eta_{BNG}} \times 0.87\right) << Q \times \left(1 - T_{ret}/T_{\mathrm{sup}}\right) \{\text{Natural Gas Boiler}\} \tag{49}$$

In the Langkazi project, with 3 MWth electric boiler having an efficiency, η_{BE} of 0.90, the following constraint applies:

$$\left(P + \frac{3\ \text{MW}}{0.9}\right) \times 0.95 < 15.6\ \text{MW}\left(1 - \frac{308\ \text{K}}{338\ \text{K}}\right)$$

There is no real solution for P with the above data, meaning that any pumping power expense will result in CO_2 emissions responsibility unless the solar panel capacity is increased to 18.6 MWth and the electrical boiler backup is eliminated. In this case, $P \ll 1.74$ MW can be a feasible solution, and the system may be close to carbon–neutral.

$$(P) \times 0.95 < 18.6\ \text{MW}\left(1 - \frac{308\ \text{K}}{338\ \text{K}}\right)$$

This example shows that electric to-heat-solutions must be avoided even the electricity comes from solar energy because this renewable electricity could be used in more useful applications, which do not have other alternatives than electricity, like lighting, mass transit, and electric machines.

4 Case Study and Results

A heat pump versus heating equipment oversizing optimality case based on exergy has been carried out. Results are compared with the temperature peaking with a cascade of two PVT panels with heat pipes (Fig. 14). Equations 33, 37a, and 37b were used. Results have also been compared with two heat pump cascade cases. The embodiment of a heat-pipe radiator is assumed to be half as much as a standard radiator. Figure 20 shows that cascaded heat pump emissions responsibility is higher at $OF = 1$ (No oversizing). However, it becomes lover than un-cascaded (Single heat pump) if OF two. For OF above 2.5 the standard radiator oversizing has more emissions responsibility. A heat-pipe radiator has the lowest emissions responsibility for all cases. A cascaded PVT with heat pipes at $OF = 2$ is the second-best option. The ideal solution might be an optimum oversizing share between heat pipe radiator (HPR) and PVT cascade with $OF = 2$.

According to Eq. 31, an economic optimization gives a heat pump oversizing of 1.5 operating with standard radiators. The result is 7.8 tons of CO_2. In comparison to this result, the exergy-based optimization reduces CO_2 to 6 tons at a common oversizing of 2.4 both for the heat pump and radiators, corresponding to about 30% reductions in emissions responsibility. The same result further improves by 3% if cascaded heat pumps are used (two heat pumps). The major improvement occurs when a cascaded heat pump configuration is coupled with heat-pipe radiators. The improvement is about 52%.

Of course, these conclusions are highly dependent on specific design cases, solar insolation, thermal loads, and the environment. Therefore, it is suggested to visualize these cases as given in Fig. 20 for choosing the best method for temperature peaking for every application and combination. Figure 20 was prepared just as an exemplary approach when exergy plays an important role in decarbonization efforts.

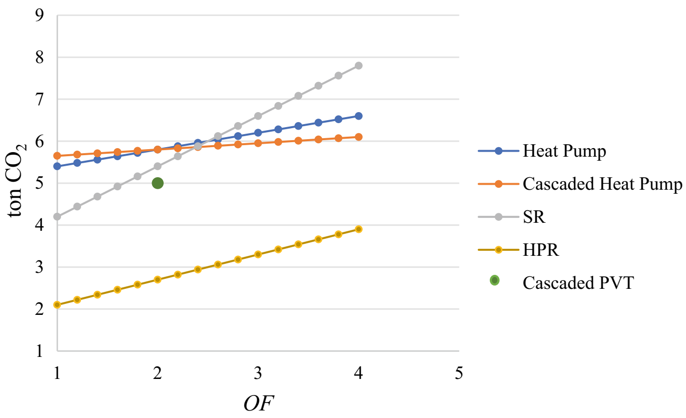


Fig. 20 Exergy-based optimum heat pump and equipment oversizing for minimum emissions

5 Discussion of Results and Conclusions

This chapter shows that climate emergency may not be effectively resolved by only applying energy efficiency and savings and replacing fossil fuels with renewables on a large scale. According to the 2nd Law, exergy destructions are inevitable, irreversible, and cause additional emissions, ΔCO_2, because the exergy destructions must be offset by spending more resources and possibly fossil fuels. Figure 4 and Table 1 explicitly showed this condition for solar energy systems. Within the given equations and context of the chapter, derived and presented by the author, ΔCO_2 emissions may be minimized if the exergy of resources-whether renewable or fossil-are utilized with maximum exergy rationality, represented by ψ_R.

$$\Delta CO_2 = CO_2(1 - \psi_R) \times (1 - R_X) \tag{50}$$

If it is assumed that the ratio of renewables in the energy mix, R_X increases at the same rate as ψ_R:

$$(\Delta CO_2/CO_2) = (1 - \psi_R)^2 \tag{51}$$

EU 2020 vision, calling for a 20% increase in efficiency, 20% increase in energy savings, and 20% increase in renewables, has not been entirely successful in decreasing CO_2 emissions. The reason is that this vision, which is now extended, addresses the increase in R_X properly, as depicted in Fig. 21. However, the same EU vision and none of the others on a global scale address the ψ_R component of emissions and therefore remain unaware of ΔCO_2. On the other hand, if exergy rationality is embedded in the decarbonization measures, thus forming a composite solution platform, ΔCO_2 levels drop faster and more. Thus, composite measures of decarbonization may converge to the Paris agreement goals.

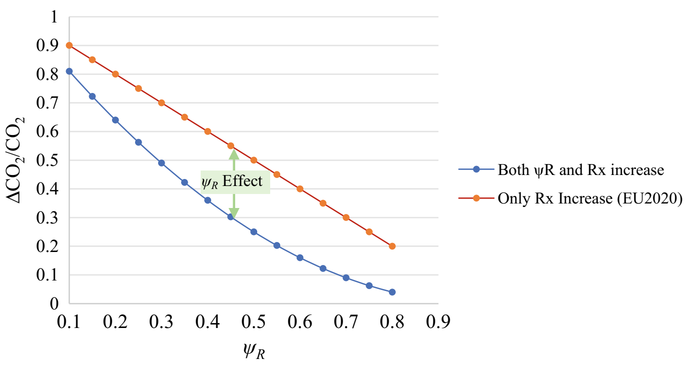


Fig. 21 Minimization of ($\Delta CO_2/CO_2$) ratio by increasing ψ_R and R_x at the same rate. The top line ignores the ψ_R effect

Figure 21 shows that the ($\Delta CO_2/CO_2$) ratio is excessively about 0.8 with the present average global value of ψ_R, which is 0.2. Therefore, current decarbonization strategies neglect exergy-based solutions, which could essentially minimize an unrecognized amount of about 80% of the observed CO_2 emissions in the atmosphere.

In other words, current strategies miss almost half of the potential solutions against global warming. For example, if ψ_R increases from 0.2 to 0.7, which is deemed as the threshold of truly green applications, ΔCO_2 becomes only 30% of direct emissions, or even less. This target is achievable by mobilizing widely available but unused low-exergy resources, including waste heat, and matching them by LowEx buildings to minimize exergy mismatches with innovative LowEx heating and cooling equipment. Figure 21 also shows that the maximum ψ_R effect is about 42% for this example at about $\psi_R = 0.45$. This means that while exergy rationality will undergo improvements its effect on total CO_2 emissions will go through a maximum and then continue decreasing while exergy rationality improves any further.

Although Eq. 51 shows that ΔCO_2 may mathematically be zero if ψ_R reaches one and renewables reach 100% (Thus eliminating CO_2). Zero carbon emissions are not possible in practice because there will always be exergy destructions present, and ψ_R will always be less than one. On the other hand, 100% renewables will not be achieved until all embodiments of their manufacturing and materials used also reach 100% renewable, which is not possible soon. For heating and cooling systems, total electrification with renewables, even if theoretically 100% goal is achieved, heat pumps destroy a certain amount of exergy. Furthermore, this chapter has shown that refrigerant leakages have ΔCO_2 emissions responsibility. CO_2 gas replacing refrigerants may be a solution if carbon is captured and stored. This will have two sets of advantages, namely replacing high *ODI* refrigerants and second, a net saving of CO_2 emissions because CO_2 will be captured and used only with a leakage amount escaping to the atmosphere again. Therefore, CO_2 is returning as a refrigerant. The previous two major problems of high pressure and high compressor temperature are advantageous now even in LowEx applications like high-temperature cooling or low-temperature heating (OU 2021). The high cycle pressure requirement means high fluid leading to smaller heat pump size, less CO_2 embodiments, and less electrical power requirement, thus less direct CO_2 emissions responsibility of a grid. The high outlet temperature means a cogeneration grade heat supply, which will eliminate conventional equipment oversizing. Such a high-exergy thermal power may be utilized in space cooling by double-effect absorption units with $COP_{abs} > 1$, further reducing the heat pump size. If X is the share of a given comfort cooling load to be satisfied by the heat pump at a COP_c value, and the reject heat will drive an absorption chiller, X is limited by the following constraint if the entire heat output is dedicated for absorption cooling thus maximizing the reduction in the heat pump capacity. Absorption chiller power demand is negligible.

$$X \leq \frac{1}{1 + COP_{abs}} \tag{52}$$

Then the only CO_2 emissions responsibility will be given by the following equation. ΔCO_2 is neglected.

$$CO_2 = c(1 - R_X)\left[\frac{X \times PEF}{COP_{HP}}\right] = (1 - R_X)\left(\frac{1}{1 + COP_{abs}}\right) \times (PEF/COP_{HP}) \tag{53}$$

This chapter has demonstrated that the 2nd Law sheds light on a wider horizon of potential and sustainable solutions with renewable energy sources and systems if they are properly addressed. Then solutions will be almost endless. Instead of standard exergy equations taught in the textbooks, the model has been primarily built on a single equation, namely the ideal Carnot cycle. This replacement has led to simpler expressions and metrics as derived in his chapter. It is understood that, among others, five metrics about lexergy-levelized cost and CO_2 emissions not only bring certain constraints to renewables but, more importantly, facilitate their penetration into practice and energy policies about 5DE systems.

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Investigating Thermodynamic Assessment of Geothermal Power Systems for Green Applications

Fatih Yilmaz and Murat Ozturk

1 Introduction

On earth with ever-growing carbon-based fuel requirements, the demand for improved techniques of power production has never before been so evident. The traditional electricity-producing ways convert energy from carbon-based sources, in a manner that has critical effects on the surroundings. Electrical energy production, for instance, is one of the best-known processes. Coal-fired electricity production sectors throw large amounts of carbon dioxide (CO_2), particulate matter (PM), and different harmful gases into the environment every year. Hence, green and cost-competitive environmentally friendly power resources are hoped to be possible options to reach long-term and sustainable resolutions. Geothermal power conversion shows one of the most promising preferences at a time when cleaner power resolutions are necessary to supply the demand of the exponentially increasing population. Because more than 90% of the world's temperature is higher than 100 °C, geothermal power sources should be evaluated as one of the most plentiful sources as an option to carbon source-based heating and also electricity generation utilizations.

Geothermal power utilization technologies are accepted under regard in two methods, which are direct utilization and power generation. Direct geothermal power utilization is vulgarly based on the application of thermal power in the absence of modification in the formation of power. In ancient times, geothermal water present at the world's surface or an accessible grade was directly utilized. Figure 1 shows the different utilizations of direct geothermal energy applications.

Electricity power application needs power conversion techniques, basically to convert thermal power into electrical power. Geothermal power should be taken into account as an answer to both power and environmental issue, and also utilization of

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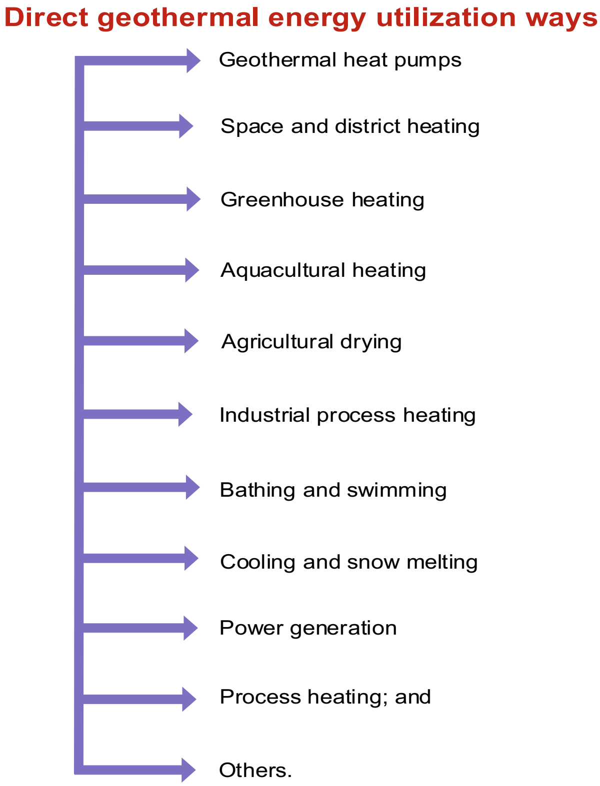

Fig. 1 Different utilizations of direct geothermal energy applications

renewable power sources. The given below combined set of actions can be taken into account for applying the effectiveness, economic, and environmental advantages of geothermal resources:

- investigation and improving,
- novelty and commercialization,
- technical evaluation,
- standards improving, and
- technologically transfer.

Figure 2 shows the geothermal energy conversion mechanisms. There are six systems for geothermal electricity production, such as (i) binary, (ii) single flashing (SF), (iii) double flashing (DF), (iv) triple flashing (TF), (v) backpressure, and (vi) dry steam power systems. Also, SF, DF, and TF system studies rely on the flash of geothermal fluid for steam generation; here DF and TF arrangements further utilize untapped geothermal water for improved thermodynamic efficiency and electricity generation.

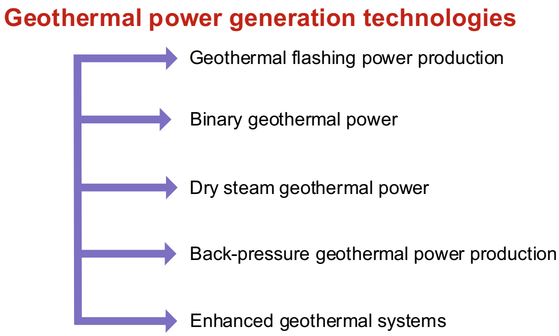

Fig. 2 Geothermal energy conversion mechanisms

For the sustainable progress of the community, hypothetically, one must connect exclusively to energy sources that create no environmental impact. Moreover, increased power production performance decreases the environmental impact, because, for similar services or outputs, less source usage and pollution are generally connected with increased performance. Furthermore, energetic performance drives to a decrease of power need and also the extension of the present sources.

Renewable energy sources should be stored in chemical (i.e., H_2) or electricity forms. Electrical power can be usually used as an energy-storing way, and it is strongly utilized on the day-to-day. H_2 has been taking an increasing quantity of significance as an outcome of its advantageous characteristics as an energetic carrier. To approve sustainable progress and handle economic, both electrical energy and H_2 should be generated from renewable power resources. (Acar and Dincer 2014). H_2 is a necessary energy transporter for the following causes: (i) H_2 owns well energetic conversation efficiency, (ii) H_2 should be generated from H_2O with without any emissions; (iii) H_2 is abundant; (iv) H_2 should be stored in suitable technologies (v) H_2 should be provided across long distances with minimum loss; (vi) H_2 should be converted into further power conditions in more ways than those of every other fuel, (vii) H_2 contains the superior higher heating value (HHV) and lower heating value (LHV) (Table 1), and also (viii) if H_2 is produced from green technologies and H_2O, its generation, storage, transportation, and recent utilization do not damage the surroundings. H_2 power plants can simultaneously tackle all of the primary power and environmental problems. Moreover, H_2 power plants are flexible sufficient to be arranged to numerous green power technologies. Meanwhile, green energy sources

Table 1 HHV and LHV of H_2 and conventional carbon-based fuels at 25 °C and 101.3 kPa (Dincer 2012)

Fuels	HHV (kJ/kg)	LHV (kJ/kg)
H_2	141.9	119.9
CH_4	55.5	50.0
Gasoline	47.5	44.5
Diesel	44.8	42.5
CH_3OH	20.0	18.1

have intermittent properties, the skill to flexibly switch between various resources in the absence of any problem is one of the necessities for the transition to green power plants for a sustainable upcoming.

Considering the studies in the literature, there are many studies about geothermal energy-based power production plants, i.e., multigeneration models. Yuksel et al. (2021) have planned a novel geothermal power-assisted poly-generation model for various useful products. They designed and thermodynamically analyzed a multi-generational plant that is mainly consisting of hydrogen and ammonia generation subcycles. Energetic and exergetic effectiveness of their suggested plant are 56.68 and 54.73%. Temiz and Dincer (2020) have modeled a multigeneration plant driven by geothermal energy and photovoltaic. For cleaner communities, they examined the techno-economic analysis of this hybrid system with energy and exergy methods. In this study, they have integrated the geothermal energy plant with the photovoltaic sub-unit and the hydrogen sub-processes. They calculated that whole energy and exergy performances are 16.3% and 14.9%, respectively.

Multi-purpose optimization of the geothermal power-based plant using the evolutionary algorithm for heating, power, and clean water production purposed and conducted by Ansarinasab and Hajabdollahi (2020). Their advised system consisting of dual fluids ORC, sterling engine, water heater, and desalination unit. They implemented advanced exergy analysis and exergoeconomic optimization on the modeled plant. Analyses results released that 52.65% exergy efficiency and 4.35 $/GJ product unit cost for the developed system. Gnaifaid and Ozcan (2021) have developed and analyzed a newly designed flash-binary geothermal energy system for multi-purposes. They investigated that the thermodynamic assessment and multiobjective optimization methods of the geothermal energy-based plant. They also investigated that efficiency by integrating the reverse osmosis desalination system and the cooling system in the proposed study. In conclusion, the optimum exergy efficiency of their plant is found as 58%.

Azariyan et al. (2021) have modeled a high-performance geothermal energy-supported integrated plant that aims to generate electricity, cooling, and H_2. Moreover, they conducted the advised multigeneration system in terms of the thermodynamic and exergoeconomic evaluation approaches. They compared the absorption and ejector cooling cycles under the same conditions. According to the results of the analysis, this proposed system has a thermal efficiency of 22.28%. Siddiqui and Dincer (2020) have designed and investigated solar and geothermal energy-based united ammonia fuel cell plant with thermodynamic methods. They have designed this proposed work to achieve the purposes of power, hydrogen, fresh water, and refrigeration. While the energetic performance of the entire plant is 42.3%, the exergetic efficiency is calculated as 21.3%. Ozturk and Dincer (2021) have proposed hydrogen generation from the geothermal power system. In their proposed book chapter, they compared hydrogen and electricity generation options in detail and examined the thermodynamics of a geothermal-based system.

When the literature is briefly considered, it is seen that studies on geothermal energy are still among the current issues. However, it can be stated that there is still a gap in geothermal energy driven hydrogen and ammonia generation. In this context,

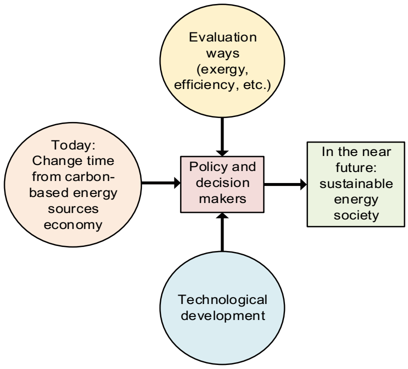

Fig. 3 The way of evaluation tools and indexes in shaping the near future sustainable community

in this proposed book chapter, mainly the thermodynamic performance analysis of the geothermal energy combined system is discussed for beneficial outputs. In this way, energetic and exergetic efficiencies as well exergy destruction rate for the whole plant and sub-systems are investigated, to determine the effectiveness of the geothermal-based system. Furthermore, a comprehensive parametric work is done to observe the influence of changes in some important indicators affecting system performance.

2 Environmental Impacts in Power Production Section

The stride in the direction of a worldwide sustainable community is significantly affected by policy and decision-makers. Figure 3 illustrates how they affect the route in which the earth's future is developed versus sustainable development supplied those suitable technical ways for sustainability analysis are done existing and new technics are improved.

3 Case Study

The maximum general ammonia synthesis plant is Haber–Bosch and the best settled hydrogen generation way is the PEM water electrolysis. Therefore, in this book chapter, the PEM electrolysis, and Haber–Bosch based ammonia generation technology is used utilizing geothermal energy. To investigate the geothermal energy-based ammonia generation process, the following diagram can be utilized as revealed in Fig. 4. The required power is acquired by using a geothermal power plant.

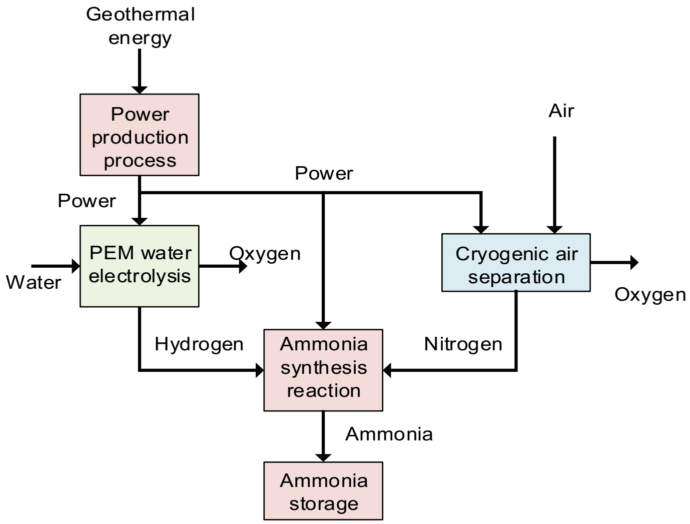

Fig. 4 Schematic presentation of ammonia generation by using geothermal energy-based PEM water electrolyzer and Haber–Bosch plant

3.1 Plant Description and Modeling

Here, a geothermal power-based multigeneration plant for electrical energy, hydrogen, ammonia, heating production is introduced, as shown in Fig. 5.

As seen above in Fig. 5, briefly, the proposed model is thermally driven by geothermal energy, and then produces the power, hydrogen, ammonia, and heating aims. Firstly, the geothermal energy coming from state 1 at about 220 °C, enters separator 1 at point 2 in the liquid-steam mixture phase after the pressure and temperature of the throttling valve drop a little. From separator 1, the geothermal fluid at point 3 as saturated steam goes to the high-pressure (HP) turbine, and electricity generation occurs here. Next, the geothermal fluid mixed with liquid vapor at state 5 enters flash chamber 2, which is a second throttling valve, and then enters separator 2. The geothermal water coming out of the separator 2 at state 13 transfers some of its heat with the heater to the ORC plant and the thermal power needed for the ORC is provided from here. Then, at state 14, the PEM heats the water needed for electrolysis and returns it injection well at about 84 °C at state 15.

After that, some of the hydrogen produced in PEM electrolysis is used for storage at state 26, while the rest goes to the hydrogen compressor at state 27 and as a result of reacting with the nitrogen coming from state 29, ammonia production occurs. Finally, the useful productions i.e., power, hydrogen, ammonia, and heating occur with the thermal energy derived from geothermal.

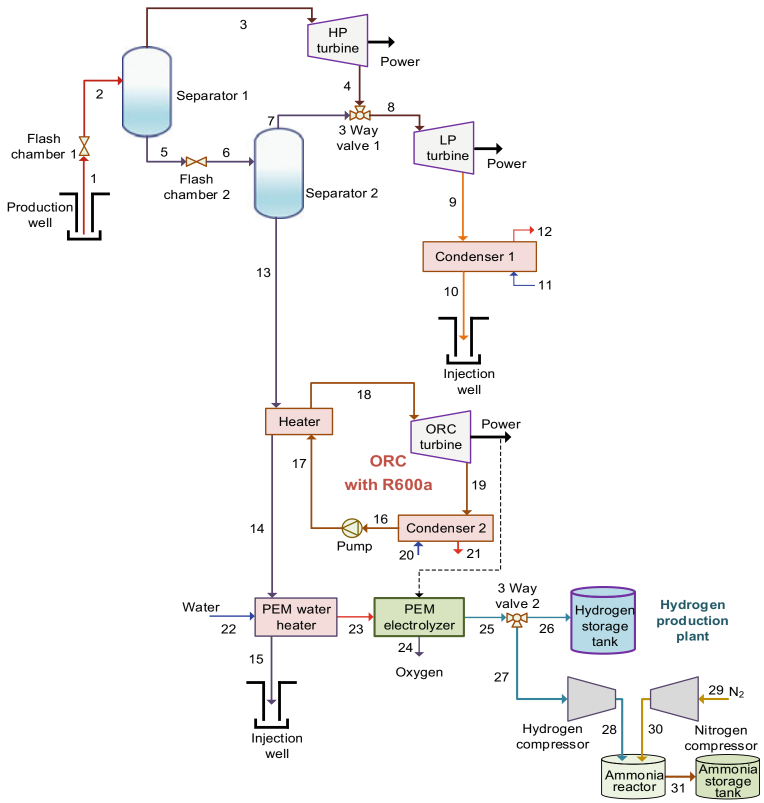

Fig. 5 A schematic diagram of the integrated flash and binary geothermal plant based H_2 and NH_3 production

3.2 *Thermodynamic Analysis*

Thermodynamical analysis has an important role in the assessment of cycles, plants, and other equipment in which energetic transfers and energetic transformations occur.

For a steady flow plant, the mass balance equation should be written as below:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

where $\dot{m}$ shows mass flow rate, subscripts in and out show the input and output states. An energetic balance equation should be written as (Cengel and Boles 2015; Dincer and Rosen 2013):

$$\sum \dot{m}_{in} h_{in} + \sum \dot{Q}_{in} + \sum \dot{W}_{in} = \sum \dot{m}_{out} h_{out} + \sum \dot{Q}_{out} + \sum \dot{W}_{out} \tag{2}$$

where, $\dot{Q}$ and $\dot{W}$ are heat energy and power transfer rate, h shows specific enthalpy. Entropy balance equation should be defined as:

$$\sum \dot{m}_{in} s_{in} + \sum \frac{\dot{Q}_{cv}}{T} + \dot{S}_{gen} = \sum \dot{m}_{out} s_{out} \tag{3}$$

where s and $\dot{S}_{gen}$ give specific entropy and entropy generation rate. Exergetic balance equation for any system should be written as:

$$\sum \dot{m}_{in}\varphi_{in} + \sum \dot{E}x_{in}^{Q} + \sum \dot{E}x_{in}^{W} = \sum \dot{m}_{out}\varphi_{out} + \sum \dot{E}x_{out}^{Q} + \sum \dot{E}x_{out}^{W} + \dot{E}x_{d} \tag{4}$$

Exergetic term demonstrates the highest work that should be generated by using the thermodynamical plant when it comes into surroundings with its dead state medium. This explanation supposes that at an initial status there is a thermodynamical plant that is not in equilibrium with the reference condition. For Eq. (4) the total specific exergy should be described as:

$$\varphi = (h - h_0) + T_0(s - s_0) + \frac{1}{2}v^2 + g(z - z_0) + ex^{ch} \tag{5}$$

Exergetic transfer between the plant and surroundings should be done by work, mass and heat transfer rates. The exergy due to work, mass, and heat transfers are given as:

$$\dot{E}x^{W} = \dot{W} \tag{6}$$

$$\dot{E}x^{m} = \dot{m}\varphi \tag{7}$$

$$\dot{E}x^{Q} = \dot{Q}\left(1 - \frac{T_o}{T}\right) \tag{8}$$

The exergy destruction has defined each other as specified under:

$$\dot{E}x_{d} = T_o S_{gen} \tag{9}$$

There are three cases as described below (Cengel and Boles 2015; Dincer and Rosen 2013):

(i) $\dot{E}x_d > 0 \rightarrow$ irreversible
(ii) $\dot{E}x_d = 0 \rightarrow$ reversible
(iii) $\dot{E}x_d < 0 \rightarrow$ impossible.

3.3 Formulations for Plant Efficiency

Whenever, effectiveness viewpoints have been of significant importance in decision-making regarding source usage and efficiency analysis of plants and utilizations. Effectiveness is frequently assessed as relations of energy amounts and is generally utilized to describe and compare several plants. Electricity generation systems, heating, and cooling processes, and thermal energy storage, for instance, are frequently compared by using energetic effectiveness or energetic-based measurements of value. There is two important effectiveness as energetic performance, based on energetic assessment and exergetic assessment. On the other hand, energetic performance is generally misleading in that it does not always supply the measurement of how nearly the efficiency of a plant methods ideality. Furthermore, a thermodynamical loss that happens within the plant (i.e., those indicators that reason effectiveness to diverge from ideality) frequently are not completely determined and evaluated with energetic assessment. The outcomes of energetic assessment may represent the primary inefficiencies to be within the incorrect parts of a plant and state of technologic performance dissimilar to what really obtains. This needs a realistic performance to be described. This can simply be built by exergetic performance since exergetic assessment allows many of the defects of energetic assessment to be accomplished. Performances defined utilizing ratios of exergetic assessment do supply the measurement of an approach to the ideal condition. For any practical plant, efficiency, generally, should be written as the ratio of applicable outlet divided by the necessary inlet as given below:

$$Efficiency = \frac{Desiredoutlet}{Requiredinlet} \tag{10}$$

Generally, energetic (η) and exergetic effectiveness (ψ) are defined for steady-state processes occurring in the plant as:

$$\eta = \frac{Usefulenergyoutput}{Totalenergyinput} = \frac{En_{out}}{En_{in}} = 1 - \frac{En_{loss}}{En_{in}} \tag{11}$$

$$\psi = \frac{Usefulexergyoutput}{Totalexergyinput} = \frac{Ex_{out}}{Ex_{in}} = 1 - \frac{Ex_{d}}{Ex_{in}} \tag{12}$$

After that, the energetic and exergetic effectiveness of the single generation option:

$$\eta_{SG} = \frac{Energyinoutputproducts}{Energyininputs} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} \tag{13}$$

$$\psi_{SG} = \frac{Exergyinoutputproducts}{Exergyininputs} = \frac{\dot{W}_{net}}{\dot{E}x_{Q,in}} \tag{14}$$

By considering the above Eqs. (13–14), the energy and exergy performances in general for the different generation options are written below:

The energetic and exergetic effectiveness of cogeneration option:

$$\eta_{CG} = \frac{\dot{W}_{net} + \dot{Q}_{heating}}{\dot{Q}_{in}} \tag{15}$$

$$\psi_{CG} = \frac{\dot{W}_{net} + \dot{E}x_{Q,heating}}{\dot{E}x_{Q,in}} \tag{16}$$

The energetic and exergetic efficiency equalities of trigeneration option:

$$\eta_{TG} = \frac{\dot{W}_{net} + \dot{Q}_{heating} + \dot{m}_{H_2} h_{H_2}}{\dot{Q}_{in}} \tag{17}$$

$$\psi_{TG} = \frac{\dot{W}_{net} + \dot{E}x_{Q,heating} + \dot{m}_{H_2} ex_{H_2}}{\dot{E}x_{Q,in}} \tag{18}$$

Finally, the thermodynamical performance equalities for the sub-plants and overall plant are defined in detail below*:*

Geothermal power system

$$\eta_{GPS} = \frac{\dot{Q}_{PP} + \dot{Q}_{ORCP} + \dot{Q}_{PEMWH}}{\dot{m}_1 (h_1 - h_{15})} \tag{19}$$

$$\psi_{GPS} = \frac{\dot{E}x^{Q}_{PP} + \dot{E}x^{Q}_{ORCP} + \dot{E}x^{Q}_{PEMWH}}{\dot{m}_1 (ex_1 - ex_{15})} \tag{20}$$

Power plant

$$\eta_{PP} = \frac{\dot{W}_{HPT} + \dot{W}_{LPT} + \dot{Q}_{Heating}}{\dot{m}_2 (h_2 - h_{13})} \tag{21}$$

$$\psi_{PP} = \frac{\dot{W}_{HPT} + \dot{W}_{LPT} + \dot{E}x^{Q}_{Heating}}{\dot{m}_1 (ex_2 - ex_{13})} \tag{22}$$

ORC plant

$$\eta_{ORCP} = \frac{\dot{W}_{net,ORCP}}{(\dot{m}_{13} h_{13} - \dot{m}_{14} h_{14})} \tag{23}$$

$$\psi_{ORCP} = \frac{\dot{W}_{net,ORCP}}{(\dot{m}_{13} ex_{13} - \dot{m}_{14} ex_{14})} \tag{24}$$

Hydrogen production plant

$$\eta_{HPP} = \frac{\dot{m}_{24}h_{24} + \dot{m}_{25}h_{25}}{\dot{m}_{23}h_{23} + \dot{W}_{PEM}} \tag{25}$$

$$\psi_{HPP} = \frac{\dot{m}_{24}ex_{24} + \dot{m}_{25}ex_{25}}{\dot{m}_{23}ex_{23} + \dot{W}_{PEM}} \tag{26}$$

Ammonia production plant

$$\eta_{APP} = \frac{\dot{m}_{31}h_{31}}{\dot{m}_{27}h_{27} + \dot{m}_{29}h_{29} + \dot{W}_{HC} + \dot{W}_{NC}} \tag{27}$$

$$\psi_{APP} = \frac{\dot{m}_{31}ex_{31}}{\dot{m}_{27}ex_{27} + \dot{m}_{29}ex_{29} + \dot{W}_{HC} + \dot{W}_{NC}} \tag{28}$$

Overall plant

$$\eta_{OP} = \frac{\dot{W}_{net,overall} + \dot{Q}_{Heating} + \dot{m}_{26}LHV_{H_2} + \dot{m}_{31}LHV_{NH_3}}{\dot{m}_1(h_1 - h_{15})} \tag{29}$$

$$\psi_{OP} = \frac{\dot{W}_{net,overall} + \dot{E}x^{Q}_{Heating} + \dot{m}_{26}ex_{H_2} + \dot{m}_{31}ex_{NH_3}}{\dot{m}_1(ex_1 - ex_{15})} \tag{30}$$

4 Results

In this proposed book chapter, the thermodynamic performance of the geothermal energy-assisted integrated model is examined in detail from the viewpoint of energy and exergy performances. Here, the influence of changes in limits such as ambient temperature, geothermal fluid temperature, and geothermal mass flow are parametrically examined and presented.

In Table 2, thermodynamic values such as pressure, temperature, enthalpy, and entropy of each flow of the system elements are presented. These values are calculated with the help of the EES package program.

It is important to investigate the influence of change in reference temperature on the system in thermal system design, such as these proposed integrated systems. Therefore, the effects of ambient temperature change are parametrically investigated in Figs. 6, 7, 8 and 9. Figure 6 demonstrations the increase in the energy efficiency of the proposed plant and sub-plants as the reference temperature rises from −5 to 45 °C. In this increased range, the energy efficiency of the overall plant increased linearly from 0.3945 to about 0.45. The reason for this increase is the increase in benefical outlets obtained by increasing the ambient temperature.

Table 2 State flow information for the geothermal energy based integrated system

Flow number	T (°C)	P (kPa)	$\dot{m}$ (kgs^{-1})	h (kJ/kg)	s (kkgK)	$ex.$ (kJ/kg)
1	220	2318	200	943.5	2.518	197.5
2	186.4	1159	200	943.4	2.532	193.1
3	186.4	1159	15.25	2783	6.535	839.3
4	157.5	579.5	15.25	2673	6.58	715.3
5	186.4	1159	184.8	791.6	2.201	139.8
6	157.5	579.5	184.8	791.7	2.213	136.6
7	157.5	579.5	11.22	2755	6.772	740.7
8	157.5	579.5	26.47	2707	6.661	726
9	45.82	10	26.47	2199	6.942	133.8
10	45.82	10	26.47	191.8	0.6493	2.814
11	18	101.3	577.5	75.56	0.2675	0.3492
12	40	101.3	577.5	167.6	0.5722	1.527
13	157.5	579.5	173.5	664.8	1.918	97.53
14	85	579.5	173.5	356.3	1.134	22.8
15	84.75	579.5	173.5	355.3	1.131	22.63
16	33.84	450	101.9	281.4	1.279	50.9
17	35.4	2700	101.9	286.3	1.281	55.09
18	147.5	2700	101.9	811.5	2.483	161.9
19	104	450	101.9	738.8	2.723	77.87
20	28	101.3	428.7	117.4	0.4088	0.06272
21	54	101.3	428.7	226.1	0.7551	5.541
22	18	101.3	0.7017	75.56	0.2675	0.3492
23	80	101.3	0.7017	335	1.075	18.94
24	80	101.3	0.6228	50.5	0.1556	4.176
25	80	101.3	0.0789	4723	55.81	118,148
26	80	101.3	0.0245	4723	55.81	118,148
27	80	101.3	0.0544	4723	55.81	118,148
28	250	10,000	0.0544	7261	42.55	6556
29	25	101.3	0.2491	309.3	6.835	0
30	250	10,000	0.2491	543	6.044	469.5
31	250	10,000	0.2119	1936	5.464	19,929

The second figure of ambient temperature, which is Fig. 7, examines the exergy efficiencies of all systems and subsystems with various ambient temperatures. It is clear from Fig. 7 that at an ambient temperature increase of 50 °C, the exergy performance of whole system rises linearly from 0.34 to about 0.39. Furthermore, the exergy effectiveness of subsystems increased linearly due to this increase. With

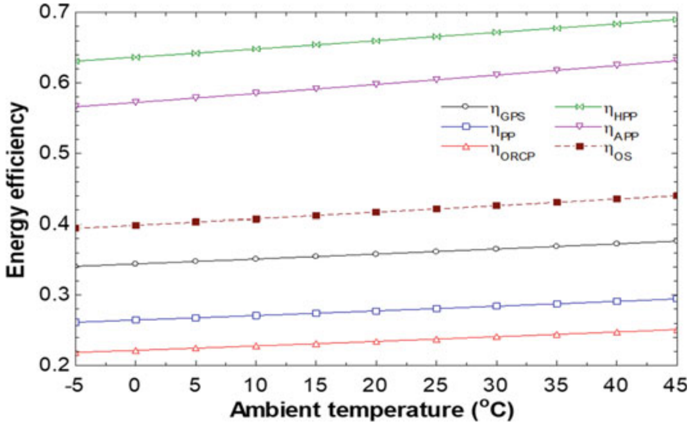

Fig. 6 The impact of ambient temperature on the energetic efficiency of the united system and its sub-systems

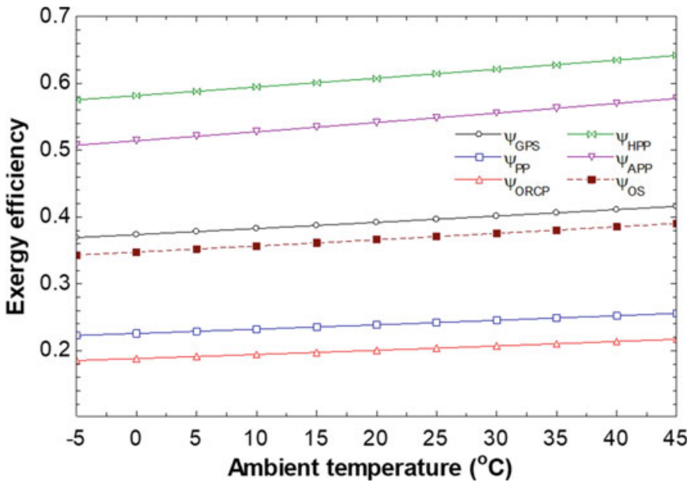

Fig. 7 The influence of ambient temperature on the exergetic efficiency of the combined system and its sub-systems

the rise in reference temperature, exergy efficiency increases due to the decrease in the exergy destruction of the system elements.

Figure 8, the third figure on the variation of reference temperature, shows the relationship between this temperature and useful outputs. As can be realized from this figure, the electrical power obtained from HP and LP turbines and ORC turbines increase linearly due to the increase in ambient temperature. Depending on this increase, hydrogen and ammonia productions also increase. Briefly, it can be said that the increment in ambient temperature has an optimistic outcome on useful outputs.

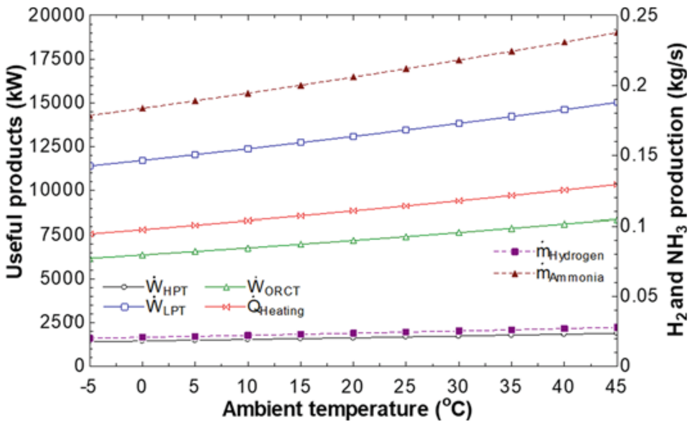

Fig. 8 The effect of ambient temperature on the useful outlets

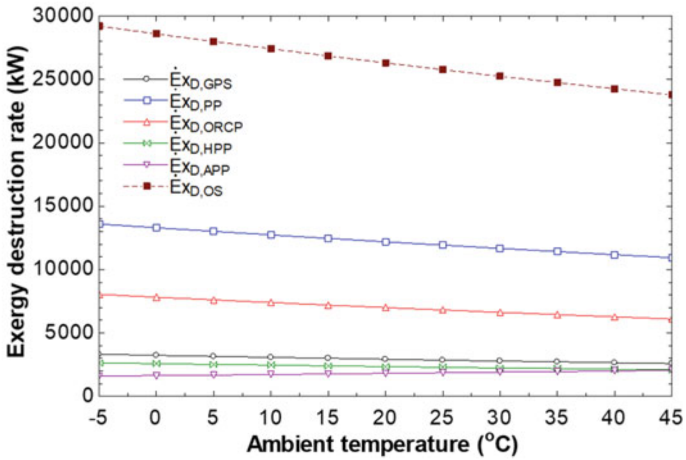

Fig. 9 The impact of ambient temperature on the exergetic destruction rates

The last figure on ambient temperature, Fig. 9, presents the relationship between ambient temperature and exergy destruction of all systems and sub-plants. Exergy destruction has a decreasing trend for the whole plant and subsystems with the rise in ambient temperature from −5 to 45 °C. This shows that it is consistent with the figures above, that is, the decrease in exergy destruction and the increase in exergetic performance are consistent.

Another important parameter is the impacts of geothermal water temperature (GWT) on the plant. Figure 10 examines the effect of GWT variation on the energy effectiveness of plant and subsystems. As should be seen from Fig. 10, the energy efficiency of entire plant is calculated as approximately 0.38, while the GWT is at 160 °C. With the GWT increasing to 240 °C, the energy effectiveness of entire plant

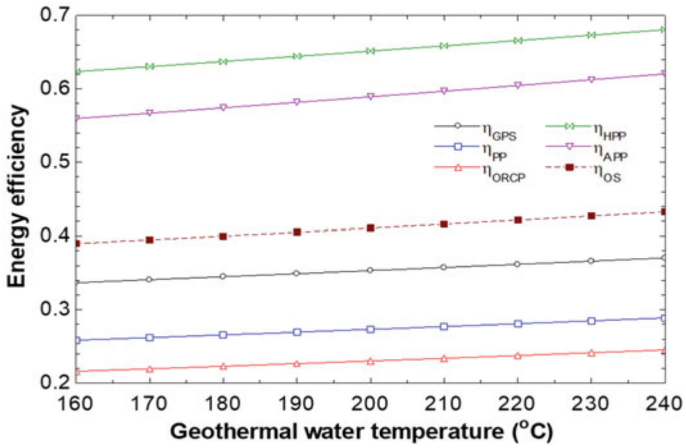

Fig. 10 The influence of GWT on the energetic performance of combined plant and its sub-systems

increased to approximately 0.43. The key cause for this increasing tendency can be interpreted as higher enthalpy inlet to the turbines and the rise in the beneficial outputs obtained as the higher temperatures are increased.

The influence of GWT on the exergergetic efficiency of plant and subsystems is investigated and figured in Fig. 11. By increasing the GWT about 60 °C, the exergetic efficiency of overall system increasing from 0.34 to 0.37. Considering the above-mentioned exergy efficiency equations, the efficiency increases directly because of the rise in the useful outlets, namely the share.

Figure 12 presents the impact of the GWT on the beneficial outputs from

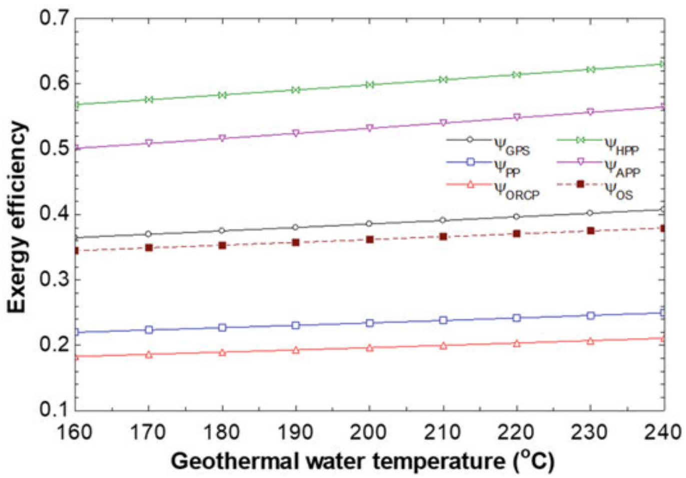

Fig. 11 The impact of GWT on the exergetic performance of combined plant and its sub-systems

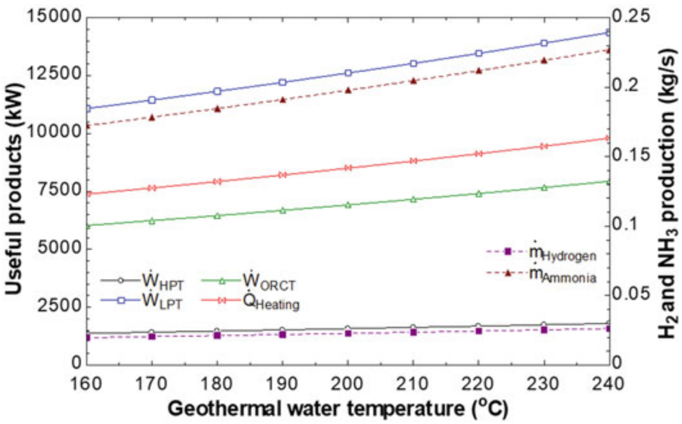

Fig. 12 The impact of GWT on the useful outputs

the modeled system. As illustrated in this figure, the benefical outlets from the modeled system increase with rising the geothermal water temperature. In the investigated GWT increase range, the amounts of hydrogen and ammonia obtained from the proposed system are approximately increasing 0.0065 and 0.0546 kgs^{-1}, respectively.

The last figure regarding the effect of GWT change, Fig. 13, shows the relationship between the irreversibility rates of the whole system and sub-plants. According to this figure, increment in the GWT leads to raising the irreversibility rate, for the overall plant and subsystems. The reason for this increase is that geothermal water at high

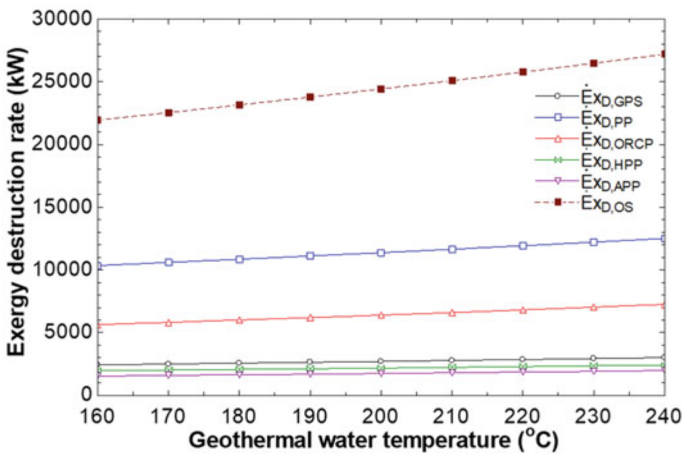

Fig. 13 The effect of GWT on the exergetic destruction rates

temperatures enters the system at high enthalpies and the irreversibility increases in the system.

In addition to the GWT, the change in the geothermal fluid mass flow rate is one of the significant limitations for plant design. Figures 14 and 15 examine the change in geothermal fluid mass flow rate in terms of energetic and exergetic performances for all systems and subsystems. In Fig. 14, as a result of the geothermal water mass flow rate increasing from 180 to 240 kgs^{-1}, the energetic efficiency of whole system

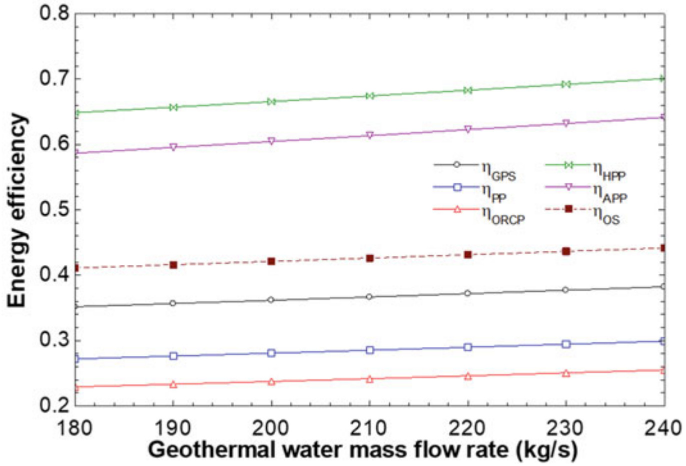

Fig. 14 The influence of geothermal fluid mass flow rate on the energetic performance of the combined plant and its sub-systems

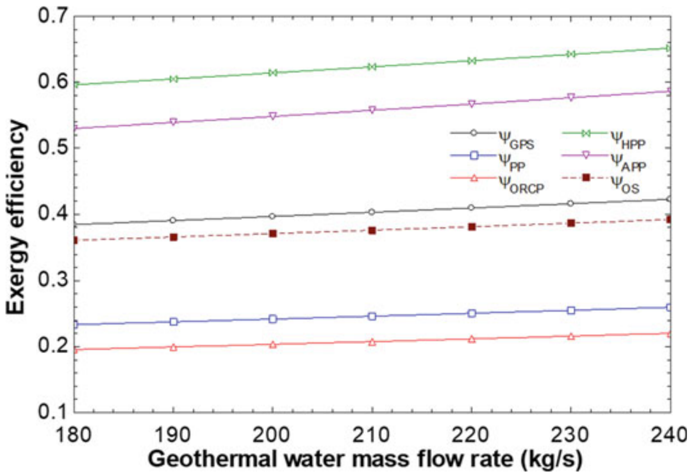

Fig. 15 The impact of geothermal fluid mass flow rate on the exergetic performance of modeled plant and its sub-systems

increased linearly from 0.41 to 0.44. On the other hand, in Fig. 15, as a result of the geothermal water mass flow rate increasing above-mentioned ranges, the exergetic performances of whole system increased from 0.36 to 0.39. The reason for this increase in both efficiency parameters is the increase in the beneficial outlets from the system with the incoming geothermal fluid mass flow rate.

The influence of geothermal fluid mass flow rate on the valuable outlets from the modeled plant is examined and figured in Fig. 16. With an increase of 60 kgs^{-1} in the geothermal water body, the amount of heat obtained in the integrated system increased linearly from 6824 to 10,718 kW. In addition, in this increased range, the amount of hydrogen and ammonia obtained is positively affected and increases. As a result, it may be possible to obtain higher power and useful outputs with high mass flow geothermal power plants.

The last parametric figure, Fig. 17, examines the influence of geothermal fluid mass flow rate on the irreversibility in all system and subsystems. As expected, the exergy destruction rates increased as the rise in the geothermal mass flow rate entering the system also increased the irreversibility in analyzed plant. In short, a mass flow rate increase of 60 kgs^{-1} can cause an extra 4589 kW irreversibility in the entire system.

In order to compare the performance and highlight the advantages of combined systems, the energetic and exergetic performances of the single generation, cogeneration, trigeneration, and multigeneration plants under the same conditions are compared in Fig. 18. The energy efficiencies of these generation options are computed as 0.28, 0.31, 0.36, and 0.42, respectively. Moreover, the exergetic efficiencies are computed as 0.24, 0.27, 0.33, and 0.37, for the same row systems. As can be clearly seen, the multigeneration plant has higher energy and exergy performance than other plants. This is the high number of useful outputs obtained.

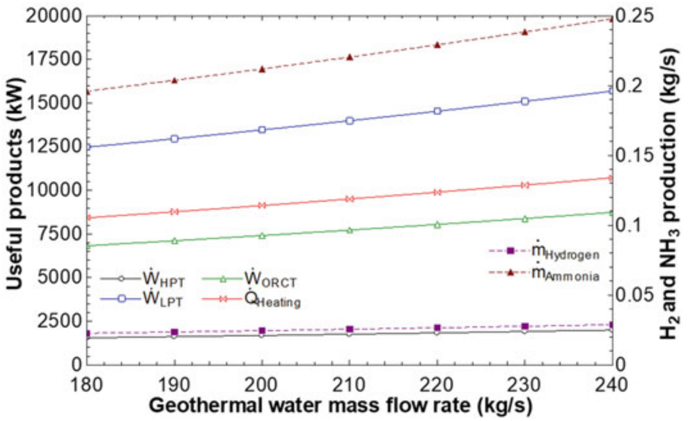

Fig. 16 The impact of geothermal fluid mass flow rate on the useful outputs

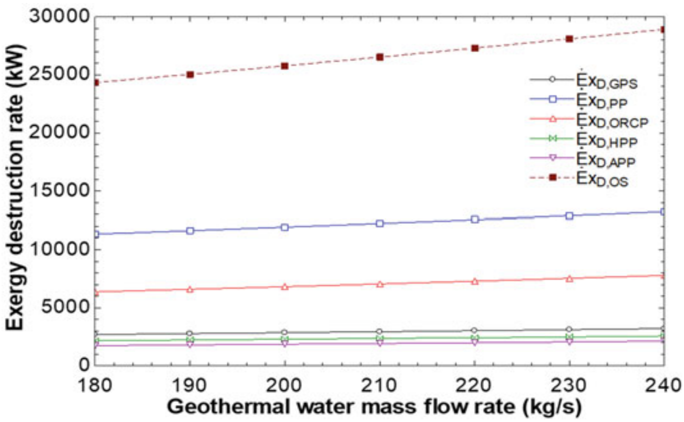

Fig. 17 The impact of geothermal fluid mass flow rate on the exergetic destruction rates

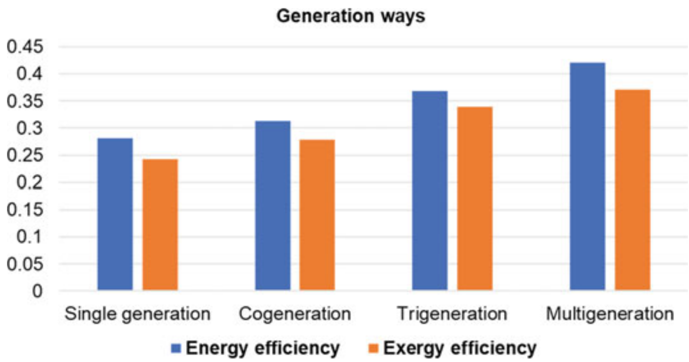

Fig. 18 Comparison of production ways for proposed system

5 Conclusion and Future Directions

In this book chapter, the thermodynamic examination of the geothermal energy-supported multigeneration model is discussed in detail. In addition, the main purpose of this proposed part is to realize power, heating, H_2, and NH_3 generation by utilizing geothermal energy and analyze this system parametrically. In this context, energy and exergy performances of all proposed systems and sub-plants, as well as useful outputs and exergetic destruction rates are investigated. Furthermore, the effects of significant bounds such as environment temperature and GWT on the advised plant are analyzed parametrically. Some of the prominent main results obtained can be given as follows:

- The displayed integrated system has an energetic effectiveness of 0.4213 and an exergetic effectiveness of 0.3706 at a reference temperature of 25 °C.

- The produced rates of hydrogen and ammonia from the designed model are 0.0245 and 0.2119 kgs^{-1}.
- The produced rates of power from the HP and LP turbines are 1685 kW and 13,458 kW respectively. As well, the amount of produced electrical energy from the ORC turbine is 7409 kW.
- The modeled multigeneration system has 25,776 kW exergy destruction rate.
- As stated by the results of analysis, the rise in reference temperature and the GWT have a positive effect on the effectiveness of proposed system and subsystems.

In short, the widespread utilization of renewable power resources is inevitable in combating environmental problems such as climatic variations. In addition, effective usage of energy sources is among the important issues. Therefore, renewable energy-supported multigeneration systems will have an advantage in tackling environmental problems.

The future direction of these geothermal energy-based systems can be identified as follows;

- Increasing the use of geothermal energy resources to combat environmental problems.
- In low-temperature applications, geothermal energy can be integrated with cycles such as Kalina and ORC to generate power. However, parameters such as investment and cost can be taken into account in reaching the desired capacity and efficiency.
- It can be researched to obtain different useful outputs from geothermal energy instead of only electricity generation.
- The production of alternative fuels such as H_2 and NH_3 with integrated plants can be investigated on a real power plant in terms of thermodynamics and economy.
- The utilization of geothermal power should be expanded for air conditioning purposes such as heating and cooling.
- By making more comprehensive energy, exergy, environmental and exergoeconomic analyzes, each value in the system elements can be examined. In this way, more efficient systems can be obtained.
- As a result, since geothermal energy interruption is an energy source, more efficient and lower-cost systems can be obtained by using integrated systems to obtain different useful outputs.

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CO_2 Capture and Utilization for Fuel Synthesis

Alper Can Ince, Can Ozgur Colpan, and Mustafa Fazıl Serincan

1 Introduction

In this century, one of the most significant issues that face today's and future humanity is energy production from fossil fuels due to its adverse impact on the environment. Greenhouse gas emission (mainly CO_2 emission) is a key indicator of the related impact. The electricity and heat production (energy sector) dominates the release of CO_2 emissions. For example, according to IEA's database published in 2018, 40% of total CO_2 emission is due to electricity and heat production, and other energy sectors (IEA 2021). Moreover, an increase in CO_2 emission leads to accelerate global warming. IPCC published a special report entitled "Global Warming of 1.5 °C" in 2018 to declare the effect of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways (Masson-Delmotte et al. 2018). Regarding this report, (Rogelj et al. 2021b) presented that global warming pursues increasing, and is expected to peak in 2070, but then will decrease under 1.5 °C in 2080, as shown in Fig. 1. In order to remain below 1.5 °C of warming (for above pre-industrial levels), the target of "net zero-emission" was announced in the Paris Climate Agreement (Tanaka and O'Neill 2018). The route to achieve net-zero emissions is when there is a balance between anthropogenic CO_2 emissions to the

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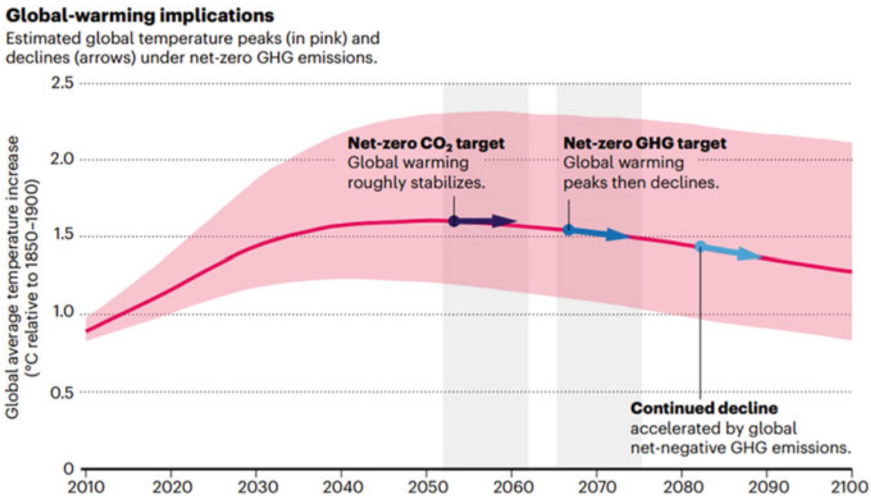

Fig. 1 The change of global average temperature (Rogelj et al. 2021a)

atmosphere and anthropogenic removals of CO_2 emission over a specified period (Masson-Delmotte et al. 2018).

Integrated carbon capture, utilization, and storage (CCUS) systems play a significant role to mitigate CO_2 emission and thus limits the increase of global warming (Fernández et al. 2020). As the basic concept of CCUS is displayed in Fig. 2, the carbon can be captured from three main sources: air (direct air capture), flue gas, and biogas. The carbon capture part of CCUS provides a strategy to mitigate greenhouse gas emissions, while the utilization part simultaneously gives alternative routes for fuel production (Marocco Stuardi et al. 2019). CCUS integrated different energy systems have therefore gained considerable traction in the last years. A few review studies that address the carbon capture and its utilization to be implemented into various systems have been recently published (Akabane et al. 2021; Hidalgo and Martín-Marroquín 2020; Ince et al. 2021; Mikulčić et al. 2019; Sun et al. 2021). Moreover, Duan et al. (2016) presented a coal-fired power plant with CO_2 capture by integrating molten carbonate fuel cell (MCFC) system. Similarly, MCFC was applied to an integrated steel mill for CO_2 capture by Mastropasqua et al. (2019).Tian et al. (2018) proposed a CO_2 capture unit integrated trigeneration system that consists of solid oxide fuel cell (SOFC), organic Rankine cycle, and absorption chiller.

The main part of CCUS is carbon capture. Different CO_2 capture and separation techniques from various carbon sources can be considered regarding of energy, economic, and environmental penalty of the system when the CO_2 capture system is integrated. For example, Vasudevan et al. (2016) compared the energy penalty performance of the CO_2 capture systems from different sources. The lowest energy penalties were found when CO_2 is captured from the combustion of natural gas. The CO_2 can be stored in two main parts: Ocean (Adams and Caldeira 2008) and geological (Voormeij and Simandl 2004). Another important part of CCUS is CO_2 utilization.

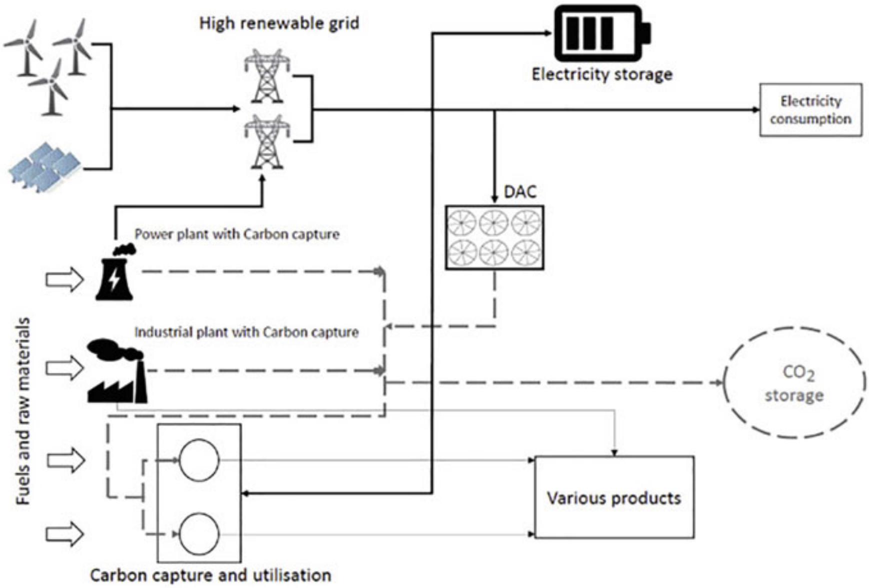

Fig. 2 A basic scheme of CCUS (Mikulčić et al. 2019)

There are mainly four different utilization options of CO_2 as chemical feedstocks, mineral carbonisation, enhanced oil recovery, and fuels. It is understood that the integration of CCUS into the energy system could become complex. The estimation of CCUS's performance has therefore gained considerable traction to determine the energy penalty. The mathematical modeling approaches offer an effective route to understand the performance of CCUS under variable operating conditions.

In this chapter, two main parts of CCUS such as CO_2 capture and utilization are considered, while the storage of CO_2 is out of scope. Therefore, this chapter consists of two main sections. In the first section, the basic introduction of CO_2 capture techniques is presented. The modeling approaches that can be applied for CO_2 capture and separation units are introduced; furthermore, the relevant modeling studies are discussed and reviewed systematically. In the second section (utilization section), the fuel synthesis is the main scope of this chapter. Two novel components are chosen for the CO_2 utilization such as membrane reactor and CO_2 electrolyzer. In this regard, these components are introduced, focusing on operating principles. Moreover, the relevant modeling studies are discussed. Finally, the remarkable conclusion from these studies is presented. Therefore, this chapter offers a guide to assess CCUS performance from an engineering perspective.

2 CO_2 Capture Process

2.1 Description of Methods and Technologies

In this section, the working principles of different CO_2 capture methods are depicted and compared in terms of their merits and challenges. Moreover, the modeling and simulation techniques for the CO_2 capture process are presented.

CO_2 can be obtained from air directly or highly-concentrated CO_2 sources (e.g., biogas, coal, cement, and iron plant) (Panzone et al. 2020). For example, the amount of CO_2 concentration can reach over 80% in the exhaust gas of the coal combustion process. Another important CO_2 source is biomass that can include 10–40% of CO_2 (Cuéllar-Franca and Azapagic 2015; Song et al. 2019). Different CO_2 sources, capture methods, utilization and storage options are presented in the literature, as summarized in Fig. 3. Several review papers have addressed individual CO_2 capture processes such as pre-combustion (Babu et al. 2015; García et al. 2011; Jansen et al. 2015), post-combustion (Samanta et al. 2012; Wang et al. 2017), oxy-fuel combustion (Habib et al. 2011; Wu et al. 2018), and direct air capture (Koytsoumpa et al. 2018).

The CO_2 separation methods shown in Fig. 3 are compared in Table 1. One of the most mature separation methods is absorption which is classified as chemical and physical depending on the reaction of the solvents used with CO_2. When the solvents react with CO_2, it is called chemical. On the other hand, if there is no reaction between CO_2 and solvent, the process is called physical. In the adsorption technology, a solid surface is typically used to remove CO_2 from the flue gas. Here, the driving force occurs due to the intermolecular forces. The adsorbent is added in a column. Then, the flue gas, including CO_2, passes through the column. On the surface, CO_2 becomes saturated. Finally, it is adsorbed through the four regeneration cycles (e.g. pressure swing adsorption, temperature swing adsorption, electrical swing adsorption, and vacuum swing adsorption) (Sifat and Haseli 2019). Several mathematical modeling and optimization studies that focus on pressure swing adsorption (Hasan et al. 2012), vacuum swing adsorption processes (Zhang et al. 2008), temperature swing adsorption (Marx et al. 2016), electric swing adsorption (Grande et al. 2009), and fixed-bed adsorption (Dantas et al. 2011) are presented in the literature. Another method to separate CO_2 from the flue gas is the cryogenics method that offers CO_2 with high purity over the other capture technologies. There are three main steps such as cooling (below −120 °C), capture, and recovery step in the cryogenics process. This method is costly due to the high energy requirement for the cooling process. (Brunetti et al. 2010; Tuinier et al. 2011). Using membranes for CO_2 capture is a promising method due to being simple and environmentally friendly and having relatively higher energy efficiency compared to other technologies. The basic membrane process is displayed in Fig. 4. The first stage is called the gas separation membrane (the working principle is based on pressure gradient), and the second stage is the gas absorption membrane. In the gas absorption, the microporous membrane is used to separate CO_2 from the gas mixture, as shown in Fig. 4. Membrane technology is the best option to capture

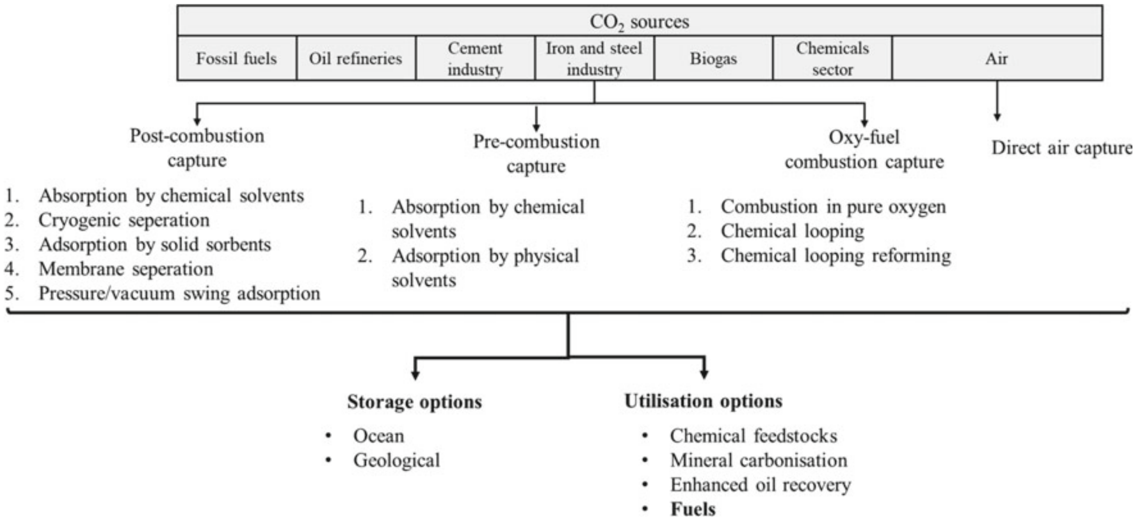

Fig. 3 CO_2 sources, storage and utilization options (modified from (Cuéllar-Franca and Azapagic 2015))

Table 1 CO_2 separation methods (Li et al. 2019; Olah et al. 2011; Riboldi and Bolland 2017; Song et al. 2019)

Separation methods	Advantages	Challenges	Energy requirements*
Chemical absorption	Mature (low solvent cost, lower energy requirement)	Corrosion, amine degradation, the slow absorption rate of CO_2, and higher pressure drops	0.582 kWh/kg_{biogas}
Physical absorption	No corrosive solvent and high purity	High operating pressure	N.A
Adsorption	Fast kinetics, high thermal stability, low environmental impact, and low capital cost	Low CO_2 selectivity, high vacuum conditions, and effect of impurities	0.209 kWh/kg_{biogas}
Membrane technology	Simple, compact, operating at ambient temperature, and low capital cost	Fouling, lower product, and having at least two membrane stages to obtain high purity CO_2	0.174 kWh/kg_{biogas}
Low temperature (cryogenics)	High recovery, pressurized CO_2, and no corrosion	High energy consumption, undesired mechanical stress, and economical when CO_2 concentration is at least 75% in the flue gas	0.284 kWh/kg_{biogas}

*Note that the energy requirement values are found for the CO_2 capture from the biogas. For the boundary conditions and calculation procedures, the study by Li et al. (2019) should be taken into consideration. The energy requirement to capture CO_2 from binary gas such as biogas can be calculated by the following equation: $E_{min} = -RT\left(\frac{xlnx+(1-x)\ln(1-x)}{x} - \frac{yIny+(1-y)\ln(1-y)}{y}\right)E_{min} = -RT\left(\frac{xlnx+(1-x)\ln(1-x)}{x} - \frac{yIny+(1-y)\ln(1-y)}{y}\right)$. Here, x and y are the mole concentrations of the feed mixed gas and separated mixed gas, respectively. T is the operating temperature

CO_2 from the biogas due to economic reasons (Basu et al. 2010). Jeanmonod et al. (2019) developed a trade-off design for a power to methane system using the biogas. To obtain CO_2 from biogas, the clean biogas is heated and fed to the catalytic reactor where O_2 is removed. In the next step, the gas is dried in the drum with eliminating water. For the CO_2 separation, they used polyimide two-stages membrane.

2.2 Modeling of the CO_2 Separation Technologies

The mathematical modeling and simulation of the CO_2 separation technologies are effective tools to find the process performance (e.g., amount of energy requirement, dynamic performance, amount of CO_2 captured, and purity of CO_2) under different

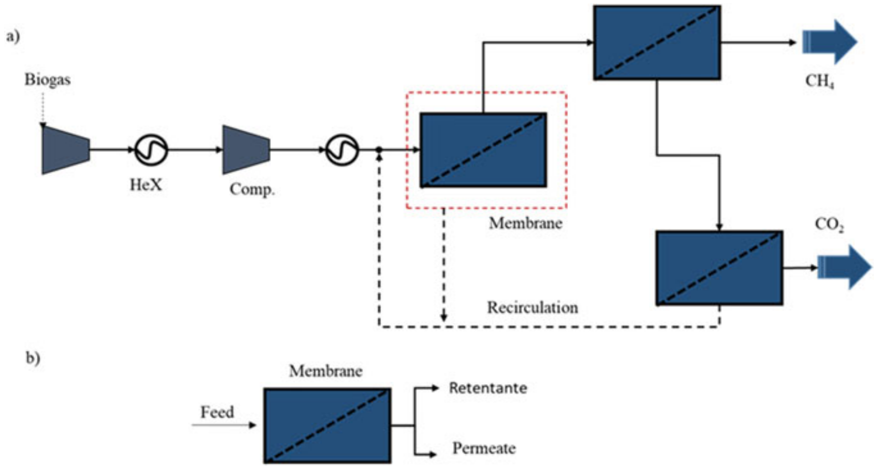

Fig. 4 The multi-stage membrane **a** CO_2 capture process, **b** the single membrane module

working conditions. For this purpose, in this section, several recent modeling studies are given and discussed in Table 2. Moreover, the modeling equations for membrane process-based CO_2 capture from biogas is described.

For the chemical absorption separation method, some studies on the economic performance (e.g., Abu-Zahra et al. 2007; Dave et al. 2011), thermodynamic performance (e.g., Greer et al. 2010; Puxty et al. 2009), and environmental performance (e.g., Luis 2016; Thitakamol et al. 2007) were performed under the steady-state operation. Similarly, the dynamic simulations for the CO_2 separation in a capture process through the chemical absorption were addressed in the studies of (Bui et al. 2014; Lawal et al. 2010). Daggash et al. (2018) studied the steady-state thermodynamic performance of CO_2 capture from the air (direct air capture, DAC) using KOH solution in the renewable methanol production system. They reported that the electricity requirement changes in a range from 1.78 to 5.4 $GJ{\cdot}tCO_2^{-1}$. The modeling studies that address to the physical absorption method for the CO_2 capture were performed in the studies of (Iancu et al. 2010; Won et al. 2012). Song et al. (2019) developed a numerical model for the cryogenic CO_2 capture process from flue gas; furthermore, the optimization analysis was also conducted through the response surface methodology to avoid energy penalty during the capture process. They found that the process was capable of capturing 95% CO_2 with the energy input of 0.52 $MJ/kg_{captured}$. Vázquez et al. (2018), p. proposed a P-t-X configuration that utilizes CO_2 from the air. For the CO_2 capture, they used the temperature-vacuum swing adsorption method. The operation was done at 90 °C and 1 bar. For this method, they used 30 kg adsorbent. Their test results showed that they obtained 3800 g CO_2 per day from the air. Jeanmonod et al. (2019) developed a trade-off design for the power to methane system using biogas. Here, for the CO_2 separation, they used a two-stages polyimide membrane. To obtain CO_2 from biogas, the clean biogas is heated and fed to the catalytic reactor

Table 2 A mini-review on the modeling of the CO_2 capture process between 2015 and 2020

Study	CO_2 source	CO_2 capture process	CO_2 separation method	Mathematical model				Main scope
				Operation	Temperature characteristic	Dimension	Software	
Hajilary and Rezakazemi (2018)	Flue gas	N.A	Membrane	Steady state	Isothermal	2-D	COMSOL multiphysics	Nanoparticles effect on the absorption process
Arias et al. (2016)	Flue gas	Post-combustion	Membrane	Steady state	Isothermal	1-D	GAMS v.23.7 and CONOPT 3.0	Optimal cost and energy input
Cormos and Simon (2015)	Flue gas	Oxy-fuel combustion	Chemical loop	Dynamic	Isothermal	1-D	MATLAB/simulink	Transient response under the load operation
Tan et al. (2016)	Flue gas	N.A	Chemical absorption	Steady state	Isothermal	1-D	MATLAB	CO_2 capture performance along the absorption column under different pressure conditions
Mondino et al. (2019)	Flue gas	Post-combustion	Temperature swing adsorption (TSA)	Dynamic	Isothermal	0-D	gPROMS	Direct comparison between the two capture technologies: Amine absorption and TSA

(continued)

Table 2 (continued)

Study	CO_2 source	CO_2 capture process	CO_2 separation method	Mathematical model				Main scope
				Operation	Temperature characteristic	Dimension	Software	
Marx et al. (2016)	Flue gas	Post-combustion	Temperature swing adsorption (TSA)	Steady state	Non-isothermal	1-D	MATLAB	Process performance including CO_2 purity, recovery, and productivity
Usman et al. (2017)	N.A	Pre-combustion	Membrane	Steady state	Isothermal	1-D	Aspen HYSYS	Economic feasibility of the CO_2 capture process and the effect of operating parameters on the system performance
Sohaib et al. (2020)	Flue gas	Pre-combustion	Membrane	Steady state	Non-isothermal	2-D	COMSOL multiphysics	The effect of the temperature and number of fibres on process performance

(continued)

Table 2 (continued)

Study	CO_2 source	CO_2 capture process	CO_2 separation method	Mathematical model				Main scope
				Operation	Temperature characteristic	Dimension	Software	
Gaspar et al. (2015)	Flue gas	Post-combustion	Chemical absorption	Dynamic	Non-isothermal	1-D	MATLAB	Capture efficiency and purity of the CO_2 product Stream under different flue gas flow rates
Shen et al. (2018)	Biogas	N.A	Vacuum pressure swing adsorption (VPSA)	Dynamic	Isothermal	1-D	Design expert software	The transient behaviours of adsorption bed in VPSA
Vilardi et al. (2020)	Biogas	N.A	Membrane and chemical absorption	Steady state	Isothermal	0-D	Aspen plus	Thermodynamic performance including exergy analysis
Sinha et al. (2017)	Air	N.A	Temperature swing adsorption (TSA)	Dynamic	Non-isothermal	0-D	N.A	Modeling study for performance and economic assessment for DAC through the TSA

where O_2 is removed. In the next step, the gas is dried in the drum with eliminating water.

3 CO_2 Utilization for Fuel Synthesis

3.1 A Description of Novel Technologies for CO_2 Utilization

3.1.1 Membrane Reactor

A membrane reactor is a promising alternative technology that can be integrated into the P-t-X processes to produce liquid hydrocarbons through CO_2 hydrogenation as well as hydrogen (Nalbant and Colpan 2020; Zhang et al. 2018). One of the important benefits of this technology is that the separation and reaction processes are merged in a single and compact unit. These reactors can improve the reaction selectivity and conversion by enhancing mass transfer, and they have better thermal stability (Hafeez et al. 2020; Zhang et al. 2020). However, the hydrocarbon production yield, water production as an undesirable product, and selectivity highly depend on the operating conditions. Therefore, a few membrane reactor configurations have been developed so far (Hafeez et al. 2020; Hapońska et al. 2019; Klinsrisuk et al. 2015; Najari et al. 2020). The working principle of a membrane reactor is presented in Fig. 5. In this configuration, H_2 and CO_2 enter from the reaction side filled with catalyst where the RWGS and FT reactions occur. A sweep gas flows through tube

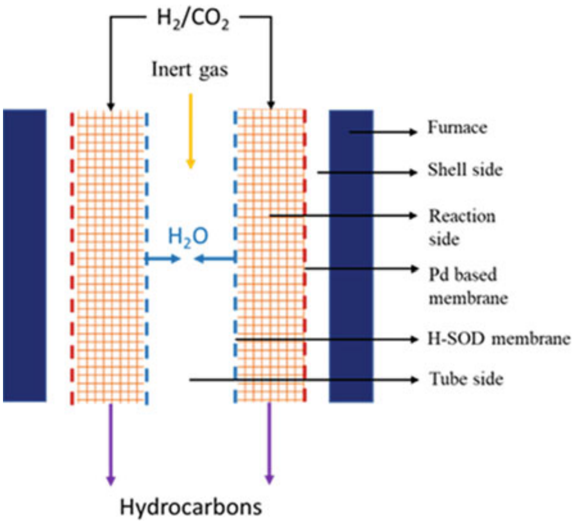

Fig. 5 Schematic diagram of membrane reactor (Modified from Najari et al. 2020)

side to remove water that is a byproduct from the reaction side via a hydroxy sodalite (H-SOD) membrane. Different catalyst types can be used to produce a wide range of hydrocarbons in membrane reactors. For example, Hapońska et al. (2019) used strontium oxide as a heterogeneous catalyst to produce biodiesel. B-doped Ru/TiO2 catalyst was used by Liuzzi et al. (2016). According to their results, the increment of high-molecular hydrocarbons yield was found as almost 70%, and methane, which is the undesired product, was significantly reduced in a packed bed membrane reactor. Wang et al. (2003) developed a Pd-based membrane reactor to produce hydrogen and other value-added hydrocarbon fuels from ethane. They used Re/HZSM-5 catalyst to produce aromatics (BTX). When compared to the Mo/HZSM-5 catalyst type, the conversion of ethane into H_2 and BTX was very low.

3.1.2 CO_2 Electrolyzer

CO_2 electrolyzer is used to produce fuel (e.g., methanol and ethanol) by converting CO_2 directly through the electrochemical reduction of CO_2. Alternatively, it can be used for the conversion of CO_2 into chemicals such as carbon monoxide (CO) and formic acid (HCOOH) to be further used for fuel processing in chemical reactors. To do this, the CO_2 electrochemical reduction can pass through various pathways, i.e. two-, four-, six-, eight-, and eighteen-electrons reduction, as given in Table 3 (Zhong et al. 2016).

Many cell architecture designs are available for CO_2 electrolysis to ascertain current density, Faradaic efficiency, and stability in the literature (Liang et al. 2020). H type-cell (Fig. 6a, e.g., Lee et al. 2020; Liu et al. 2021, p. 2), polymer electrolyte membrane (PEM) flow cell (Fig. 6b, e.g., Salvatore et al. 2018; Wang et al. 2018),

Table 3 CO_2 electrolysis reactions (Schneider et al. 2012)

$CO_{2(g)} + 2H^+ + 2e^- \leftrightarrow CO_{(g)} + H_2O_{(l)}CO_{2(g)} + 2H^+ + 2e^- \leftrightarrow CO_{(g)} + H_2O_{(l)}$
$CO_{2(g)} + 2H^+ + 2e^- \leftrightarrow HCOOH_{(l)}CO_{2(g)} + 2H^+ + 2e^- \leftrightarrow HCOOH_{(l)}$
$CO_{2(g)} + 6H^+ + 6e^- \leftrightarrow CH_3OH_{(l)} + H_2O_{(l)}CO_{2(g)} + 6H^+ + 6e^- \leftrightarrow CH_3OH_{(l)} + H_2O_{(l)}$
$CO_{2(g)} + 8H^+ + 8e^- \leftrightarrow CH_{4(g)} + 2H_2O_{(l)}CO_{2(g)} + 8H^+ + 8e^- \leftrightarrow CH_{4(g)} + 2H_2O_{(l)}$
$2CO_{2(g)} + 12H^+ + 12e^- \leftrightarrow C_2H_{4(g)} + 4H_2O_{(l)}2CO_{2(g)} + 12H^+ + 12e^- \leftrightarrow C_2H_{4(g)} + 4H_2O_{(l)}$
$2CO_{2(g)} + 12H^+ + 12e^- \leftrightarrow C_2H_5OH_{(l)} + 3H_2O_{(l)}2CO_{2(g)} + 12H^+ + 12e^- \leftrightarrow C_2H_5OH_{(l)} + 3H_2O_{(l)}$
$3CO_{2(g)} + 18H^+ + 18e^- \leftrightarrow C_3H_7OH_{(l)} + 5H_2O_{(l)}3CO_{2(g)} + 18H^+ + 18e^- \leftrightarrow C_3H_7OH_{(l)} + 5H_2O_{(l)}$
$2H^+ + 2e^- \leftrightarrow H_{2(g)}2H^+ + 2e^- \leftrightarrow H_{2(g)}$

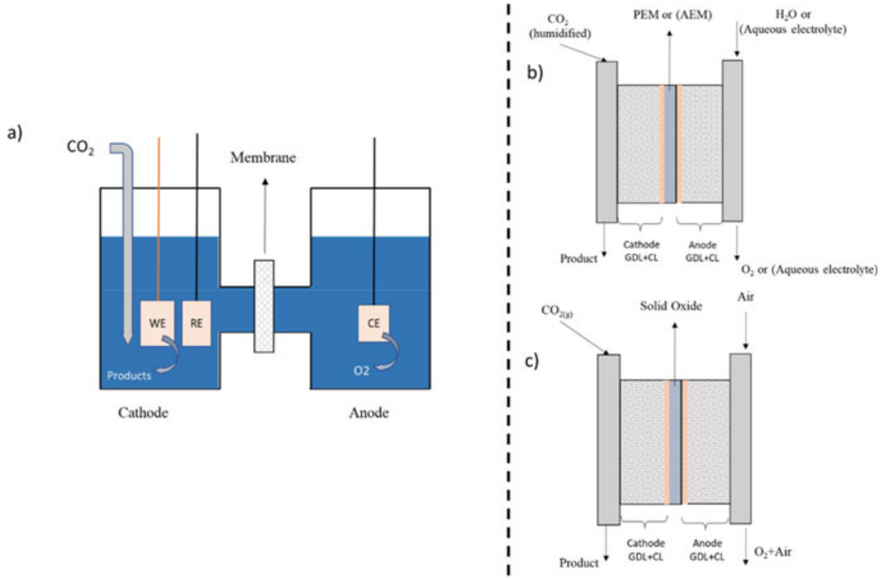

Fig. 6 Various CO_2 electrolyzer designs (modified from Liang et al. 2020)

and solid oxide cell (Fig. 6c, e.g., Jiang et al. 2021; Skafte et al. 2018) are the main cell designs for the CO_2 electrolysis. H type cell and PEM flow cell work at ambient conditions (low temperature CO_2 electrolyzers), while SOE cell structure for CO_2 electrolysis is operated at elevated high temperatures (High temperature CO_2 electrolyzer). In H type cell, the anion exchange membrane or cation exchange membrane is used as the membrane type, while Cu and Ag are the main type of electrocatalysts. PEM cell is one of the most feasible gas-phase electrochemical devices for CO_2 electrolysis. The CO_2 electrolysis can be conducted in a PEM cell at ambient temperatures through the electrocatalysts of Pd, Ag, Zn or Cu oxides. The electrolysis of CO_2 at low temperature suffers from low operating current density due to the slow mass transport and diffusion kinetics (Zhang et al. 2017). Therefore, CO_2 electrolysis in high temperature electrolyzer (solid oxide cell) has gained considerable interest in the last decades (Xi et al. 2021). The CO_2 electrolysis in SOE cells is very attractive due to high catalytic activity and good chemical stability. In this context, Küngas et al. 2017 reported that high-temperature electrolysis of CO_2 in solid oxide electrolysis cells yields higher efficiency and durability. Moreover, they reported that low temperature electrolysis technology has early-stage technology readiness levels (TRL 1–4), whereas high temperature electrolysis is almost available for commercialization (TRL 8). However, there are still many problems to be handled such as Ni oxidation, carbon deposition, grain coarsening, and impurities contamination etc.

3.2 *Modeling of the Novel Components*

In this section, the mathematical modeling of novel components considered is discussed and compared in Table 4. The number of modeling studies on CO_2 electrolyzer and membrane reactors are not abundant in the literature. The existing studies are generally in lab-scale and aim to develop a component architecture. Regarding the scope of this chapter, the cell level modeling of the CO_2 electrolyzer is presented.

The modeling and simulations for CO_2 electrolyzer are generally based on micro-scale to investigate materials behaviour in CO_2 electrolyzer. In the literature; the micro electrochemical kinetic models (Delacourt et al. 2010; Delacourt and Newman 2010), Monte Carlo simulations (Kannan et al. 2019; Kopač et al. 2017), DFT calculations (Lv et al. 2020; Zhou et al. 2020), and microfluid flow model for liquid phase CO_2 electrolyzer types (Lu et al. 2018a; Shi et al. 2013) are abundant. Ni (2010) developed a two-dimensional thermo-fluid and electrochemical model for solid oxide cell for CO_2 electrolyzer. The model was implemented into in-house CFD code written in Fortran. They reported that when the inlet gas velocity increases from 0.1 to 0.2 $m\,s^{-1}$, the electrochemical performance can be improved significantly. Narasimhaiah and Janardhanan (2013) presented a comprehensive electrochemical model for CO_2 electrolysis. The equation of the model was solved through the LIMEX that is differential–algebraic equation solver. The significant results showed that although achieving 100% conversion of CO_2 electrolyzer is possible, conversion of 95% is appropriate owing to the Boudouard reaction equilibrium. Shi et al. (2013) developed a one-dimensional, steady-state and isothermal model for CO_2 electrolyzer producing CO in a solid oxide cell. The coupled charge and mass transfer, as well as the kinetic model within the electrode, were incorporated. They reported that high temperature contributes to the increasing conversion of CO_2 to CO with low carbon deposition. Wang et al. (2013) developed a numerical model for the microfluidic electrolytic cell where CO_2 converts to HCOOH through the finite-volume method that is implemented into an in-house code in Fluent 6.3. Microfluid flow, mass transfer and electrochemical models for the porous cathode were incorporated. The effect of CO_2 velocity on the current density and CO_2 conversion efficiency was investigated. When the velocity of CO_2 feed increases, the conversion efficiency of CO_2 decreases, whereas current density increases. It was concluded that the optimum velocity of CO_2 is around 0.1 m/s to achieve current density and CO_2 conversion efficiency of 50 mA/cm^2 and 0.3, respectively. Kotb et al. (2017) conducted an isothermal mathematical 2-D modeling study for a liquid phase CO_2 electrolyzer that produces CH_3OH with the electrochemical reduction of CO_2 through the Ag–Cl catalyst. Species transport, microfluid flow, electronic and ionic charge balances, and electrochemical kinetics for the electrodes were considered in the model. The effect of electrolyte flow rate on the CH_3OH formation was investigated through the model. It was found that when the electrolyte flow rate decreases, the outlet concentration of CH_3OH increases significantly. Lu et al. (2018a) developed a mathematical model to determine the performance of microfluidic electrolytic cell (PMEC) for the conversion of CO_2 to HCOOH. Microfluid flow, electrochemical, mass transfer and

Table 4 A mini review on mathematical modeling of membrane reactor and CO_2 electrolyzer for fuel synthesis

Study	Component	Mathematical model				Main conclusion
		Operation	Temperature characteristic	Dimension	Software	
Najari et al. (2020)	Membrane reactor	Steady state	Non-isothermal	1D	MATLAB	The optimized operating conditions (e.g. pressure, temperature, and sweep ratio) are enabled to achieve the maximum olefin yields
Currie et al. (2019)	Membrane reactor	Dynamic	Non-isothermal	1D	MATLAB	When membrane space velocity (upper panel) is low, H_2 depletion and, as a result, CO_2 conversion decreases significantly
Ni (2010)	CO_2 electrolyzer	Steady state	Non-isothermal	2D	FORTRAN	When the inlet gas velocity increases from 0.1 $m \cdot s^{-1}$ to 0.2 $m \cdot s^{-1}$, the electrochemical performance can be improved significantly
Narasimhaiah and Janardhanan (2013)	CO_2 electrolyzer	Steady state	Isothermal	1D	LIMEX	Although achieving of 100% conversion of CO_2 electrolyzer is possible, conversion of 95% is an appropriate owing to the Boudouard reaction equilibrium

(continued)

Table 4 (continued)

Study	Component	Mathematical model				Main conclusion
		Operation	Temperature characteristic	Dimension	Software	
Shi et al. (2013)	CO_2 electrolyzer	Steady state	Isothermal	1D	COMSOL multiphysics	High temperature contributes to the increasing conversion of CO_2–CO with low carbon deposition
Wang et al. (2013)	CO_2 electrolyzer	Steady state	Isothermal	2D	FLUENT 6.3	When the velocity of CO_2 feed increases, the conversion efficiency of CO_2 decreases, whereas current density increases
Kotb et al. (2017)	CO_2 electrolyzer	Steady state	Isothermal	2D	COMSOL multiphysics	It was found that when the electrolyte flow rate decreases, the outlet concentration of CH_3OH increases significantly
Lu et al. (2018b)	CO_2 electrolyzer	Steady state	Isothermal	N.A	COMSOL multiphysics	The model showed that the bubble formation highly depends on the channel size and the dimensionless gas–liquid flow ratio

microkinetic models were considered. The model showed that the bubble formation depends on the channel size and the dimensionless gas–liquid flow ratio.

One of the most important engineering tasks is the reactor modeling. The recently published studies are compared in terms of the reactor space dimension (e.g., 0D-3D), time, phase modeling (e.g., heterogeneous and homogenous), software, modeling approach (e.g., chemical equilibrium, kinetics), and temperature characteristics (e.g., isothermal and non-isothermal). Here, Langmuir–Hinshelwood-Hougen-Watson (LHHW) and power-law are generally considered in kinetic models, while Vanden Bussche and Froment kinetic model can also be used. Mathematical modeling studies are very limited for hydrocarbon fuel production in a membrane reactor even though there are a lot of modeling studies for the other conventional chemical reactors (e.g., Sabatier, FT reactor, and HB reactor). For example, a one-dimensional model for a membrane reactor is developed by Currie et al. (2019). The performance of the membrane reactor was estimated under transient conditions. Under optimized parameters, model predicted 97% CH_4 yield with the component operation of 10,000 h. Najari et al. (2020) developed a 1-D non-isothermal mathematical model for a membrane reactor to predict the performance of the reactor. They investigated the effect of temperature, feed ratio, sweep ratio, and pressure ratio on the hydrocarbon products yields. They reported that higher temperatures at a low flow rate of sweep gas and low-pressure ratios are favourable for the olefins production, while yields of paraffin, which is an undesired product, are decreased. Specifically, they found the optimum temperatures in the reactor and shell and tube sides, the pressure ratio, and the sweep ratio as 325 °C, 306.96 °C, 325 °C, 1 and 1, respectively for the olefin production.

4 Conclusions

This chapter aims to develop an engineering guide for the CO_2 capture and utilization system to be implemented into synthetic fuel production systems. For this purpose, the basic introduction of CO_2 capture with separation techniques is presented; furthermore, the studies that address the mathematical model of CO_2 capture techniques are discussed and reviewed. Moreover, the basic operating window of novel components such as membrane reactor and CO_2 electrolyzer for the fuel production from the CO_2 utilization is presented. Most importantly, the studies focusing on the cell scale mathematical modeling of these components is discussed and compared systematically. The important gaps found in the literature can be listed as follows:

- The number of studies on the implementation of the sub-models of the CO_2 capture process into a synthetic fuel production process model is insufficient. Moreover, the dynamic model for the CO_2 capture process is very limited in the literature.
- There are limited studies on the mathematical modeling of the membrane reactors to produce synthetic fuel, even though there are a lot of modelling studies on these reactors used to produce pure hydrogen. However, according to the authors' best

knowledge, no study addresses to the implementation of a membrane reactor model into the system-level model synthetic fuel production process.

- The micro and mesoscopic scale modeling of a CO_2 electrolyzer are abundant. However, the number of studies on the macroscopic level (cell-scale) modeling of a CO_2 electrolyzer to produce synthetic fuels directly is very limited. Moreover, the implementation of the CO_2 electrolyzer model into the synthetic fuel production process model is found rarely in the literature.

This chapter showed that the energy penalty is an important challenge to implement a CO_2 capture unit. One of the minimum energy requirements is found as around 5 GJ/ton^{-1} when 95% of the CO_2 is captured from flue gas through the cryogenic separation method. The CO_2 capture from the biogas can be favourable when the membrane separation method is used. For example, the energy requirement is found as 0.174 kWh/kg$_{biogas}$ for the membrane separation method, while the energy requirement is 0.582 kWh/kg$_{biogas}$ in the case of the chemical absorption method. The chapter also showed that the direct electrochemical reduction pathway through the CO_2 electrolyzer and catalytic membrane reactor under feasible operating conditions could be a significant for prospective system design for CO_2 utilization.

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Hydrogen Related Technologies and Application a Major Pathway for the Energy Transition

Tanay Sıdkı Uyar and Moaz Bilto

1 Introduction

The global efforts we are witnessing now to reduce the effect of climate change on the planet, an energy transition where renewable energy supported by green hydrogen providing it whenever its needed is inevitable powered by new advancement in energy related technologies and strong influence from governments, many changes are occurring across energy sectors worldwide.

2018 witnessed the emergence of a large movement demanding the change towards climate change mitigation policies in Europe and elsewhere. In a number of countries where parties with green agendas gained particular proportions in Europe, this movement has effectively changed the political landscape, therefore, policy and decision makers in many countries sharpening their emission reduction targets for 2030 and 2050.The capabilities of hydrogen as a key role in the upcoming transition to a more sustainable green energy future have increased rapidly in recent years and gained interest globally in exchange to gradually reduce the reliance on fossil fuel, and how hydrogen as a renewable energy resource already passed the turning point impacting the global transition, social economics while proving that expensive costs now will give back profit in the future. Shifting from fossil fuels to renewable such as green hydrogen where these changes could play a role facilitating

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the transition (J. C. (Guidehouse) 2020), our approach towards this transition will determine the challenges that we will face now, and in the future, competitiveness is also needed for the renewable transition to succeed where convincing decision makers, high tech companies to shift to renewable is also considered a challenge. Covid 19 pandemic showed us how every breath that we take for granted counts which shows how important air quality is for us as human beings. A shift to renewables equals a more resilient energy grid. Commissions and decision makers choices now will decide how far until we reach an energy-efficient sustainable future especially for us when every breath counts clean air quality matters. The late twentieth century marked the start of an era where the effects of global warming became obvious with plenty of warnings especially in 1988 when a scientist named James Hansen proved that the greenhouse effect is already here (van Nuffel 2020). The first meeting addressing global warming was held at Geneva 1979 names World Climate Conference almost 10 years later the (The Intergovernmental Panel on Climate Change) IPCC was established in 1988 with the mandate to provide the world community with the most up-to-date and comprehensive scientific, technical, and socio-economic information about climate change and to set objectives that the modern work can work on (https://unfccc.int/process/the-convention/history-of-the-convention#eq-1). IPCC released their first report that stated the importance of climate change as a challenge with global consequences and requiring international cooperation to work on certain objectives. Followed by the Intergovernmental Negotiating Committee (INC) was a framework convention on climate change Held in Washington, D.C. Coming up to 1992, countries joined an international treaty, the United Nations Framework Convention on Climate Change, which works as a framework for big international cooperation to combat climate change. The UNFCCC United Nations Framework Convention on Climate Change came into its presence on the 21st of March, containing over 197 countries which are called parties to the convention they all set a mission for the UNFCCC which is preventing and stopping harmful human interference with the climate system (IPCC 1988). Further to 1995, countries launched negotiations to strengthen the global response to climate change, and, two years later, adopted the Kyoto Protocol. The Kyoto protocol connects countries to many targets that aim to reduce emissions, working on this protocol first started in 2008 and ended in 2012, a second period started in January 2013 and ended in 2020, There are now 197 Parties to the Convention and 192 Parties to the Kyoto Protocol (https://unfccc.int/process-and-meetings/the-convention/what-is-the-united-nations-framework-convention-on-climate-change). The IPCC'S fourth assessment report which analyzed many topics that have impact and effect on climate change, causes, projected impact in the future, adaptation options and long-term vision (Solomon et al 2007). Many conferences and convention with similar mission and effort were also held between 2007 and 2015. In 2021 COP26 this is the United Nation 26th climate change conference which will be the most significant meeting since the Paris agreement in 2015, 5 years ago world leading nations have committed to a noble agreement to tackle global warming, which they all agreed to keep temperatures rising below 2 degrees Celsius, countries will also be discussing their Emission target and what they have achieved in the past 5 years (https://www.glasgow.gov.uk/cop26). A huge role in climate change negotiations is played by non-governmental organizations they mostly participate as observers, although some of them contribute to the negotiations and influence the position of parties.

1.1 Most Influential NGO'S in the UNFCCC

UN agencies taking the lead in two programs as follow United Nations development program (UNDP) and United Nations Environment Program (UNEP). International Agencies such as Intergovernmental Panel for Climate Change (IPCCC) and Global Environment Facility (GEF) also contribute and provide environmental studies. Non-governmental organizations have their own contribution to the scientific community for example Environmental NGOs (ENGOs) which have the most diversity out of all organizations, and it is mostly concerned about influencing awareness on climate change towards the public. Business and Industry NGOs (BINGOs).

Are known for having the most influence on agendas, decision-makers, and policy frameworks, since it is a business organization it combines many companies with different views from all around the globe. Research and Independent NGOs (RINGOs) are the voice of the development and research organizations that provide research and information to all different parties such as technological advancement that helps fight climate change, causes, and the damage that can happen because of global warming. Trade Unions (TUNGOs) works on enabling the transition while underlining that joint work needs to be done between workers, trade unions, and communities concluding that societies contribute to employment, providing opportunities for the future to make the transition possible. Intergovernmental organizations (IGOs) International Energy Agency (IEA) which has the most studies published and has the highest impact. Other small observer organizations are indigenous people's organizations (IPOs) and local governments and municipal authorities (LGMAs). NGOs have a huge potential and importance in the fight against climate change even though most do not take apart as decision-makers, their goal as observers remain as important as any other contributors towards climate change which shows why the number of Newly admitted NGOs increase dramatically over that past decades (https://unfccc.int/topics/adaptation-and-resilience/the-big-picture/new-elements-and-dimensions-of-adaptation-under-the-paris-agreement-article-7). And the famous Paris agreement was adopted in Paris on 12 December 2015 which opened a pathway for developed nations to provide help for developing nations in setting frameworks, reports mitigations, and many more. The mission adopted for the agreement was to push investments to decarbonize and maintaining a strong response to global warming by keeping the global temperature rise under 2 °C future it was the last action that the united nation adopted so it can lead the way for a joint global effort to fight global warming and climate change (https://unfccc.int/process-and-meetings/parties-non-party-stakeholders/parties/party-groupings). According to the United Nations parties are divided into five main groups with several other small groups (https://unfccc.int/topics/climate-finance/the-big-picture/climate-finance-in-the-negotiations). The most important framework of this agreement is transparency working on improving the understanding of global warming where Groups (parties) must provide accurate data and information related to their climate footprint and the adaptation that they follow. The agreement asks all parties should coordinate, support, and monitor with each other to work and adapt national plans together so these plans can be implemented followed accordingly. Article 9 of the agreement states that developed country parties should lead in financing, utilizing, and mobilizing funds from a different diversity of sources, while other small groups like least developed countries are also encouraged to provide support voluntarily. Not to mention that a steady financial source can boost adaptation and alleviation which can especially help the countries that are most affected by climate change (I. C. W. Team 2007). Mitigations are the responsibilities of each party to achieve the goal which is holding the temperature below 2 °C or limit it at best to 1.5 °C.

1.2 Irena

Connecting 164 members the international renewable energy agency is one of the top leading organizations in the energy transition as it acts as a center of innovation proving the countries with policies, frameworks, and the latest technologies that can play a role in the energy transition.

Some of the latest Irena contributions are their latest publications focusing on hydrogen.

1.2.1 IRENA and Global Warming Alleviation

Previous reports aligned with internationals effort towards 1.5 °C goal can be achieved with hydrogen especially if cost reduction of hydrogen is implemented in the future which could lead electrolyzers to be 40% cheaper by 2030 (https://climatepolicyinfohub.eu/observer-ngos-and-international-climate-negotiations).

Green hydrogen is showing its potential every day and in all different end-sectors (industries), it is a promising solution for replacing fossil fuels in industrial processes that require high temperatures to work such as Cement and steel industries, nevertheless, green hydrogen is also capable to contribute Residential, commercial, and industrial building by heat production. The power sector will also have its shares from hydrogen for example technologies that have green hydrogen integrated into it such as hydrogen gas turbines and large power output stationary fuel cells.

1.2.2 Green Hydrogen Market Potential According to IRENA Coalition for Action

The members active in this coalition that is working on green hydrogen is working to develop a minimum of 5GW of electrolyzers capacity and 250 GW of renewable generation capacity by 2030 (Addamo 2021). Some challenges will also be experienced regarding the workforce market, finance and the existing energy grid, so in order to ensure a complete profitable outcome, strong research institutions should ensure policy coordination across the region to accelerate the energy transition both economically and industrially. The coalition for action also proposes that governments who are planning to remove fossil fuel out of their sectors, they need to ensure the proper path and mandate to back up all the worker that are already in the coal, oil and gas marker upon any closure that could happen due to the transition, and create new programs to reskill all the workforce that worked in any of the fossil fuel backed industries for a sustainable job, and ensuring maintenance, operation and construction throughout the whole phase. Government and institutions should also provide businesses with strategies to support the emergence of renewables into the network, policies will also have to be declared such as enact policies that will ensure the availability of skilled workers and resources in the market and that industries can absorb and utilize the new wave of workers.

2 European Green Deal

The EU aims to achieve a climate neutral state by 2050, driven by the European green deal enabling the transition for Europe to be the first climate neutral continent insuring the availability of a healthier environment, creation of new jobs, and a higher quality of life. The transition to a carbon free society is a big challenge that will open the path for many opportunities to build a better future for Europe. All parts of society and economic sectors will play a role starting from the energy sector to industry, mobility, building and agriculture. The European Union is leading paving the way so called transition to renewables by investing into realistic technological solutions, empowering its citizens, and aligning action in key industrial policies, finance, and research while ensuring economical social fairness where new regulation is made towards the new outcomes of the transition. The European Green Deal also had its own shares out of the Next Generation EU recovery plan and the EU's seven-year budget which accumulated at 600 billion US Dollars.

2.1 Action Plan (Strategy)

The European Green Deal Action Plan Consists of boosting the efficient use of resources by moving to a circular economy and investing in environmentally friendly technologies that will support industries to innovate in their fields, decarbonizing the energy sector while rolling out cleaner, cheaper, and healthier forms of private and public transportation methods.

In March 2020 the commission proposed a law that states a 2050 net-zero emission followed by a detailed plan in June 2020 for reducing emission by 50% in the next decade, these actions will support the reduction of cars emissions by 50% and increasing renewable energy production by 40% (Energy 2021) while addressing energy poverty in many parts across eastern Europe and reducing the dependency on external energy sources and ultimately creating new jobs.

2.2 Impact of the Green Deal on Growth

The European green deal isn't only a strategy to reverse the effects of climate change but also a response to help in the creation of new jobs through connecting and reforming all energy-dependent sectors mostly transportation and industrials. The benefits that will be provided of such a plan will impact the whole current system, if successful the green deal will provide constant growth to the European Gross Domestic Product (GDP) by connecting big tech companies together and providing jobs for the EU population (Balke 2021).

2.3 Mitigations and Adaptations

The EU realized that some of the impacts of climate change are unavoidable, for the transition to work the commission will adopt a set of principles that will ease the plan to become climate neutral by 2050. Minimizing the subject effects of climate change, information, and data available can be analyzed for assessing risks in specific regions such as agricultural areas. The quickness of adapting to new challenges and technologies will help in developing solutions that will reduce risks driven by climate change and of course the EU is pushing for international actions through scaling up funds and providing more worldwide commitment.

2.4 Financial Support

Significant investment from both the EU and the national public sector, the European Green Deal's Investment Plan—the Sustainable Europe Investment Plan are working together to fund their projects through EU financial instruments. The financing movement consists of 3 main parts, Financing: Providing at least €1 trillion investment over the next decade. Enabling: providing tools for investors by adding sustainability and sorting them as a high priority while encouraging green budgeting and approving aid for regions that undergo a transition. Support: The Commission will provide support to public authorities and project promoters in planning, designing, and executing sustainable projects. Financing the green transition can only be possible when both Eu and decisions makers across all states are backed by the people participating in the process financially and with their actions. The Just Transition Mechanism (JTM) is a precise tool that ensures that the transition towards a climate-neutral economy happens in a fair way, leaving no one behind, created especially for the cause of that now while all regions of the continent require help, some regions are affected more than others, this movement aims to provide €100 billion over the period 2021–2027 to the most affected regions.

2.5 European Commission Sustainable Blue Economy Plan

Part of the provided EU recovery funds is improving the Eu blue existing economy plan, like the European green deal, the oceans are an important source of life that provides Oxygen, food, and many other resources that's how we conclude that the European green deal works side by side by the blue economy plan. Including all industries related to sea, oceans, and coasts, whether it's on land (pears, harbors, and coastal infrastructure) or offshore (rigs, seafood, and energy generation).

2.5.1 Mission

The blue economy plan will help and support the European green deal achieving their desired goals improving many other aspects such as connecting data and sustaining development between both plans. It works on developing renewable energy technologies related to the ocean such as offshore generation rigs, carbon-free seaports, and decarbonizing maritime (zero-emissions vessels and fuels). Building environmentally friendly coastal/shore infrastructure that benefits both scenery and the economy and protecting marine life and decarbonizing existing offshore platforms such as Oilrigs to achieve offshore zero pollution, which will ensure future sustainability in seafood production and protecting biodiversity in marine life.

Preserving coastal zone and re innovating them into green ones is key to protect the environment and reducing the impact of global warming (sea rise) in this case.

The (Emanuele Taibi 2020) report stated that almost €500 billion worth of services is generated within a 10 km coastal zone in the EU annually. However, sea-level rise leading to increased coastal erosion is projected to decrease this value by more than €15 billion annually. Hydrogen leading the green transition. As more and more countries are pledging alliance with Europe strategy to a net-zero carbon goal of 2050 and achieving a carbon–neutral society, hydrogen plays a big role here, for the last 10 years hydrogen applications and technologies have advanced dramatically, it also can play a huge role in solving challenges facing our goals. Europe is shifting away from using fossil fuels, hydrogen will be the next-gen fuel, while the EU is currently utilizing grey hydrogen (Hydrogen derived by using fossil fuels) and blue hydrogen which is as grey and mostly derived from natural gas with less environmental impact than grey hydrogen and finally green hydrogen which will be fueling the heart of the transition in the upcoming years. The European commission goal regarding hydrogen is integrating (green) hydrogen as much as possible into the transition, the Commission wants to scale up cost and efficiency, production-wise and since hydrogen is a flexible fuel it can be used in all different industries and sectors such as steel production which can be called later "green steel" (Emanuele Taibi 2020).

As we also notice in the past few years renewable energy had its own share of electricity generation in many parts of Europe this can lead the hydrogen to hand in hand with it, and give the network an immerse boost in flexibility, hydrogen can be extremely efficient and helpful for power-grids as it can balance the supply and demand of electricity.

2.6 European Industrial Strategy

Adapted on the 4th of March 2020 it introduced a strategy that helps to optimize and deliver three key drivers. Maintaining European industry's global competitiveness and leveling the field if needed while proceeding to achieve a climate-neutral state by 2050 while shaping Europe digital future. Other actions taken within this strategy are to uphold copyrights of any new technological dominance and to fight intellectual property theft and adapt the legal framework to the green and digital transition that will follow. Comprehensive measures to modernize and decarbonize energy-intensive industries while supporting sustainable and smart ones and establishing a clean hydrogen alliance to accelerate the decarbonization of industries such as focusing on improving innovation, skills and investment and financially and logistically helping small and medium enterprises. An integrated vision for 2050 is set to work by connecting all related EU policies to tackle and prevent pollution and reduce emissions to low levels that are no longer harmful to humans. Focusing on ensuring the delivery optimization of required material to new renewable industries such as green hydrogen, mobile electrolysis, and fuel cells, with special effort to learn on how to utilize digital solutions to combat pollution.

3 Hydrogen Color Spectrum

For the past decade hydrogen started to be viewed as a key energy carrier where it can play a vital role in decarbonizing many high carbon dependent industries, currently the most abundant form of produced and used form of hydrogen is (gray hydrogen), its produced out of fossil fuels, where carbon dioxide is released and not captured, and the process is called steam reforming of methane (SMR). According to ENEL until of today hydrogen is a climate polluter since 98% of produced hydrogen is in gray form (López Prados 2021). Blue hydrogen on the other hand is a cleaner form of gray hydrogen only difference is carbon is captured and stored during the production process. All this comes up with additional technological difficulties and increased costs. Nowadays it became easier and cheaper to step up to blue hydrogen from its gray variant, reaching the ultimate form of clean hydrogen (green hydrogen) which seems to be the vision for future net-zero energy, where all our needs regarding energy i.e., electricity produced from carbon-free sources.

3.1 How Friendly is Blue Hydrogen?

A study published in Energy Science and Engineering by Howarth (2021) suggested that blue hydrogen which is produced by steam reforming emits high amounts of CO2 from burning natural gas to obtain both high pressure and heat needed for steam methane reforming (SMR), even if we assume a zero-emissions scenario by integrating renewables to replace natural gas we still have methane emissions associated in this 100% renewable-powered process, his research showed that there is really no future role for blue hydrogen in a zero-emission future since greenhouse gases (GHG) are still active in the process, there is no advantage in utilizing blue hydrogen in this transition especially if still fueled by natural gas or even with renewables such as solar and wind power, suggesting that blue hydrogen is a small part that plays a role in the transition to a carbon-free future.

3.2 Accelerating Green Hydrogen Utilization

Apparently COVID-19 global pandemic wasn't enough for Europe to commit to a plant to utilize green hydrogen, as of today green hydrogen in Europe is mostly used in refineries (oil). Most of that non-green used hydrogen is produced from two sources coal and natural gas and the small amount of green hydrogen used that is becoming more popular is produced by electrolyzing water using renewable energy and for now, only 0.1% out of 120 million tons of utilized hydrogen is produced from renewable energy (Thompson 2019).

For green hydrogen to rise in the market governments must provide more commitment, same goes for private sectors participation from both sides is needed, integrating hydrogen into the energy system will also accelerate the process, innovating the current infrastructure with new compatible power grids to transmit the electricity needed to electrolyzers to operate.

Some policies are also required to speed up the process, starting with policies that reduced high investment and building costs and accelerate capacity and production, reducing funds needed for renewable electricity required to produce green hydrogen, improving sustainability and stability that will provide green hydrogen with an easy entry to the market and the energy transition. Finally grey, blue, or even green hydrogen will not have the full capabilities to scale up largely unless the government supports this cause. In the context provided before many challenges need to be overcome to achieve a high scaled green hydrogen industry globally.

3.3 Green Hydrogen Cost Reduction

As countries are racing to become climate neutral with zero-emission levels possible green hydrogen which is produced from renewables becomes a key driver here this report focuses on how improving and scaling up electrolyzers applications and technologies that are utilized today can make hydrogen a cost competitive renewable energy resource as of 2030.

Green hydrogen could achieve climate neutrality (net-zero Co_2) Carbon dioxide in high energy consuming industries. Such as hard to decarbonize sectors (steel, transportation, and aviation) (Shi 2020) December 2020. Reaching a cost reduction economical hydrogen through automation and increasing stack production can scale up manufacturing facilities to consume less and produce more, few technical improvements are model design and sizes also can play a role in reducing costs. Materials used in the cell composition for example sacrificing efficiency for higher densities with acceptable performance, reducing membrane thickness can increase efficiency, replacing expensive coating with some suitable stable protective coating that does not contain platinum or gold. Of course, many challenges are encountered when trying to improve the performance of PEM electrolyzers here are the Highest Challenge-High reward ones such as creating a titanium free porous transport layer (PTL), protecting the (PEM) surface from passivation (the oxidation of titanium) and not using platinum or gold will be a huge milestone in reducing the costs of (PEM) electrolyserz.

For AEM electrolyzers we see that improving membrane durability is a must such as high requirements for high performance which means efficiency needs to be improved, failures are encountered even at low temperatures and current densities, water management difficulties which lead to performance losses, for example, a small spike in voltage can cause a cell water-level imbalance and few challenges are still facing commercial use of AEM technologies, at high temperatures water management is still a difficult task due to increased dehydration, carbonation which is when the cell is exposed to carbon performance loss is encountered of course most common source of carbon is the surrounding air, degradation caused by the surrounding air containing $CO_{2,}$ degradation caused by carbon oxidation which is caused by the water supply if it contains carbonated ions. For SOE electrolyzers some problems are still encountered, for example increasing stacks component to obtain a higher Mw, achieving thermal stability since solid oxide electrolyzers are known for high operating temperatures especially when efficiency is high, and maintaining stability after long operating hours while improving kinetics for oxygen and hydrogen is still not solved.

3.4 Green Hydrogen in the Global Market

Energy demand in each country affects the strategy that this country follows, countries that are rich in renewable resources can benefit from the utilization of green hydrogen faster than other low countries on renewables. Joint efforts are also being developed to create a global green hydrogen trading network. Classes of hydrogen energy that are applicable for trade are Liquid hydrogen (H_2), gaseous hydrogen (H_2) and Ammonia (NH_3).

3.5 Stability, Efficiency, and Flexibility

At different required loads on hydrogen dependent grids, electrolyzers can increase or decrease operating capacity to the desired output which will benefit us also from an economical perspective, few points that can be addressed for PEM water electrolyzers are reducing membrane thickness on all scales and replacing expensive coating with cost effective and efficient materials which will allow us to Optimize existing electrolyzers design to improve efficiency and different optimization can be made for each individual industry as it requires.

3.6 Hydrogen Application

Industrial applications of hydrogen such as oil refining, production of ammonia for fertilizers (on a large scale through the Haber–Bosch process), methanol production and steel production.

In transportation: Hydrogen can have a variety of applications: Battery Electric Vehicle (BEV) that rely on battery electric powered vehicles and fuel cell electric vehicles (FCEVs), Even if it is not fully mature today, the FCEV market could reach $14 billion by 2026, 72 Daimler (or Volvo) Trucks has already revealed plans to introduce hydrogen trucks. In the market several countries in Europe use hydrogen to fuel public buses, Solaris the Urbino 12, which was first used in Stockholm, now consists of 25 fleets on the streets of Wuppertal and 15 in the streets of Stockholm. Cologne, and on the other side of the railway, where the French hydrogen trains Alstom entered regular service in Germany and Austria in September 2020.

In construction: Hydrogen can be blended into existing natural gas distribution networks, in commercial and residential buildings 73 Direct use of hydrogen in a hydrogen boiler or multi-family fuel cells, particularly in densely populated cities while long-term prospects could include.

In power generation: Hydrogen can supplement batteries such as medium to long term storage (i.e. Seasonal) and long-term as blending fuel in CCGTs (or even powering 100% new generation turbines).

4 EU Hydrogen Strategy

Popularity of hydrogen strategies has boomed around the world, with Japan being the first country in 2017, followed by South Korea, New Zealand and Australia in 2019, Japan has already started some partnerships. The International Conference on Green Hydrogen, with Australia and Brunei for example, and the Netherlands, Austria and Norway and Portugal, Germany, and France to accede in 2020. In June 2020, the German Federal Government adopted a strategy. National hydrogen worth 9 billion euros, of which 7 billion euros is earmarked for intensifying the presence of hydrogen technologies in German market and an additional €2 billion for international partnerships. In Europe, the hydrogen economy sparked within the "Green Deal" launched by the European Union Commission the new plan has been launched in December 2019, with the goal of becoming the first carbon–neutral continent by 2050, and lays out the plan An ambitious target that must already be reached by 2030: to reduce greenhouse gas emissions by 50% lower (from 1990 levels), enhancing the share of renewable energy and deploying a wide range of energy-increasing practices, now in order to achieve energy efficiency the European Union relies on strong partnerships with neighboring countries to build a sustainable hydrogen market with a wide range of applications and pathways such as legal framework development, scaling up technology, reallocation of existing gas pipelines and development of required infrastructure. On July 8, 2020, Frans Timmermans, Executive Vice President of the European Commission in charge of the European Green Deal, announced that the highest priorities in the energy transition, as it will help remove carbon faster and be more beneficial to our economy. Hydrogen is one of the main strategies that the commission is taking on to fight climate change, the EU Hydrogen Strategy was first introduced on the 8th of July 2020 it will enhance the adaptation of hydrogen in the transition and utilize clean hydrogen production in Europe. Hydrogen can be used as a feedstock, fuel, or energy carrier and storage, and has many possible applications which would reduce greenhouse gas emissions across industries, different transportation sectors, and electricity generation power plants. Hydrogen will have the biggest role in decarbonizing future Europe, the hydrogen strategy consists of 3 consecutive steps (E. Commission 2021). For hydrogen to deliver a positive role in the energy transition, it must be produced and delivered to end uses in a sustainable manner regarding costs, energy system, environmental impact, and jobs. On the production side various technology options exist, note that most of the EU hydrogen is produced on-site (captive hydrogen; 64% of total production capacity) typically in large industrial settings and the remaining hydrogen is generated as a byproduct of industrial processes. The commission focuses firstly on the most mature electrolytic ways of generating hydrogen: alkaline (ALK), polymer electrolyte membrane (PEM) and solid oxide (SOEC) electrolysis. Starting from 2020 up to 2024 the commission is planning to install 6 GW of hydrogen electrolyzers in the Eu boosting production up to 1 million-tone of green hydrogen. 2025 to 2030 Hydrogen will become an integrated part of all renewable energy systems, with a minimum supply of 40 GW hydrogen electrolyzers and pumping production up to 10 million tons of renewable Hydrogen across Europe, through 2030 and beyond Renewable hydrogen will be utilized and deployed on a large scale across all hard to decarbonize sectors mainly high carbon-emitting industries. Promoting hydrogen is a huge part of the strategy too such measures taken by the commission will help in promoting the use of green hydrogen, creating a sustainable industrial value chain which will increase the production of hydrogen while pushing the demand for clean hydrogen for industrial applications and transition related technologies, enabling the right market opportunities with a supportive framework, as well as dedicated infrastructure and a logistical network to support the required mobility, providing financial support that will fund research and innovation for clean hydrogen technologies, securing and creating opportunities within Europe and with the surrounding regions to establish global hydrogen market and most importantly scaling up hydrogen production since renewable hydrogen is the focus of this strategy, as it has the biggest decarbonization potential, the strategy also realizes the role of low carbon hydrogen production method that can be used early until green hydrogen production is widely accessible, and to clean what they are already producing from grey hydrogen to be able to scale up the market in the future therefore hydrogen is the most suitable option within the EU's climate neutrality goals.

4.1 Other Programs Introduced by Other Countries

In the European Union, there is a €170 million project for hydrogen powered cars is which is currently in its second phase, demonstrating it functionality, for fuel-cell vehicles and the expansion of the network of hydrogen fuel stations in the European Union. China, with its growing number of cars, is seeking to quickly convert cars away from fossil fuels to reduce pollution in its environment which became one of the main political challenges to the government. After the successful conversion to electrification of short-distance vehicles, of which 250 million of two-wheeled vehicles and the 4.0 million city buses currently on Chinese roads, Introducing fuel cell-powered buses and trucks for use in long-distance transportation. Many Chinese cities are adding more buses that are fuel cell-powered vehicles into service on the roads, China has invested 4.12 billion US dollars in subsidizing hydrogen fuel cells for vehicles. In February 2019, the construction of the first solar water electrolysis plant in the Middle East began in Dubai, operated by the Electricity and Water Authority. Dubai, with an annual capacity of 250 tons, and it relies on technology produced by the German company Siemens.

4.2 Challenges Facing Green Hydrogen Transition

Hydrogen can be burned like and used in cars but because it does not contain carbon, it will not produce CO_2 emissions. Challenges to widespread hydrogen adoption include the lack of a refueling and distribution infrastructure such as hydrogen station (storage), and high costs. Most of these challenges are being addressed as hydrogen is scaled up over the next decade. Storage wise technical difficulties are encountered since high temperatures or pressure are needed same things fall for transportation. Producing green hydrogen means a high amount of electricity is needed which contributes to a huge increase in wind, solar, and hydropower. For green hydrogen to become competitive in the global market, the price per kilogram must be reduced to 2 $/Kg, while according to Bloomberg Energy Finance that 1 $/Kg of hydrogen is achievable by 2050, the price of green hydrogen has already gone down 50% in the past 5 years with an expected 30% by 2025 if such prices are achieved hydrogen can compete with the current cheapest source of electricity Natural gas. Storage wise technical difficulties are encountered since high temperatures or pressure are needed same things fall for transportation. Producing green hydrogen means a high amount of electricity is needed which contributes to a huge increase in wind, solar, and hydropower.

4.2.1 Small Limited Workforce and Expensive Maintenance Costs

The hydrogen energy transition will create countless opportunities such as jobs and investments for big tech companies, but current engineers/worker lack the required knowledge, training, and skill to work on this field. So, governments and companies should find a solution to solve this shortage in workforce.

4.2.2 Storage and Transportation of Hydrogen

The biggest technological barrier facing hydrogen deployment is volumetric hydrogen storage. In addition to this storage challenge, discovering the best price per kg and simplified handling/logistics are the other key components to hydrogen storage solutions. Hydrogen is the lightest element out of all the others on the periodic table, and therefore it is hard to store. For example, 1 kg of hydrogen gas at average temperature and pressure occupies over 11 m^3 so, for the storage of hydrogen to be economically available, its storage density must be increased, costs reduced, and transportation improved. For now, storage via batteries is the most approved method, but this poses many problems such as the low "energy density", especially in terms of weight, as replacing a car tank with a capacity of a few tens of liters of gasoline requires a battery weighing hundreds of kilograms. And the manufacture of these batteries requires large quantities of minerals hydrogen itself has a high energy density by weight, as 3 kg of gasoline can be substituted for 1 kg of hydrogen. A car using one kilogram of hydrogen can travel 100 km. We can store hydrogen because we know how to change its density in different ways using pressure, but the hydrogen storage process in turn uses a lot of energy. The hydrogen liquefaction process is more complicated, as it requires more energy consumption and a lower temperature (−253 °C). Storing hydrogen at normal temperature and pressure requires specific solids or liquids. One of the shortcomings of some new sources of renewable energy is that they are intermittent, and we need to store the energy they generate when there is wind, sun, current or waves for use later when needed. This requires huge storage resources.

4.3 Emerging Hydrogen Technologies Accelerating Green Hydrogen Utilization

Hydrogen will play a central role in decarbonizing the energy transition, even though hydrogen as an energy carrier is linked to several uncertainties, technological improvements are a must to scale up the production, which is the biggest challenge facing hydrogen now, and in order to meet the demand of the market companies must work on improving their technologies to increase production and efficiency of their hydrogen generation plants such as plants working on electrolysis. While many of the hydrogen generation plants are built within the old grid which alone is a challenge to insure the most output out of the grid while transitioning to a green hydrogen infrastructure.

4.4 Use of the Biomethane Mixed with Hydrogen European Infrastructure

Biomethane and hydrogen will play an important role in the transition to a decarbonized energy system, according to the different scenarios of the European Commission's 2050 Long-Term Strategic Vision, gas demand in the EU will decrease from the 2015 levels by 20–60% in the long term. Addressing the technical potential for hydrogen and synthetic methane production based on renewable electricity is large enough to replace the (remaining) natural gas demand in the future.

4.5 Potential for Hydrogen Production

The annual hydrogen production potential for EU28 is estimated at 6500 TWh in 2020, increasing to 7900 TWh in 2040/2050 due to efficiency gains in electrolysis.

The technical potential for hydrogen largely exceeds the calculated gas demand, none of the scenarios for 2030 or 2050, estimates a gas demand higher than 4100 TWh/a, no other restrictions are taking into consideration. So technically the idea of missing hydrogen with biomethane or gas is possible with few limitations if existed such as biomethane admixed to the natural gas network should not be foreseen in distribution networks with hydrogen admixture, as hydrogen could then escape into transport network sections locked in hydrogen admixture, unless a fixed hydrogen admixture rate is enforced for the gas transport network Europe-wide, or hydrogen can be extracted from the bottom-up gas flow once it leaves the distribution network. And it must be legalized by national regulation. Being technically possible, this would however not be in the interest of a common EU future gas infrastructure or equipment and appliances manufacturers. Maybe after the first Hydrogen transition is done where hydrogen is widely available this idea could be implemented since there will be enough hydrogen produced for a constant hydrogen admixture rate because it would need to be always guaranteed and in all locations. And the use of fossil fuel will sharply decline due to this strategy (https://www.solidar.org/en/news/eu-green-deal-social-economy-manifesto). Further analysis of the role of hydrogen that subsequently could grow into one large hydrogen network by integrating it into the gas pipeline network while planning for new energy infrastructure should be more integrated and be based on the overall future energy system while optimizing the use of existing infrastructure and large-scale deployment of clean hydrogen at a fast pace is key for the EU to achieve its climate neutral goals. It is the missing part of the puzzle to a fully decarbonized economy. The hydrogen strategy adapted until 2030 includes three major steps, each step contains a set of goals that will be accomplished by the given timeline (Uyar 2017). Starting in 2024 Hydrogen infrastructure will be mapped out by setting frameworks and policies on the use of liquid hydrogen so it can be accessible by the market and innovating current grey/blue hydrogen production into green hydrogen by installing 6 GW of green hydrogen electrolyzers. Building Hydrogen Valleys will start in 2030, The term Hydrogen Valleys refers to a place of land (region, island, settlements, industrial areas) and so on, on these areas complex hydrogen applications are integrated together to form a hydrogen system that consumes and produce hydrogen without relying on outer sources, of course for such system to work efficiently it should utilize production, distribution, final energy demand, storage, and energy carrier, there are currently almost 30 valleys at 18 different countries in 2021, a 40 GW of green hydrogen electrolyzers, hydrogen applications that benefit both transportation and steel industries while improving cross-border (trading goods) logistics infrastructure and finally, 2050 will be the latest stage, by increasing work required and pushing it to decarbonize all high carbon dependent sectors and utilizing synthetic fuel at a higher scale meaning that more sectors should be driven by these fuels.

5 Obstacles Facing Renewable Energy Policies Regarding Decision Makers, Implementations, and Its Finance

Renewable energy policies have promoted an increase in renewable energy shares through helping to overcome various obstacles impeding the development of the required technology and spreading renewable energy across the globe. Qualitative obstacles to policy making can lead to renewable energy, implementation, and financing (such as market failures) also hindering the deployment of new energy which is the opposite of what the energy transition wants to achieve.

Such obstacles that are stopping developing and enacting policies include lack of information and awareness of the civil communities on renewable energy resources, technologies and policy options and lack of understanding of the best policy designs or how to carry them out, not to mention that price estimation difficulties like quantitative and internalizing external costs and benefits, and adherence to current technologies and existing policies. Obstacles related to implementing policies are the concern regarding them conflicting with current applicable rules that are set by decision makers, lack of skilled personnel and institutional capacity to implement energy policies of renewable energy.

5.1 Financial Obstacles

The lack of awareness, information and correct timing to enter the market among funders and investors with projects issues and limited tracking data because of weak institutions, in many countries immature capital market and insufficient access to financing at acceptable cost, all of which lead to an increased risk and cost making it difficult to obtain financing for renewable energy projects, more importantly many of the current renewable energy technologies do not have economic competitiveness compared to market prices for current energy market prices, which leads to a lower profit for investors since policy support and capital investment restrictions are still haven't coped to the energy transition nor the decision maker have.

5.2 Research and Institutional Role in Financing

Availability of research development and innovation of carbon capture technologies will benefit the society beyond those imagined by the innovator which will lead to a decline towards funding these efforts, and on that governmental and private institutions can play an important role in developing and innovating new technologies from public funds, research and development on renewable is being reinforced in most countries where there is a level of financial support towards such research. Government policies in the field of research and development include positive incentives such as academic funding for research done on required subjects, granting awards for successful projects.

5.3 Possible Environment and Regional Issues

Renewable energy technologies can play a huge role in mitigation if implemented in conjunction with suitable policies that go with preventing climate change, easing the change in the renewable energy system which includes various parts that are all connected to one another such as financing and business departments, followed by the civil society and government, infrastructure is also a part of this environment including networks and markets, policy outcomes such as international agreements, cooperation and strategies towards climate change have the most impact on policy/decision makers.

6 Hydrogen Technologies Road Map for Turkey (Hydrogen Technologies Association ISTANBUL 2021)

Economical changes supported by population growth and new infrastructures and affecting the world resources of energy such as materials, fuels, and so on, the need for energy and thermal power is also increasing rapidly to meet the needs of today's world.

Emission-free (fossil fuels-free) efficient and sustainable energies are needed to replace the depletion of fossil fuels and to help fight against global warming.

Hydrogen is a key driver here as a primary fuel of renewable energy, that can help eliminate the use of fossil fuels. While also boosting environmental and economic conditions all over the world (https://www.iea.org/fuels-and-technologies/hydrogen). This report aims to discuss the current energy situation in turkey and creating a plan based on available data to pave the road down for renewable technologies driven by hydrogen.

6.1 Covid-19 and Hydrogen

The pandemic has opened our eyes regarding many factors that can have an impact on human lives mainly, Air, Water, Food, and energy so maintain these factors clean and should be our priority.

As far as the pandemic fossil fuels have been used widely as the main source of generation for energy, the use of these fuels is starting to decline until it comes to an end, and this is where the transition to hydrogen age will start, COVID-19 which has affected almost every person one way or another, and since it affected mainly respiratory system in the body it showed how vital breathing is for us which leads us to air quality where we can conclude that we can no longer continue with the carbon age and the beginning of the hydrogen age has arrived. Economic development, improved sustainability, improved air quality which leads to a healthier community and integration of more renewables into a hydrogen eco-system are all benefits that will be brought if this strategy succeeds.

6.2 Road Map to Hydrogen Transition to Be Followed in Turkey

At the national hydrogen association 11th meeting Prof. Dr. İbrahim Dinçer drew attention to what is happening in the world now in almost every country (pandemic wise) and how it can help to prepare a strategy that will be the foundation for a hydrogen roadmap in Turkey, he also called the hydrogen roadmap as a game changer, since COVID-19 Pandemic helped the carbon age in peaking to all time high, which drew everyone's attention on how most countries heavily rely on fossil fuels and carbon-emitting industries, for example, many Commercial oil companies realized the inevitable which is that carbon age is fading away and the need for a new source of fuel is a must. So, SHELL which is a known petrol company started to invest in renewable energies such as Hydrogen, Bp (British petroleum is following the same road too, it even rebranded its name to Beyond Petroleum. While he also mentioned National hydrogen association in Turkey with few other organizations should adopt frameworks within this given responsibility, where a strategic approach in terms of institutional and educated individuals with sufficient knowledge should contribute to the roadmap. With the help of his Ph.D. students, they will provide data that can shorten the time required to release the roadmap as the following key points are addressed, what are the benefits provided if hydrogen is utilized, viewing side effects if existed, available hydrogen production methods that can be used, comparing them each with their requirements and how will hydrogen be stored. Which sectors can use and benefit from hydrogen-derived systems, fuel cells, and many other applications is yet to be defined with the use of hydrogen as the main energy carrier and some of its applications such as using an integrated mix of hydrogen with natural gas. The success of such a road map which can be called a transition also depends on how efficient this transition can connect all clean energy sources together so they can form a complete energy system, for example, right now fuel cells are widely available in cars but charging availability is not enough which leads to a decline in fuel cell usage commercially (Hague 2021). Establishing the hydrogen roadmap also requires sufficient information on what technologies can be accessed and used, what type of renewable ecosystem does a hydrogen map needs, and so on. This information provided when organized together will form the hydrogen roadmap for Turkey. Sufficient information is also required such as research papers and publications related to Hydrogen Scope in Turkey, what and which topic did these studies focus on and what conclusions and statistics were obtained from these studies, the data and statistics obtained from the studies (institutional and individual) can be organized and summarized where it can benefit in the creation of the Hydrogen roadmap. Prof. Dr. İbrahim Dinçer also explained the cause, now it is necessary to understand that humans need

3 things to live a healthy life. Clean air, water, food, and energy is the most important subject since it affects all three, that's why solving the root of the problem is to move towards clean renewable energy, which will carry out the improvements required to transfer to a healthier living standard. Emphasizing that Hydrogen farms need to also be considered regarding location weather it depends on sun, wind, or any other renewable source of energy, working capacity and many other factors are yet to be determined, not to mention that if Turkey doesn't have the capabilities to produce hydrogen, then technologies and applications related to hydrogen will have no use in the Turkish energy system. Producing hydrogen domestically is required so we can determine the technologies that can be utilized based on how much hydrogen we can produce. Oil, gas, and coal are very important for the improvement in economics of a country but have no place in the future. Turkey is mostly dependent on such conventional sources of energy while knowing its harmful effects for human health and environment like greenhouse effect and climate change. Turkey is a country where renewable energy sources such as solar, wind and hydropower are available in huge parts of the country. The only obstacle in a plan to utilize all these renewable energy sources are decision makers and financial availability to fund such big projects, improved air quality, clean water, and land with an increase in employment all together will improve the life standard in turkey income development and regional impacts, all of this can be reached with the help of accurate utilizing of renewable energy grids. Along with many of the benefits that can be sustained from renewable energy, current renewable energy systems technologies are hard to install and require special environment, maintenance etc.

6.3 Private Sector's Role in the Hydrogen Roadmap

Sectors will have to prepare many resources so that they can cope with the hydrogen transition. Human resources for new technologies to rise human working power is required, merged with financial resources to create projects funding backed up by institutional Support that can provide data and information required. Prof. Dr. İbrahim Dinçer also mentioned that a hydrogen based economic system will change everything thus it is a game changer, and that politics are a part of the solution, where politicians must learn and understand the roadmap e so it can be implemented later.

6.4 Hydrogen Opportunities in Transportation Sector

Transportation sector consumes 26% of the total energy, transportation sector uses an energy mix, with fossil fuels dominating it such as oil products which represent more than 99% of the total fuel demand (Howarth 2021) where gas is a negligible contributor in the transportation network. Electricity's acquires around 0.4% and renewables represent a negligible share less than 0.1% of the total energy, this proves that the transportation sector is the largest oil consumer in turkey private vehicles in Turkey compromise the use of three types of fuels which are gasoline, diesel, and liquefied petroleum gas (LPG). While electric powered cars have an exceedingly small share from the pool of a total of less than 2000 vehicles. There are growing concerns related to the environmental impacts of the booming vehicle use in Turkey. Since most of these emissions occur in urban areas with high traffic congestion, which are a result not only impacting climate change but also human health.

7 Conclusions

Renewable hydrogen has a major role in decarbonizing industries and even whole countries, which can be mainly achieved by replacing fossil fuel dependent societies.

Green hydrogen relies on three important factors, high renewable generation production, cost reduction, and competitive prices, and major support for hydrogen and renewable backed technologies. Certain green hydrogen projects were created for specific use cases with a connection between producer and consumer. The Commission presented the European Green Deal with a huge goal of becoming the first climate-neutral continent in the world by 2050, Europe's transition to a sustainable economy means significant investment efforts across all sectors: ranging from residential to industrials. Providing solutions for different existing problems and new strands of action together to create a suitable environment to scale up clean hydrogen for a climate-neutral economy. The strategy is creating the conditions across the whole energy chain for clean hydrogen to contribute cost-effectively towards boosting and decarbonizing the economy which will support identifying the role that clean hydrogen can play in the context of the green recovery to reach a climate-neutral Europe by 2050. COVID-19 Pandemic triggered the start of the Hydrogen Age by drawing attention to how important it was. Creating new opportunities for the Turkish energy system and many new jobs will arise. Turkey must produce it owns hydrogen so new technologies and application can be utilized. Hydrogen age will transform people's mentality and open it up on renewables and the lifestyle that it brings with it. The Consumer needs cleaner air and a suitable environment and Air quality, human resources are required, engineers that are experienced in renewables are needed in the future with new workers that must be trained and prepared to work on future projects. The report aimed to gather and research on chemicals used, electrolyzers technologies to reach a goal which is enabled by new technologies to produce hydrogen completely from renewables and to reach a price of 1 USD$ per 1 kg of hydrogen. Turkey has a great potential for renewable energy generation especially from water such as tides and currents and regarding resources, a remarkably high potential is available in Turkey. National Hydrogen Association has contributed and will continue to provide meaning and sufficient reports to benefit the country. The whole energy sector needs to be rebuilt so it becomes compatible and ready for hydrogen to be integrated into it. The role of the government is critical for the plan to succeed, where new laws and policies are introduced, we are confident that green hydrogen will prove itself to be the ultimate energy source for all our current and future needs.

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Current Status and Future Prospects of Power-To-Hydrogen Towards 100% Renewable Energy

Canan Acar

1 Introduction

The global energy demand has been increasing steadily since the industrial revolution, which is because of growth in global population, enhancement of living standards of human beings, and increasing industrial activities. The increase in energy demand has been partially offset by improvements such as increasing energy efficiency or decreasing energy intensity. However, these improvements did not stop the steady and consistent increase in global energy consumption. The historical global energy consumption presented in Fig. 1 shows that global energy consumption has never decreased over the last sixty years, except for a few years. 2009, which is the year after the global financial crisis, is an example of the decrease in global energy consumption.

Making affordable and clean energy available for everyone is an essential target to reach almost all of the Sustainable Development Goals of the United Nations (2021). However, making affordable and clean energy available for everyone significantly increases the global demand and causes significant challenges to tackle while transitioning to low- or zero-carbon energy systems. The data presented in Fig. 1 indicates that since 1800, global energy consumption has increased by 30-fold. In 1800, the dominant primary energy source to meet the global demand was biomass and a relatively small coal supply. Since then, coal use to meet the global primary energy demand has increased by more than 400-fold while biomass use has only doubled. However, when we look at the last 30 years, there is a different picture.

As shown in Fig. 1, since 1990, coal, oil, biomass, and hydropower use have been almost flat compared to the other primary energy sources. Since 1990, national gas

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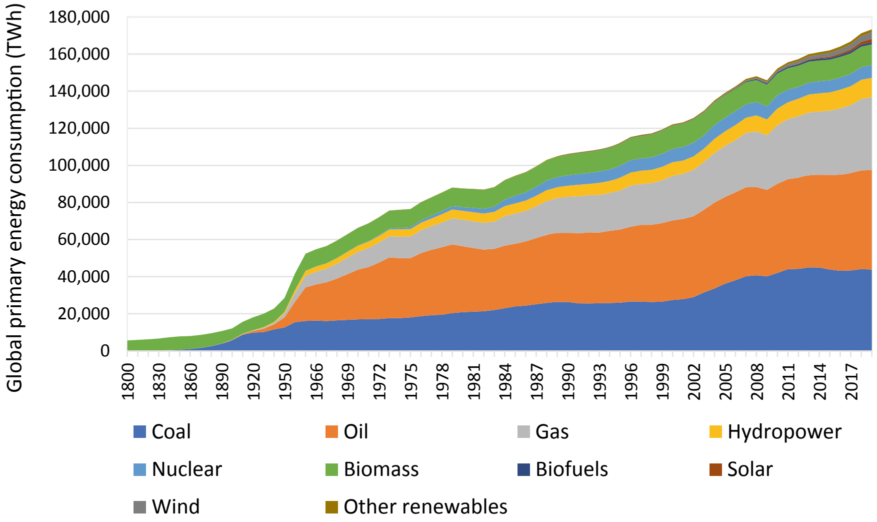

Fig. 1 Change in global primary energy consumption by IEA 2020 source between 1800 and 2019 (data from)

use has nearly doubled, and biofuel use has increased more than 12-fold. But the most significant transition is the wind, which has increased about 354-fold, and solar has had a breakthrough with an almost 1800-fold increase since 1990. Still, fossil fuels are the main energy sources to meet the global primary energy consumption. For instance, 2019 data shows that fossil fuels meet almost 79% of the global primary energy consumption. In 2019, coal had 25%, oil had 31%, natural gas had 23%, nuclear had 4%, hydro had 6%, and biomass had 6% shares. Despite the enormous growth in capacity in the last 30 years, wind met 2% of the global primary energy demand while solar's share was about 1% (IEA 2020).

The world is still primarily using fossil fuels to meet its energy demand. However, there are many indicators that swift decarbonization is needed for the sustainability of future energy systems (IPCC 2018). One effective strategy for swift decarbonization is quickly replacing fossil fuels with renewable energies. Historically, the share of renewable energy sources in the primary energy mix is growing. Although it is good news for decarbonization, the progress is very slow, and the increase in consumption overcomes the decarbonization effect. In Fig. 2, the breakdown of primary energy consumption by the source is shown. The primary sources are grouped into three categories, namely fossil fuels, nuclear, and renewables. From 1965 to 2019, the share of fossil fuels decreased by almost 10%. Within the given period, nuclear's shared first increased first; from 0.2% in 1965 to 6.6% in 2001. However, nuclear's share has been steadily decreasing since 2001, and in 2019, its share was 4.3% (IEA 2020).

Figure 2 shows that from 1965 to 2000, the renewables' share increased slowly from 6% to 7.4%. However, since the last 20 years, the transition to renewables has

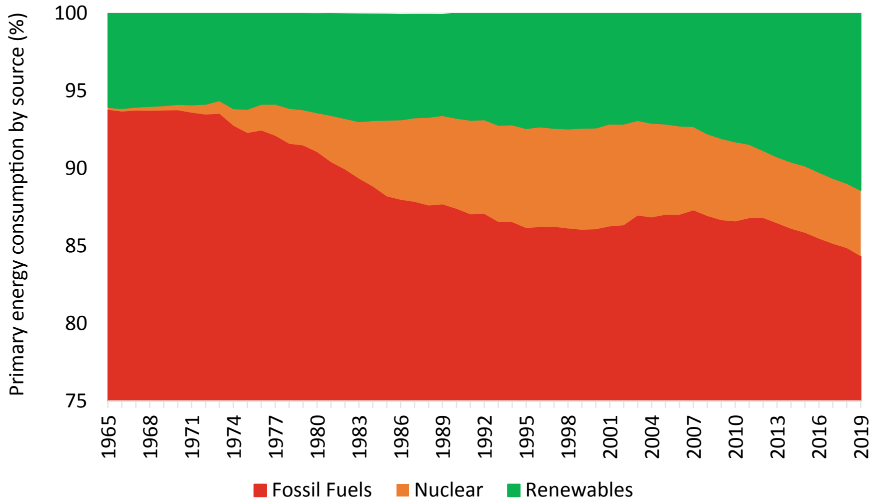

Fig. 2 Change in global primary energy consumption by share of source IEA 2020 between 1965 and 2019 (data from)

been faster: yet still, the share of renewables has only increased by 4%. The successful transition towards renewables requires making progress fast enough to reduce global emissions. We need to reduce emissions to stay within the remaining carbon budget and limitations of the Paris Agreement. Even though we are making progress, it is not fast enough currently. However, the last two decades' momentum and the introduction of renewable hydrogen could accelerate the transition significantly (IEA2020).

The primary energy consumption includes electricity generation, transportation, and heating. Electricity generation is relatively easier to decarbonize compared to transportation and heating, especially high-temperature heating. Transportation and heating still heavily rely on fossil fuels, particularly oil and gas, and are considered harder to decarbonize. For this reason, renewable energy sources meet the highest share of global electricity production. As shown in Fig. 3, renewable energies provided about 27% of the electricity generation worldwide, while renewables in the global primary energy mix were about 11% in the same year. One strategy to decarbonize all sectors is electrification via using renewable power. However, there are several challenges in terms of complete electrification.

First and foremost, the existing grid could not support the high-power demand of all sectors. Another challenge is long-term storage and long-distance transportation of energy in electricity form. On the other hand, hydrogen could be distributed by the existing gas network with minor modifications or by tanks, ships, etc., to longer distances. Also, hydrogen could store energy in longer durations, making daily or seasonal storage of renewables possible. With electricity, hydrogen could increase renewables' share not only in electricity production but also in transportation and heating.

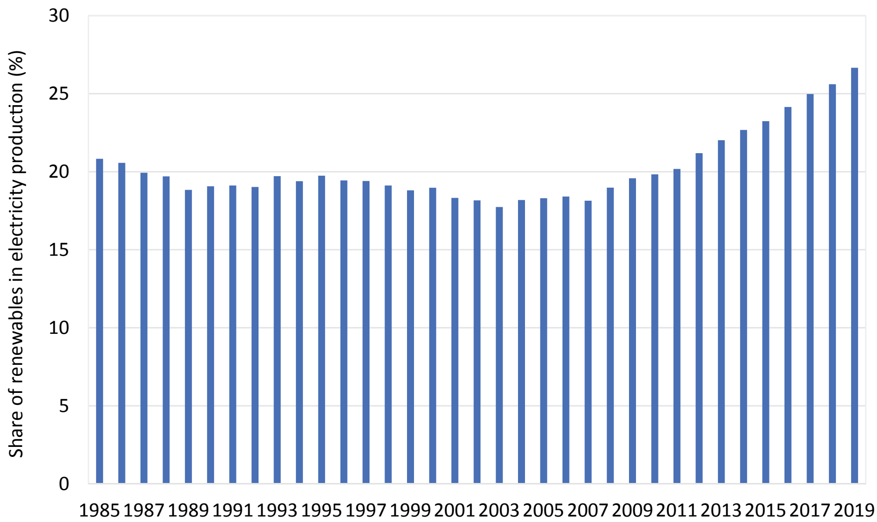

Fig. 3 Change in share of renewables in the global electricity production mix between 1985 and 2019 (data from IEA 2020)

There is a severe consequence of the heavy dependence on fossil fuels worldwide, which is CO_2 emissions. As a matter of fact, there is almost no doubt in the scientific community that fossil fuels are the main reason for CO_2 emissions. This can be seen in Fig. 4, which shows the annual global CO_2 emissions by source. For instance, in 2019, coal caused 39%, oil caused 34%, and natural gas caused 21% of total global

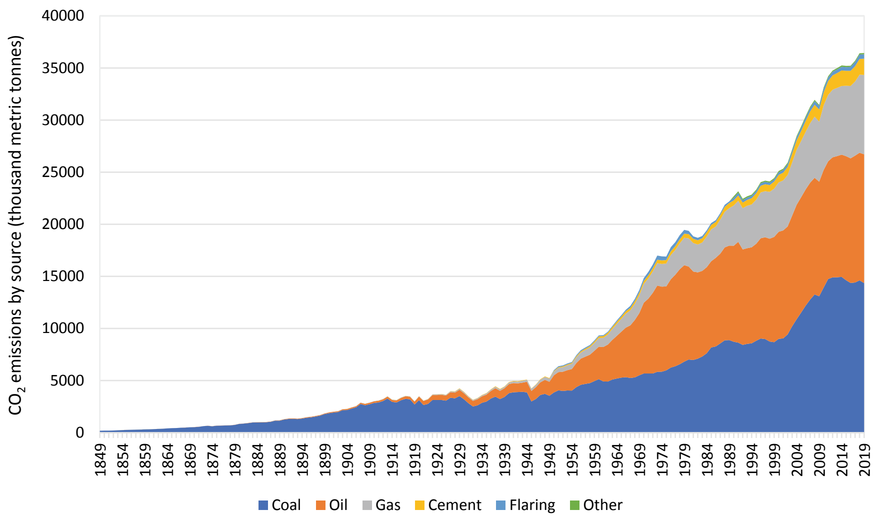

Fig. 4 Change in annual CO_2 emissions by fuel type between 1849 and 2019 (data from IEA 2020)

CO_2 emissions. In total, fossil fuels were the reason for 94% of the global CO_2 emissions in 2019. Global CO_2 emissions keep increasing, mainly because we use more fossil fuels every year. In the last ten years (between 2009 and 2019), fossil fuel use to meet primary energy demand increased by an average of 1.33% every year. As a result, global CO_2 emissions increased by an average of 1.22% every year within the same period.

CO_2 is one of the major greenhouse gases, along with methane and nitrous oxides. Throughout the entire life cycle, fossil fuel extraction, distribution, and end-use emit significant amounts of greenhouse gases. In fact, fossil fuels are the primary source of greenhouse gas emissions. When we look at the end-use side, we see that energy is the primary driver of greenhouse gas emissions. When we take the direct and indirect use of energy into account, energy is the reason for about 75% of the total global greenhouse gas emissions. The effect of greenhouse gases on climate change, and the need to prevent greenhouse gas emissions are clearly presented by prestigious scientists and institutions (IPCC 2018). Therefore, one of the immediate steps to tackle climate change is to reduce greenhouse gases by replacing traditional fossil fuel-based energy systems with renewable energy-based alternatives. Achieving this goal would require finding reliable, affordable, clean, efficient, and safe ways to store renewables. And hydrogen might be the key.

As stated by the Paris Agreement and the latest reports on climate change [such as (IPCC 2018)], there is a strong correlation between atmospheric greenhouse gas (mainly CO_2) concentrations and the global average temperature. Therefore, the first step to tackle climate change and slow down the rising average global temperatures is to stabilize greenhouse gas, especially CO_2, concentrations in the atmosphere. However, slowing down emissions would not immediately stop temperature increases because greenhouse gases would still be accumulating in the atmosphere. Therefore, it is essential to act fast on emissions via decarbonization, and renewable energies are critical.

Figure 5 shows the global average atmospheric CO_2 concentrations throughout the last 800,000 years. For over 800,000 years, atmospheric CO_2 calculations fluctuated between 170 and 300 ppm over ice ages and interglacial periods. The main reason for these fluctuations is the change of Earth's orbit around the sun. However, currently, we see the impact of human-caused emissions in the atmosphere. For more than 800,000 years, the atmospheric concentrations did not exceed 300 ppm, and the fluctuation did not exceed 130 ppm in that long period. Clearly, this situation has dramatically changed with the Industrial Revolution. After that, humans started burning more fossil fuels every year, mainly to meet their energy demand and support industrial growth. The rapid rise in global CO_2 concentrations over the past few centuries, and in recent decades, in particular, has not been seen in the recorded history. For the first time in more than 800,000 years, atmospheric CO_2 concentrations did not only surpass 300 ppm but already passed 400 ppm. For 800,000 years, the fluctuation did not pass 130 ppm, while just in the last 100 years, atmospheric CO_2 concentration increased by more than 130 ppm. The rate of increase in concentrations is worrying scientists (IPCC 2018).

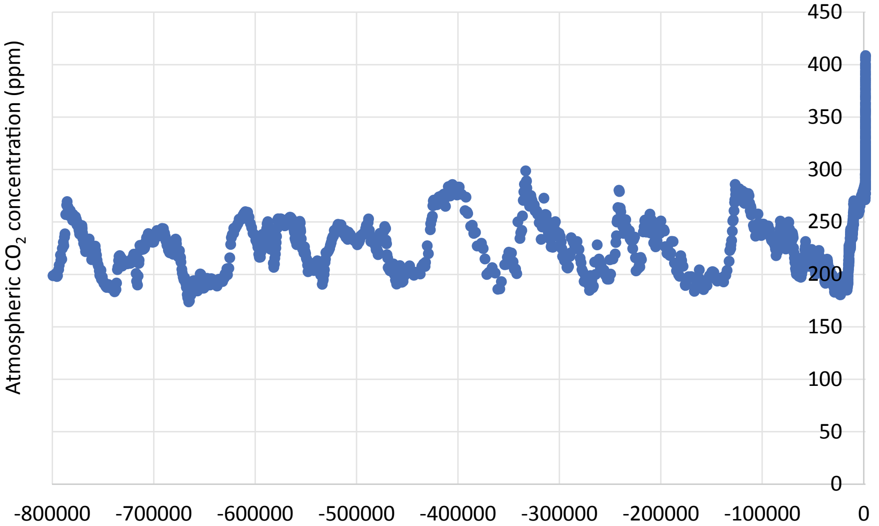

Fig. 5 Change in the atmospheric CO_2 concentrations in the last 800,000 years (data from IPCC 2018)

Compared to 800,000 years ago, CO_2 concentration in the atmosphere increased by about 200 ppm and almost doubled. But this increase was not consistent throughout the time. Most of it happened after 1900. Since 1900, CO_2 concentration in the atmosphere increased by about 128 ppm and increased by almost 1.5-fold. This means more than 60% of the increase in atmospheric CO_2 concentrations in the last 800,000 years actually happened during the previous 120 years. This is a significantly rapid change in the composition of the atmosphere.

To understand the effect of atmospheric CO_2 concentrations on warming, it is crucial to understand how the global average temperatures have been changing. In Fig. 6, we see the global average temperature relative to the average of the period between 1961 and 1990. We see that over the last few decades, global temperatures have risen sharply to approximately 0.7 °C higher than our 1961–1990 baseline. When extended back to 1850, we see that temperatures then were a further 0.4°C colder than they were compared to the 1961–1990 average baseline. Overall, the global average temperature increase adds up to about 1.1 °C.

It should be noted that the temperature increase depends on the base year. Some studies take the 1850–1900 average into account, and some studies take 1900 as the basis. In summary, we can say that the global average temperature increase since the "pre-industrial" times is currently between 1 and 1.2 °C. The last Intergovernmental Panel on Climate Change (IPCC 2018) report clearly states the seriousness of climate change and the effect of human-caused activities as

> Anthropogenic greenhouse gas emissions have increased since the pre-industrial era, driven largely by economic and population growth, and are now higher than ever. This has led to

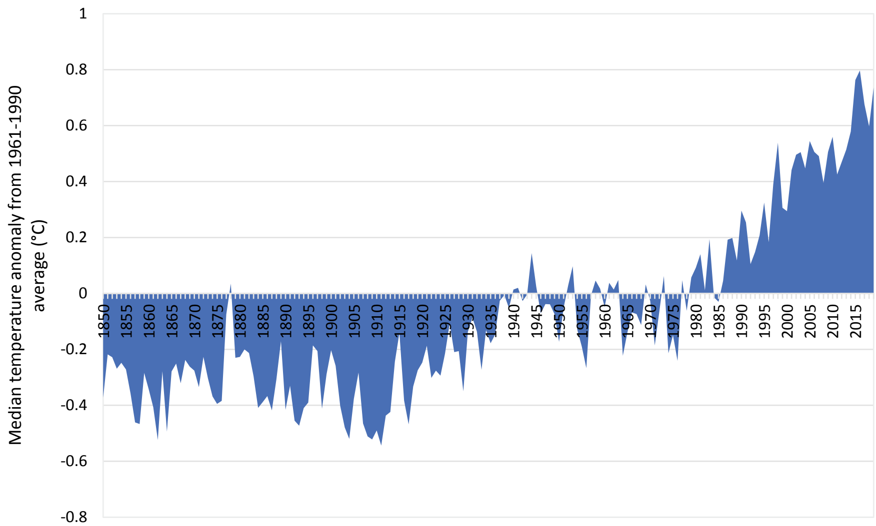

Fig. 6 Median temperature anomaly from 1961 to 1990 average between 1850 and 2019 (data from Our World in Data 2021)

> atmospheric concentrations of carbon dioxide, methane and nitrous oxide that are unprecedented in at least the last 800,000 years. Their effects, together with those of other anthropogenic drivers, have been detected throughout the climate system and are extremely likely to have been the dominant cause of the observed warming since the mid-20th century.

Our heavy fossil fuel-dependent energy systems are the primary driver of climate change. We see the results of climate change in its impacts on the environment, economy, health, biodiversity, and more. Extreme weather events, biodiversity loss, droughts, wildfires, disappearing of Arctic and Antarctic ice, sea-level rise, and loss of agricultural productivity are some of the effects of climate change that are expected to be worsened in the future if no actions are taken. More information can be found in the latest IPCC report (IPCC 2018).

In order to tackle all of the issues related to climate change, stopping the problem at its source, transitioning from fossil fuels to renewables is a must. Hydrogen is the key to enable this transition.

2 Renewable Power-To-Hydrogen

Hydrogen produced by using electricity generated from renewable energies via different processes such as electrolysis is called renewable power-to-hydrogen (P2H). Renewable P2H can be used as a medium for energy storage and for applications such as producing heat for buildings, refueling fuel cell vehicles, and as a source of feedstock for industry (Fig. 7). An essential distinction between hydrogen and other

Fig. 7 Application fields of renewable P2H

energy storage forms is that hydrogen can be stored and transported through the existing natural gas network. Little investment is needed to adapt natural gas infrastructure to transport hydrogen. It is also possible to blend hydrogen with natural gas in the existing network. Currently, there are many ongoing efforts to blend up to 20% hydrogen in the existing natural gas pipelines (Vries et al. 2017; Ozturk and Dincer 2021). Blending hydrogen with other gases means that pure hydrogen is no longer available for direct use in end-use applications, e.g., fuel cell vehicles. Although it is technically possible to extract pure hydrogen from the blended gas at the end-use point, the process is complicated and expensive. Therefore, there is an economic trade-off to be considered in applications that require pure hydrogen.

Renewable P2H could accelerate power generation's decarbonization by increasing the share of renewables in the electricity mix. Besides, renewable P2H could benefit the hard-to-abate sectors, namely heat (especially high-temperature heat) generation and transportation. As a result, decarbonization of the industry, building applications, and transportation can be achieved. With the introduction of new markets opening for renewable P2H, the share of renewables in the primary energy mix can be increased substantially.

Hydrogen has some different characteristics than the fuels used in the traditional energy systems. For instance, hydrogen is a highly flammable gas, and it can burn in a wide concentration range. Therefore, renewable P2H utilization in the end-use side requires ensuring safe operation in stationary and portable applications in buildings and industry. Hydrogen safety can be ensured by defining safety standards in all types of end-use applications. Proper ventilation and leak detection are also needed for safe operation with hydrogen. Hydrogen safety standards already exist for use in industrial applications as a feedstock. However, the use of hydrogen as a fuel in transportation, industry, or buildings or as an energy storage medium would require the standards to be revised depending on the nature and requirements of each application type, e.g., stationary/portable.

Some of the advantages of hydrogen compared to other energy storage technologies (Table 1) show that renewable P2H might be one of the most effective strategies to tackle some of the issues during the transition to renewables that require reliable, affordable, efficient, high-capacity, long-term storage. In terms of capacity and duration, hydrogen offers the best performance compared to other energy storage technologies. The efficiency of hydrogen includes the production, storage, and end-use points. Therefore, any efficiency improvement in hydrogen production and fuel cell technologies would make hydrogen more competitive. The commercialization of

Table 1 Comparison of various energy storage technologies (adapted from IRENA 2019)

Technology	Efficiency (%)	Capacity (MW)	Discharge duration (h)	Technological maturity
Battery	70–85	Up to 100	Up to 5	Mostly R&D, commercialized in some regions
Compressed air	45–70	Up to 10	5–100	R&D
Flywheel	**85–100**	Up to 1	Up to 1	R&D
Hydrogen	30–45	**Up to 1000**	**Up to 1000+**	R&D
Pumped hydro	70–85	**Up to 1000**	Up to 500	Commercialized

hydrogen requires large-scale, efficient, and cost-competitive renewable P2H technologies to be developed. Here, the first step to look at is hydrogen production. More efficient, larger scale, and cheaper electrolyzers could accelerate the integration of renewable P2H to the market.

Table 2 shows the characteristics of hydrogen fuel cells in the transportation sector. Hydrogen fuel cell vehicles offer higher load capacity, which makes them a suitable candidate to decarbonize heavy-duty vehicles such as trucks. Fuel cell vehicles have longer driving distances, shorter refueling/charging time, and lower overall GHG emissions than battery vehicles. For a typical passenger fuel cell vehicle, it takes 3–5 min to get a full tank that provides more than a 300 km driving range. Having similar refueling times with conventional internal combustion engine vehicles is a significant advantage of hydrogen, which could help decarbonizing transportation.

Accomplishing similar performance to current gasoline and diesel vehicles is an essential demand of the end-user side. In most cases, people who would like to switch to zero-emission vehicles are hesitating due to cost, performance, and lack of infrastructure. Tackling and overcoming these hesitations is a must to decarbonize the transportation sector. Compared to battery vehicles, fuel cell vehicles have another advantage that the hydrogen infrastructure can be implemented in a similar fashion as conventional fuels at every gas station. Compared to battery charging, hydrogen does not require expensive and complex upgrades in the existing grid. Besides, hydrogen does not increase the load of the electrical grid or require the installation of chargers in every household for their vehicles.

In terms of cost, hydrogen fuel cell vehicles have the potential to become more affordable than battery electric vehicles. There are already substantial efforts to standardize hydrogen fueling stations. Large-scale hydrogen production already exists since hydrogen has been used as an industrial feedstock for more than a century. The issue is this production is heavily based on fossil fuels. The challenge is to make large-scale renewable P2H cost-competitive with conventional fuels. Then, hydrogen fuel cell vehicles would become a reasonable alternative for customers, and they could decarbonize road, sea, and air transportation.

In the literature, well-to-wheel (WTW) analysis is used when evaluating the overall efficiency and emissions of vehicles. WTW analysis can be divided into

Table 2 Comparison of hydrogen fuel cell vehicles with the alternatives (adapted from Deloitte 2020)

Vehicle type	Fuel cell	Battery	Internal combustion engine
Load capacity (tons)	3.2	~3	~3
Driving distance (km)	≥305	200	400
Vehicle length (m)	6.4	5.97	5.9
Tailpipe emissions	No	No	Yes
Vehicle lifecycle	Under testing	Battery replacement needed after several years of use	~10 years
Refueling/charging duration	Minutes	Hours	Minutes
Infrastructure	Limited	Limited	Well-developed
Production efficiency (%)	23–69	35–60	82–87
Delivery efficiency (%)	54–80	81–85	~ 99
Use efficiency (%)	36–45	65–82	17–21
Well-to-wheel efficiency (%)	4–25	18–42	14–18
GHG emissions of energy carrier production (kg CO_2-eq./km)	~110	20–120	130–230
GHG emissions of production, delivery, and use of energy (kg CO_2-eq./km)	~150	10–100	160–250
Overall GHG emissions (kg CO_2-eq./km)	40–60	140–210	180–270

two stages as well-to-tank (WTT) and tank-to-wheel (TTW). WTT stage includes the production of the energy carrier and its delivery to the vehicle. The second stage, TTW, consists of the use of the energy carrier during the vehicle's operation. There are some different specifications while evaluating the WTW efficiency and emissions of the selected vehicle types (Argonne National Laboratory 2015):

- Fuel cell: Hydrogen production, distribution to fueling station, storage at the fueling station, delivery to the vehicle (fueling), storage in the vehicle, and fuel cell use during the vehicle's operation.
- Battery: Electricity generation, transmission in the grid, charging the vehicle battery (fueling), storage in the vehicle, and battery use during the vehicle's operation.
- Internal combustion engine: oil extraction, refining, distribution to the fueling station, storage at the fueling station, delivery to the vehicle (fueling), storage in the vehicle, and fuel use during the vehicle's operation.

Table 2 shows standard ranges in terms of energy efficiency at each step of the process for each type of drivetrain technology. The impact on the overall energy efficiency of fuel cell vehicles is heavily dependent on hydrogen production and transportation, as well as the fuel cell technology in the vehicle converting the energy stored in hydrogen to drive the vehicle.

One of the arguments against P2H and fuel cell vehicles is the fact that fuel cell vehicles have more energy conversion steps which lower the overall efficiency and increases the environmental impact. In battery vehicles, renewable energy sources converted to electricity are used to charge the battery and the battery gives the energy needed for the vehicle's operation. In fuel cell vehicles using renewable P2H, renewable energy sources converted to electricity are used to produce hydrogen, and then hydrogen is converted back to electricity in the vehicle via the fuel cell. However, hydrogen has some significant advantages compared to electricity, such as longer transportation distances and storage duration. These advantages make renewable P2H and fuel cells a viable alternative to battery vehicles.

Currently, only 4% of the global hydrogen supply is renewable-based, and the remaining 96% comes from fossil fuel resources. Regarding the cost of electrolysis, PEM-based hydrogen production cost was 6.7 Euros per kg, and it is expected to drop to 4.1 Euros per kg in 2025. PEM technology is selected as a basis due to its flexibility. The investment cost of PEM-based hydrogen production is expected to decrease from 1200 Euros/kW in 2017 to 700 Euros/kW in 2025. The investment cost of alkaline electrolyzers is expected to decrease from 750 Euros/kW in 2017 to 480 Euros/kW in 2025. When it comes to infrastructure, including production, distribution, storage, and end-use, the current estimates are 7–8 Euros/kg, and the estimations are 3–4 Euros/kg. Australia, Austria, Canada, Chile, Denmark, France, Germany, Japan, United Kingdom, and the United States are the countries that have P2H applications already. Current hydrogen demand is about 8 EJ, and IRENA projections indicate that global demand is expected to increase up to 29 EJ (IRENA 2019).

Renewable P2H requires further research, development, and innovation to reduce costs and emissions and enhance overall technoeconomic performance to be competitive with traditional energy systems. Policy support is also needed. There are already many governments supporting renewable P2H by offering incentives, research funds, obligatory targets, laws and legislations, and partnerships between the public and private institutions. The growing momentum in hydrogen energy is already getting promising results. Hydrogen's role in the transportation sector is becoming more visible all over the world. Globally, the number of hydrogen-fueled vehicles in use were 11,200 cars and 20,000 forklift trucks by the end of 2020. The number of hydrogen fueling stations worldwide was 381. In 2015, there were 80 hydrogen refueling stations. This means the number of hydrogen refueling stations increased by five-fold in the last five years (McKenzie 2020).

Similar to improvements in hydrogen infrastructure, fuel cell performance has increased significantly in the recent years. In the last five years, fuel cell costs have decreased by more than 50%. Current fuel cell costs are about 3% of the fuel cells developed in 2005. In addition to the economic performance, fuel cell durability has increased significantly. State-of-the-art fuel cells' durability can reach by around 10,000 h. There are several stationary fuel cells reported to have a durability of around 80,000 h, too (McKenzie 2020).

All of the developments discussed so far point out the importance and potential of renewable P2H in the decarbonization of the energy mix. There are promising developments in the hydrogen infrastructure and fuel cell performance. In the next session, the first step of renewable P2H production is thoroughly investigated. Transitioning to a hydrogen economy requires hydrogen to be produced in a clean, efficient, affordable, and reliable manner. For this reason, renewable P2H options' energetic, economic, and environmental performances are comparatively investigated in the next section.

3 Renewable Power-To-Hydrogen Production Methods

Hydrogen is the most abundant element; however, it is not present in free form. Therefore, it needs to be extracted from a material resource such as ammonia, biomass, fossil fuels, hydrogen sulfide, or water by consuming energy (e.g., electricity, heat, etc.). In renewable P2H, renewable electricity is used as the energy source. In order to ensure GHG emission-free operation, the material resource should be water. For this reason, the production methods investigated in this study use renewable power and water as energy and material resources, respectively. The selected renewable energy sources are solar, and wind and the selected methods are electrolysis, high-temperature electrolysis, and hybrid thermochemical cycles.

3.1 Electrolysis

In water electrolysis, external energy is applied to separate water to hydrogen and oxygen. This dissociation is an electrochemical reaction driven by the external energy, which could be in electricity or heat form. Electrolysis is considered to be one of the most straightforward industrial processes. However, currently, the electrical energy supplied to electrolysis is heavily fossil fuel dependent. For renewable P2H, the electricity should come from 100% renewable energies.

There are several challenges related to renewable P2H production via electrolysis, such as cost and scale. Different solutions such as catalysts and membrane electrode assemblies exist to tackle the challenges related to renewable P2H production. The aim of these solutions is to increase the viability through increasing the efficiency of the electrochemical reaction and the overall system. Currently, alkaline and proton exchange membrane (PEM) electrolyzers are considered to be the most viable electrolysis technologies. In Table 3, the operating conditions and critical properties of alkaline and PEM electrolyzers are summarized.

Table 3 Operating conditions and critical properties of alkaline and PEM electrolyzers (adapted from Bhandari et al. 2014)

	Alkaline	PEM
Technology level	State-of-the-art	Demonstration
Operating temperature (°C)	60–80	50–80
Operating pressure (bar)	<30	<30
Current density (A/cm^2)	0.2–0.4	0.6–2.0
Cell voltage (V)	1.8–2.4	1.8–2.2
Power density (W/cm^2)	Up to 1.0	Up to 4.4
Voltage efficiency (%)	62–82	67–82
Electricity consumption (kWh/Nm^3)	4.5–7.0	4.5–7.5
Hydrogen production (Nm^3/h)	<760	<30
Stack lifetime (h)	<90,000	<20,000
System lifetime (year)	20–30	10–20
Hydrogen purity (%)	>99.8	99.999
Cold start up time (min)	15	< 15

Presently, alkaline electrolyzers are the most matured technologies for water electrolysis (Ursúa et al. 2016). The basic setup for the alkaline electrolyzers includes two or more electrodes which are submerged in an electrolyte. The most typical electrolyte used in alkaline electrolyzers is distilled water with about 5–40% sodium hydroxide or potassium hydroxide.

When an electrical potential is applied to the electrodes, a direct current (DC) is generated, which flows through the electrolyte. If the external energy is high enough to initiate the water splitting reaction, hydrogen and oxygen are generated in the gas phase. In this electrochemical reaction, reduction takes place, and the cathode and the products are hydrogen gas (H_2) and hydroxide ions (OH^-). The hydroxide ions (OH^-) formed at the cathode are oxidized in the anode section to generate oxygen gas (O_2) and water. The electrons released from the oxidization reaction in the anode are used in the reduction reaction, which takes place in the cathode.

In the literature, there are numerous studies investigating ways to enhance the current efficiency and density of electrolysis reactions. Buttler and Spliethoff (Buttler and Spliethoff 2018) have investigated the performance of renewable-based electrolysis options and provided a technoeconomic analysis for renewable P2H applications. In another study, ezzahra Chakik et al. (ezzahra Chakik et al. 2017) have investigated the effect of operating parameters on hydrogen production by electrolysis. There are also different studies related to catalysts in order to enhance current density and efficiency and increase the rate of electrolysis reaction. Platinum is the most common catalyst in the literature (Burton et al. 2021). The catalysts used in the electrolyzers can be homogeneous or heterogeneous. Homogeneous catalysts generally have higher turnover rates than heterogeneous catalysts. The high turnover rates lower the lifecycle cost of homogeneous catalysts. Some homogeneous catalysts are reported to have turnover rates around 2.4 mol of hydrogen per mole of catalyst and second (Karunadasa et al. 2010).

Although PEM electrolyzers were formerly considered to be the most efficient electrolysis technology with the highest potential in future energy systems, the latest improvements in alkaline electrolysis technology have brought alkaline electrolyzers to a similar level to PEM in terms of efficiency (Buttler and Spliethoff 2018). In addition, PEM has some disadvantages, including high cost. Since the electrochemical reaction in PEM takes place in an acidic environment with pH around 2 (Burton et al. 2021), the reactor components must be resistant to corrosion, and the operation must not be hindered. Besides, the equipment needs to be robust enough to handle high-pressure gases. Another factor increasing the cost is the need for expensive catalysts such as platinum or titanium. Besides, PEM electrolyzers are highly sensitive to impurities. Application of membranes (El-Bassuoni et al. 1982) to eliminate the impurities or to use catalysts (Ni et al. 2006) to ensure high performance operation when the feed has impurities are the two most common methods used in PEM electrolyzers.

3.2 High Temperature Electrolysis

In high-temperature electrolysis, external energy is applied to split steam into H_2 and O_2. The typical operating temperature of high temperature electrolyzers is between 600 and 1000 °C (Posdziech et al. 2019). Since the electrical energy needed for electrolysis decreases with increasing operating temperature, high temperature electrolysis shows higher performance in terms of efficiency. The first step of high temperature electrolysis is steam generation. In the literature, steam generation is generally done via applying thermal energy directly, but steam can also be generated via electrical heaters. For renewable P2H, emission-free and renewable sources must be used to generate steam and provide the energy needed to split steam into H_2 and O_2.

High operating temperatures cause some specific challenges that are different than alkaline and PEM. The system components must be durable and operating effectively at high temperatures. Ensuring process safety is also critical. Therefore, high temperature electrolyzer components have to meet specific safety requirements against incidents such as an explosion, melting, fire. Presently, there are several other challenges that high temperature electrolysis faces, and these challenges can be tackled by developing:

- Electrolytes that are chemically stable with high conductivity at high temperatures
- Porous and stable electrodes with good conductivity during the redox reactions
- Electrodes and electrolytes with a similar coefficient of thermal expansion
- Chemically stable system components at high temperatures and in highly reducing/oxidizing environments.

Table 4 Operating conditions and critical properties of solid oxide electrolyzers (SOE) (adapted from Bhandari et al. 2014)

	SOE
Technology level	R&D
Operating temperature (°C)	900–1000
Operating pressure (bar)	<30
Current density (A/cm^2)	0.3–1.0
Cell voltage (V)	0.95–1.3
Power density (W/cm^2)	–
Voltage efficiency (%)	81–86
Electricity consumption (kWh/Nm^3)	2.5–3.5
Hydrogen production (Nm^3/h)	–
Stack lifetime (h)	<40,000
System lifetime (year)	–
Hydrogen purity (%)	–
Cold start up time (min)	>60

Solid oxide electrolyzers (SOE) are the most common high temperature electrolyzers in the literature (Myung et al. 2016; Zheng et al. 2017). SOE has high operation temperatures around 600–900 °C and delivers fast electrochemical reaction kinetics. As a result, SOE generally has higher energy conversion efficiency. Using industrial waste heat to generate steam is a strategy to reduce the electrical and thermal energy demand of SOE and increase overall system efficiency. Typical operating conditions and critical properties of solid oxide electrolyzers are provided in Table 4.

3.3 Hybrid Thermochemical Cycles

Thermochemical cycles are processes that have more than one chemical reaction, and they are driven by thermal energy only. In hybrid thermochemical cycles, heat and another form of energy (such as electricity) are used together to provide the necessary energy required to drive the reactions in the cycles. Hybrid thermochemical cycles have lower operating temperatures than thermochemical water splitting cycles. Since hybrid cycles operate at lower temperatures, a wide variety of sustainable thermal energy sources (such as recovered waste heat from other industrial processes) can be used to supply the energy demand. Hybrid thermochemical cycles also have the efficiency advantage compared to thermally driven cycles; their efficiencies could reach up to 48–50% (Safari and Dincer 2020).

The two-step hybrid sulfur cycle known as the Westinghouse cycle is the most commonly known hybrid thermochemical cycle for hydrogen production. It was designed in the 1970s by combining thermochemical and electrochemical reactions for large-scale hydrogen production. It is the first demonstrated hybrid thermochemical water splitting process with only two reactions, which is the combination of the thermal decomposition of sulfuric acid with the electrochemical oxidation of SO_2 with water to yield sulfuric acid and hydrogen (Sattler et al. 2017). In the literature, one of the most commonly studied hybrid thermochemical cycles is the Cu–Cl cycles. Cu–Cl cycles have the advantage of relatively low operating temperatures, which do not go above 550 °C (Safari and Dincer 2020). Recent studies show the promising performance of Mg-Cl cycles (Ozcan and Dincer 2018, 2016). Hybrid thermochemical cycles show great potential to support renewable P2H, especially in cases where moderate-temperature waste heat is available from a different process.

4 Current Status of Renewable Power-To-Hydrogen

In this study, cost, the social cost of carbon (SCC), global warming potential (GWP), acidification potential (AP), and energy and exergy efficiencies of different electrolysis methods and hybrid thermochemical cycles are comparatively assessed. More information on evaluating each method's environmental impact, cost, and efficiency and the 0–10 ranking procedure can be found in Acar and Dincer (2014) and Dincer and Acar (2015).

4.1 Electrolysis Options

Here, the selected electrolysis options are solar, wind, and high temperature electrolysis. The overall performance comparison is presented in Fig. 8.

From Fig. 8, it can be seen that high temperature electrolysis has a higher overall performance. Wind electrolysis has the advantage in terms of global warming potential, acidification potential, the social cost of carbon, and exergy efficiency. In terms of research and development activities, solar based electrolysis requires efficiency and cost improvements in PV modules. Another possible direction is to enhance the lifetime of PV and wind turbines. Besides, it is essential to find effective strategies to recover and reuse PV and turbine materials at the end of their lifecycle. High temperature electrolysis has a relatively better performance compared to solar and wind electrolysis. However, its performance, especially efficiencies and cost, can further be enhanced by lowering the temperature with cheap and effective catalysts and more modular designs. Here, it should be noted that this analysis is a comparative investigation. Therefore, it does not reflect the absolute performance of each selected method. The aim here is to provide research and development directions by highlighting the strengths and weaknesses of each method. Further, and more detailed information can be found in Acar and Dincer (2014).

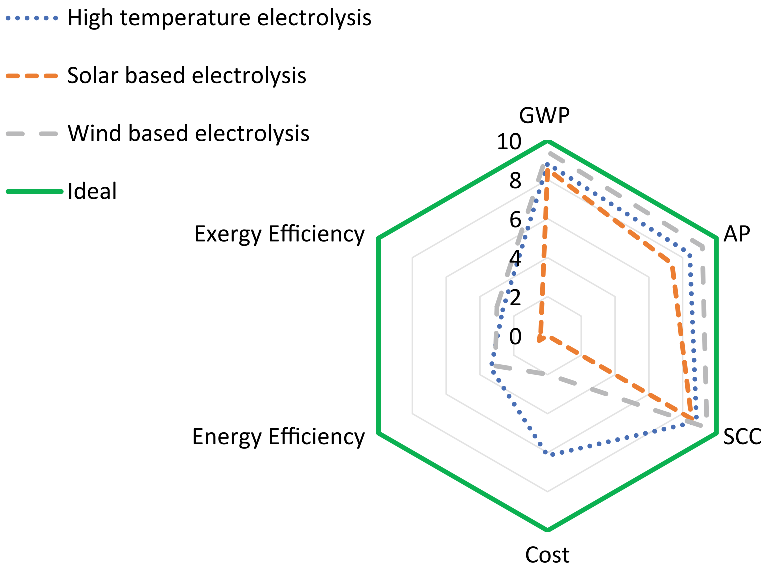

Fig. 8 Comparative sustainability performance analysis of selected electrolysis methods (adapted from Acar and Dincer 2014)

4.2 All Renewable Power-To-Hydrogen Options

In this study, there are three renewable power-to-hydrogen production methods which are electrolysis, high temperature electrolysis, and hybrid thermochemical cycles. Electrical energy-based methods give higher energy and exergy efficiencies compared to thermal and photonic energy based and hybrid hydrogen production methods. In terms of production costs, electrical energy gives competitive results to already mature fossil fuel technologies. The comparative performance investigation of selected renewable-to-power hydrogen production options is given in Fig. 9.

Overall investigation shows that hybrid thermochemical cycles have the best performance when all technical, economic, environmental, and social criteria are considered. Compared to the other selected to renewable P2H production options, hybrid thermochemical cycles method has especially better performance in GWP, AP, and SCC categories. Higher score means hybrid thermochemical cycles method has lower social cost of carbon emits and lower amounts of CO_2 and SO_2.

Electrolysis shows a great potential in integrating renewables into our energy systems because it is already a well-established and pretty straightforward process with almost zero greenhouse gas emissions during operation. For this reason, electrolysis is a key renewable P2H production method. But there is further research and development in materials science needed to enhance the durability and efficiency of the electrolyzers. In addition, renewable electrolysis costs need to be reduced significantly to compete with traditional energy systems, which requires engineering

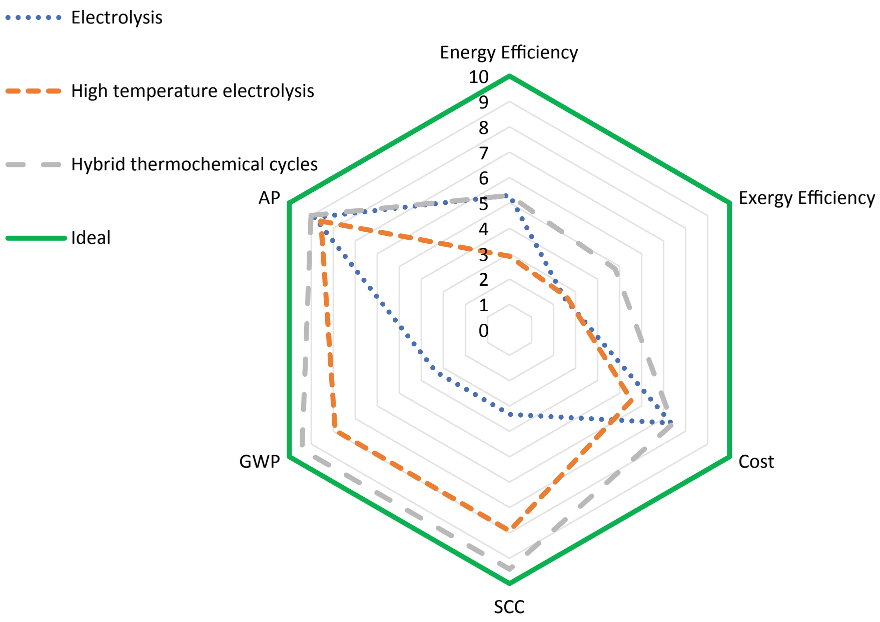

Fig. 9 Comparative sustainability performance analysis of selected renewable power-to-hydrogen methods (adapted from Dincer and Acar 2015)

solutions. We already see tremendous amount of development in renewable power-to-hydrogen generation. In the last ten years, the cost of renewable P2H has decreased by almost 80% (Council 2020).

Figure 10 shows the motivation behind renewable power-to-hydrogen strategies. Hydrogen has strategic importance in decarbonization and transition to 100% renewable-based energy systems. The industry's growing momentum is the indicator of hydrogen's importance. In terms of emissions, there are ten years left in the global carbon budget to reach the 1.5 °C limit set by the Paris Agreement. In addition, 66 countries have committed to achieving net-zero emissions by 2050.

Hydrogen is a crucial solution to reduce emissions significantly and help countries achieve their net-zero goals effectively. In the last ten years, renewable power-to-hydrogen cost has decreased by almost 80%, and the global electrolysis capacity has

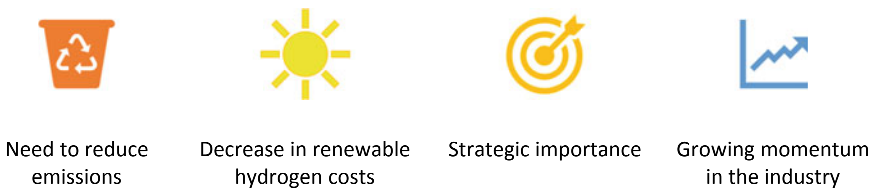

Fig. 10 Motivation behind renewable power-to-hydrogen strategies

increased by 55 times. According to the Hydrogen Council's 2020 Report, 70% of the global GDP is linked to hydrogen country roadmaps, which shows the strategic importance of hydrogen. Hydrogen Council started in 2017 with 13 members, and by the end of 2020, there are 60 members in the council (Council 2020).

5 Future Prospects of Renewable Power-To-Hydrogen

Renewable P2H has many promising applications that could decarbonize hard-to abate sectors. Namely, renewable P2H can be used as a fuel in the gas grid or in fuel cells (Figs. 11 and 12). Hydrogen in the gas grid is a clean fuel that can decarbonize buildings, industry,.and transportation. Hydrogen also can be used to produce electricity with zero emissions and then this electricity could be used in the grid or in transportation.

- **Transportation**: Hydrogen could be used to decarbonize land, sea, and air transportation. Road transportation is a particularly difficult sector to decarbonize. Hydrogen can be used in two different ways in road transportation via use in fuel cell and internal combustion engine vehicles. In both applications, hydrogen fueling stations and infrastructure must be developed. In internal combustion engine application, existing engines need to be modified for safe operation with hydrogen. Another requirement for both vehicle types is lowering the cost of vehicle ownership and fuel. Both types of hydrogen vehicles have zero CO_2 emissions during operation. For complete decarbonization, renewable P2H should be

Fig. 11 Future applications of renewable P2H

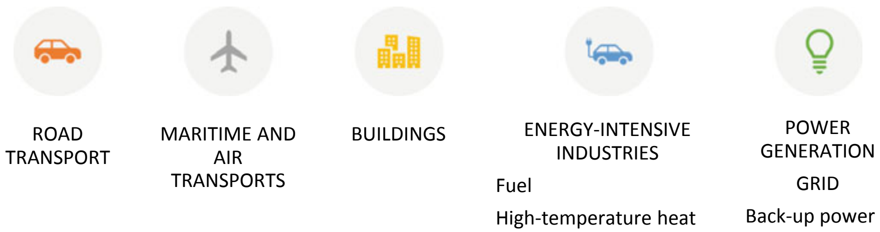

Fig. 12 Renewable P2H in the future energy mix

used in both vehicle types. In passenger cars, the ownership and fuel cost would be the determining factor when selecting hydrogen or battery vehicles. In heavy-duty vehicles on road and in maritime operations, hydrogen is the strongest decarbonization strategy because batteries are not viable in these options. In the aviation industry, switching to hydrogen requires minor changes in system design, fueling infrastructure, and airports. In all applications, renewable P2H needs to become cheaper in large scale.

- **Buildings**: Hydrogen could be used as a fuel to supply heat in buildings. Also, hydrogen could meet the electricity demand of buildings via fuel cells. Considering the fact that buildings' share in the global primary energy consumption is about 30% and the majority of this need is about heating (McKenzie 2020), hydrogen becomes an important heating strategy. In the near term, hydrogen can be used in building heating by blending in the existing natural gas network. In the long run, existing natural gas infrastructure can be modified for operation with 100% hydrogen. Hydrogen could also be used power heat pumps for building heating. Using hydrogen power in heat pumps can reduce the load in the electricity grid, which would be very beneficial especially in areas with dense population or high heating demand.
- **Industry**: Hydrogen can be used in the industry as a chemical feedstock and energy carrier. With hydrogen, heating and electricity of the demand can be met simultaneously. Hydrogen's major advantage compared to electricity is its potential in hard-to-abate sectors such as steel, aluminum, cement, and refineries. Electricity is not suitable for providing high-temperature heat in the industry. On the other hand, hydrogen can provide high-temperature heat to many industrial processes such as melting, gasifying, drying, catalytic converting and more.
- **Electricity generation and storage**: Hydrogen can be used to store energy in longer durations compared to electricity. Therefore, with hydrogen, it is possible to store renewable power for longer durations. Other advantages are reducing the peak load demand and the overall load of the grid.

Table 5 shows the perspectives, goals, and metrics related to enabling large-scale deployment of renewable P2H in power generation, buildings, industry, and transportation sectors.

Transitioning to 100% renewable energy-based economies require renewable P2H to be reliable, affordable, efficient, safe, clean, and environmentally and socially

Table 5 Perspectives, goals, and metrics to enable large-scale deployment of renewable P2H

Perspective	Goal	Metrics
Technology	Maturation of new technologies	e.g., manufacturing readiness level
Cost	Lower production, storage, distribution, end-use costs	e.g., EUR/kg H_2, EUR/kW, EUR/kWh
Production	Large-scale to meet the demand	e.g., tons H_2/year
Supply chain	Stronger supply chain and infrastructure	e.g., coverage percentage

Fig. 13 The role of renewable P2H in decarbonization with different strategies

responsible. For this reason, the first perspective is technology: new technologies should be developed and matured for commercialization. Mature and sustainable technologies are needed in every stage of hydrogen value chain from production to end use. Cost is another important perspective since it is a challenge keeping hydrogen from dominating the energy market. Large-scale hydrogen production is the third perspective because when hydrogen technologies get more mature and cheaper, the demand will increase. Therefore, the supply needs to match the scale of the demand. Last, but not least, stronger supply chain is needed for renewable P2H to be competitive with traditional fuels and energy systems.

Figure 13 shows the established and emerging renewable P2H with short and long-term decarbonization strategies. In distributed energy systems, hydrogen could provide back-up power and grid stabilization. Since it is a promising energy carrier and storage medium, hydrogen can bridge the gap between supply and demand in distributed energy systems. In addition, there are already some hydrogen applications in the industry, such as trucks, passenger vehicles, forklifts, and devices that are used for material handling. When it comes to material handling equipment or even automobiles and factories, hydrogen fuel cells have proven to be a realistic replacement for today's conventional means of powering machinery and equipment.

Hydrogen also contributes to the industry as a feedstock for oil refineries, ammonia production, metallic ore reduction, hydrochloric acid production, and hydrogenation. In short term decarbonization strategies, hydrogen is expected to increase its role in steel, aviation, high-grade industrial heat, and buildings. The growth of hydrogen within steel production demonstrates the viability of the technology outside of direct energy production. Incorporating hydrogen into industrial processes is necessary for wide-scale decarbonization and worldwide emissions reduction. As hydrogen continues to become readily available, so will the opportunities to make industries green. In medium and long-term decarbonization strategies, hydrogen is expected to be used for low and medium-grade heat generation and centralized power applications (Lux and Pfluger 2020).

6 Conclusions

Renewable power-to-hydrogen is an essential component of the transition to 100% renewable energy-based economies and societies. Renewable power-to-hydrogen can also help governments to achieve their Paris Agreement targets and further decarbonize their economies for a sustainable future. Besides, renewable power-to-hydrogen is in alignment with the United Nation's 7th Sustainable Development Goal, which is "Ensure access to affordable, reliable, sustainable and modern energy for all'. For this reason, in this study, the current status and future prospects of renewable power-to-hydrogen are investigated and presented. According to this study, large-scale, reliable, safe, affordable, efficient reliable power-to-hydrogen and its wide-spread application requires:

- Renewable power-to-hydrogen production needs to be scaled up by creating a sustainable value chain.
- The demand for renewable power-to-hydrogen from industrial applications, buildings sector, and mobility technologies should be encouraged and supported.
- Renewable power-to-hydrogen needs a supportive framework, well-functioning markets, and clear rules, as well as dedicated infrastructure and a logistical network.
- Promoting research and innovation in renewable power-to-hydrogen technologies is crucial.
- Cooperation and collaboration among different governments, sectors, industries, and stakeholders are essential to establish a global hydrogen market.
- A robust infrastructure should be developed, which requires investments to switch from fossil technologies to renewable power-to-hydrogen.

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Green Hydrogen in Europe

Wolfgang Palz

1 Introduction: Early Interest in Green Hydrogen Since 1975

The European Union (EU) started in 1975 a new R&D programme on *Non-Nuclear Energy*. One of its components was *Hydrogen*. The programme was decided by the Council of Ministers of the EU and the European Parliament. The first 4-year programme was associated with a budget of some 100 million €, or ECU as the € was called in those days. It was followed by several others, each of a duration of 4 years.

The EU Commission was in charge of programme implementation. After calls-for-proposals, cost-sharing contracts were concluded with research establishments and the industry from all over Europe by the EU Commission. A lean programme administration was set up in Brussels; it was associated with Advisory Committees of the EU Member Countries' Governments and panels of the best specialists available in Europe.

The hydrogen part of the Non-Nuclear Energy programme had the 3 components.

- Electrolytic hydrogen production
- Hydrogen storage and transport
- Thermo-chemical hydrogen production.

The programme manager was my colleague G. Imarisio. Results were published in specialised Journals and books.

Another component of that Non-Nuclear Energy programme was *"Solar Energy"*. It comprised as an absolute priority *Photovoltaics*, then Solar Heating and Cooling,

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Wind Power, all kinds of Biomass and organic Waste, Ocean energy. It was drafted and managed by myself. I was sitting with my staff next to that of G. Imarisio in the prestigious EU building "Helmut Kohl" in the centre of Brussels.

Next to us in Brussels there was our colleague and friend J. Gretz. He was based as an EU Official at the Joint-Research Centre JRC at Ispra, near Lago Maggiore, in Italy. Originally he had promoted "Concentrated Solar Power, CSP". Then he turned his interest to hydrogen. Being aware that PV and Wind power were not yet ripe for large-scale implementation in the early days, he promoted Green Hydrogen from Hydro. He imagined and promoted the "100 MW Euro-Québec Hydro-Hydrogen pilot project" published in 1990. As the province of Québec in Canada has ample water resources Gretz proposed to produce hydrogen from Water power in Canada and ship it by special tankers to Europe. His hometown of Hamburg had agreed to cooperate and offered a place for it in the city's harbour, one of the largest in Europe. The project was too ambitious to be implemented fast; Gretz passed away in 2012 and it lost its prime initiator.

But the idea has not been vain. As part of the new global interest in GH, the city of Hamburg plans now in 2021 an electrolysis plant of 100 MW from *Wind power*; it signed to this end a letter of intend with Shell, Vattenfall and Misubishi. Instead of a brand new coal plant, just removed after 5 years on the net, the city wants to build a GH plant to feed into a new North-German hydrogen gas pipeline.

On the other side of the Atlantic, Hydro Québec builds now an 88 MW electrolysis plant from *Water power* to be ready by year end 2023. The industry in charge is Thyssen-Krupp and Uhde Chlorine Engineers. The GH produced will serve for cracking of biological residues into transport fuels.

At last it is worth mentioning that the world's interest in GH found a common voice since 1976, a year after the EU's first programme on hydrogen, in the publication of the "International Journal of Hydrogen Energy" with 6 issues a year. A yearly Congress on Hydrogen is being held, too. The first took place in 1976 at Miami Beach.

2 Green Hydrogen Newly on the Agenda Today

Climate change is a key concern of modern society. Stopping or at least alleviating it is the objective as articulated for the world since the "Paris Treaty" adopted in 2015.

As climate change has its origin in the always increasing content of the greenhouse gases (GHG) and in particular CO_2 in the air that capture the incoming Sun irradiation, the way forward is to reduce those GHG emissions. In practice that means to reduce or even stop the CO_2 formation by the combustion of carbon resources such as oil, natural gas, and coal. And stop the use of nuclear that is also a fossil energy.

There are not many ways to achieve this, there is only one: to meet all our energy demand by Renewable Energy (RE), exempt of net CO_2 emissions. The challenge is to associate the new ones and their technologies, Solar, Wind, Bio-fuels, and a few others with the conventional Hydro and Biomass.

Only very recently, since the year 2000, when their development took a meteoric rise, PV, the Solar electricity, and Wind power have reached sizable shares in the world's energy markets. Those are even leading the global power markets of today as we are going to see in a later chapter. But on top of the RE electricity there is the world demand for RE fuels. Nowadays 80% of global energy demand is still met by the fossil fuels, oil, natural gas, and coal.

And the clean fuel to replace them is Green Hydrogen (GH). One will need enormous amounts of it.

Green Hydrogen is produced from water through electrolysis by means of RE electricity. Other forms of electricity for the purpose are technically possible—but not desirable—such as the nuclear one; that hydrogen is not called GH.

We saw in the Introduction that there was a long-standing interest for GH, but markets didn't take off. The economics were not yet right.

The reason for a change by now is the fact that the decision makers in politics and industry became aware that the cost picture of the main ingredient for GH, the Renewable electricity, Solar PV and Wind power, has turned: around the year 2020 it became clear for all stakeholders that there are new opportunities for GH. And as we'll see, a political and industrial revolution has begun.

3 The Hydrogen Markets of Today

At some 70 million tonnes a year, hydrogen does not weigh much in the global energy markets of today. The EU consumed 10 million tonnes in 2020. And virtually all of it was of fossil origin, produced by "steam reforming" of natural gas or as a side-product of chlorine production. It is associated with the generation of 13 tonnes of CO_2 for each tonne of hydrogen produced. This hydrogen is called "grey hydrogen"; contrary to "Green Hydrogen" it is not renewable and sustainable at all. Of the total of 70 million tonnes only 1 million goes into the energy market, the rest serves as industrial feedstock: for fertilizer production via ammonia, for oil refineries, cement, ceramics, the glass industry, for pharmaceuticals, etc. The region NRW in Germany operates already a 240 km hydrogen pipeline.

One of the world's largest manufacturers of grey hydrogen is the German/US firm Linde. Its main production plant is at Leuna in Germany. In 2020 Linde generated a business of $2 billion with hydrogen.

4 The Challenge of Up-Scaling GH Development in the Energy Markets

We have seen that the overall hydrogen market is very small *today*. And *global GH consumption* is only a tiny part of it, less than one million tonne in 2020. It is associated with the hydrogen electric car business, nowadays very much a Japanese affaire. Japan has 40,000 hydrogen cars on the streets. The car manufacturers Toyota, and Honda in Japan and Hyundai in S. Korea, market 10,000 a year of them. Today's largest electrolyser for GH production stands in Japan; it has an input of 100 MW. The technology that comes also into play with hydrogen electric cars is the fuel cell. Instead of piston engines, the hydrogen cars are driven by electricity generated in fuel cells from hydrogen.

In Europe, Germany has the largest park of hydrogen cars on the roads, albeit only less than a thousand of them. But the number of hydrogen filling stations, a hundred in early 2021, is steadily increasing there along the roads and highways.

The hydrogen car markets in the US and China are not any better off than in Germany: Germany had less than a thousand hydrogen cars sold in 2020 and so did the US; China had some 3000 hydrogen pickups and busses running that year.

Hence, GH markets today find themselves in a very early stage. But this is going to change. The EU Commission announced in July 2020 that GH should provide *12–14% of Europe's energy mix by 2050*, just 29 years from now. Already for 2024 the Commission projects one million tonne of GH produced by electrolysis from 6 GW RE electricity.

In Germany it was estimated that for reaching the country's ambitious climate goals by 2050, 80 GW of additional power to generate GH by electrolysis are needed. The corresponding energy is 3-times Germany's renewable electricity of today, Europe's highest. Today half of Germany's households are connected to gas pipelines for heating (may I say, mine in Brussels as well and it's very user-friendly). A priority target for new GH implementation is to enter this market. And the markets in transport, too: next to the car market mentioned above, the fuel market for trucks, buses, ships, trains, or airplanes.

All this is relevant as well globally, where GH should enter the markets occupied today by natural gas and oil. And eventually one has to displace coal. Coal power stations are on the verge of loosing by now the market dominance they used to have. But coal's market position remains important also in other industrial sectors, such as steel production. For instance in Germany that one is today responsible for 30% of all CO_2 generation there.

GH is *not cost competitive* today. The key technologies involved in its production and use, electrolysis and fuel cells, are well known. What is lacking is mass-production to decrease cost—and with no markets today there is none. The vicious circle is the same as in the early days of Photovoltaics: no market without sufficiently low cost through mass-production and no mass-production without a market. The turnaround comes through political incentives. In a following chapter we'll see that they are on their way now.

Grey hydrogen is already produced on a reasonable scale today as we have seen. It comes at €1.5/kg or so. GH is almost 4-times more expensive currently at approximately €5.50/kg. The Norwegian hydrogen specialist Nel ASA announced that it might reach the $1.5/kg cost-level already by 2025 assuming a RE input cost of 2 cents a kWh. Nel will have still in 2021 a large electrolyser for a 500 MW RE input running in Norway. Nel publicised to have so far sold 110 hydrogen gas stations for buses, trains, and ferries in many countries. A lot of institutions have also analysed the cost prospects for GH. The "Hydrogen Council" found that the competitive cost would imply a mass-market of over 500 million tonnes with an input of 70 GW of renewable power.

A factor of market competitiveness of GH is the price imposed on CO_2 associated with fossil-fuel use. Europe is only starting now to tax CO_2 production, and it is on a modest scale.

All in all, it can be expected that eventually GH will become cost-competitive in the foreseeable future.

5 The RE Power Penetration Achieved in the Markets Since the Year 2000

In 2018 was published my book "THE TRIUMPH OF THE SUN, The Energy of the New Century". It reports in detail how the REs conquered recently the global energy markets. The most spectacular in case was Solar Photovoltaics. PV started exactly in the year 2000 with the new Millennium its breathtaking growth. It went from a zero market volume to the fastest market introduction of all new power in 2020; from the highest cost at the start to the lowest today.

The market of the RE since 2017/18 until now was well predicted in my book: a continuous dramatic growth that no Donald Trump or COVID-19 has affected. Following statistics from the IEA in Paris 90% of all new power capacity additions in 2020 worldwide were RE; half of them were PV.

27% of global electricity consumption in 2020 was of the RE type; and even more to be expected for the future. Still following the IEA, PV and Wind power capacity together will by 2024 come ahead of each of all leading global electricity providers of today, i.e. coal, natural gas, and even Hydro.

In 2020 the world added 130 GW of PV power, achieving a total of 760 GW. China came first, followed by the EU, the US, India, Japan, Vietnam, and many others. Global Wind power comes 775 GW today. Some 90 GW wind power have been added in 2020, China first with 45 GW (the figure stands for the newly built *and* grid connected power there; it is 72 GW counting also those built the year before and only connected in 2020), the US second with 26 GW and the EU-27 third at 10.5 GW + 4.2 GW for the UK, and a few more GW for Norway, India, Brazil, etc. China is the world champion of clean power with 530 GW of PV and Wind power installed, 1/3 of the world's total. Costs at the best sites came down to just over 1cent/kWh for PV and 2cents/kWh for Wind electricity. In central Europe that has less favourable sites they stood at approximately 5cents/kWh.

Eurostat, the Statistical Office of the EU published latest official data for the EU in January 2021; they are for 2019. It announced that the REs, and in particular PV were the fastest growing energies in Europe. In the EU-27, the 27 Member countries without the UK after the Brexit, the RE stood on average for almost 20% of gross final energy consumption in 2019: Sweden had the highest part, followed by Finland; France and Germany, resp. at 17.2 and 17.4%, came far behind. 22% of the EU's overall energy demand for Heating and Cooling was met from the RE, 8.7% of that for Transport.

For our current report on Green Hydrogen, it is the RE electricity that is of interest: its share of the total electricity generation was 34% (the estimate is that it raised to 36% in 2020). Of the overall RE generation.

35% were provided from respectively Hydro and Wind power. Electricity from Solid Biomass stood at 8%. Solar PV electricity generation came at 13%, less than half that of Wind, but it was the fastest growing: PV's boom becomes evident comparing the total capacity figures for PV and Wind power that are closer in size than the generation figures. One kW of PV generates as a rule less electricity than a kW of Wind power. 40% less on an EU average.

6 EU and Country Strategies for Green Hydrogen

In early 2020, a "Green Deal" was decided by the EU, the Council and the European Parliament on a proposal by the EU Commission. The goal is to make Europe net emission-free of GHG by 2050. By 2030 emissions should come down 55% compared to 1990. The Green Deal includes a comprehensive list of actions and budgets.

As a follow up, the Commission presented by mid-July 2020 its strategy to make Green Hydrogen an important clean energy for decarbonising the continent. As mentioned before, the plan is to have by 2050 hydrogen for 12–14% of the EU energy-mix. The hydrogen is supposed to be derived from RE electricity such as Wind power and PV. By 2030 10 million tonnes of GH derived from 40 GW of RE should become newly available.

Under German Presidency of the EU Council was issued a "Manifesto" on European Hydrogen technologies and systems. It has been adopted and signed by 23 EU Member Countries on Dec 17 2020. It is interesting to note that 5 countries, Austria, Denmark, Luxemburg, Portugal, and Spain issued the following day a warning that the initiative must not be used as a backdoor to support hydrogen from nuclear or decarbonised gases. It is well known that for instance France thinks in that direction.

In July 2020 the EU Commission got off the ground the "European Clean Hydrogen Alliance". A declaration has been issued that is signed by all participants supporting the goal to develop hydrogen from 40 GW of RE by 2030. The EU Commission announced to organise a Hydrogen Forum as part of it each year. An impressive number of stakeholders have already joined that initiative: more than a thousand companies, associations, Ministries and public authorities, financial institutions, research institutions. The Alliance is open to everybody.

There have also been many country strategies on GH newly issued since 2020. Germany has now a National Hydrogen Strategy. In its stimulus package of June 2020 to combat the economic crisis due to Covid-19 €9 billion have been reserved for

GH development; of it €2 billion for international cooperation projects. Its Ministry of Research supports a Power-to-Gas Action Plan, the development of fuel cells, the clean steel industry, etc. The government has decided a plan of GH for steel production.

Italy has now a National GH Strategy. The goal is to commit €10 billion by 2030 and build an electrolysis capacity for 5 GW. GH should meet 20% of energy demand by 2050.

France intends to commit €7.2 billion for clean hydrogen, also from nuclear.

By now virtually each European country has a national hydrogen strategy; just to name a few more, Spain, Portugal, Austria, The Netherlands, Norway.

7 Well-Established Industry with New Interest in GH: Initiatives and Projects

An incredible number of new projects on GH were initiated in 2020; and one wants to go ahead fast in order to have an impact on the urgent task to combat climate change and the necessary energy revolution. This article is going to mention in the following just a few oft hem:

As part of the €9 billion support budget mentioned before, called an IPCEI, Important Project of Common European Interest, Germany initiated 3 major projects with over a hundred large companies,

- The biggest is *H_2GIGA* on series production of electrolysers. With 112 partners, Dechema, Thyssen-Krupp, Siemens Energy, Linde-ITM Power, MAN/HTEC, Sunfire, Schaeffler, Evonic, Shell
- *TRANSHYDE* is on transport technologies for GH, liquid or linked with ammonia. It has 89 partners, PWE Renewables, the Max-Planck Institute
- *H_2MARE* on GH production from Wind power on the sea. With RWE, Siemens Energy, Salzgitter.

H2MOBILITY also in Germany with Shell and Linde.

GH for steel mills in Duisburg with Thyssen-Krupp and EWE. Other initiatives with Arcelor Mittal in Bremen. And still others with Salzgitter, Flachstahl.

NortH2 at Groningen Seaport, NL, with Gasunie, Equinor, RWE and Shell: for 4 GW from Wind power in 2030, a centre for GH in North-Western Europe. GH hub in port of Rotterdam, Shell, ENCO from Wind off-shore. In Vlissingen, also in NL from Wind off-shore GH by 2030 for over €1 billion investment.

H_2FUTURE in Linz Austria, GH from PV and Hydro from the utility Verbund.

Project GreenHydrogen@BlueDanube, Hydro from Verbund and import of RE electricity from South-Eastern Europe. High-temperature electrolysis for producing GH for decarbonising refineries. With Bosch for stationary fuel cells. GH for ships.

In Lingen, Germany, BP with the Danish Oersted, GH from off-shore Wind power.

Linde and Daimler for liquid GH for trucks.

Airbus for the hydrogen plane.

In Italy ENEL Green Power, SNAM, ENI GH for refineries.

Supported by Germany, in Saudi Arabia on the Red Sea for green ammonia by electrolysis from 4 GW of PV and Wind power.

Also supported by Germany, in Chile, Power-to-Gas, with CO_2 use as well; with Siemens Energy, Porsche, etc.

In France Air Liquide, Engie, Michelin, Total have committed themselves to GH.

Most significant is the case of the French Engie, with the 100 GW it owns, a major utility operator in Europe. Engie has again confirmed its interest in Biomass and GH while announcing in February 2021 to give up by 2025 all the coal power plants it still operates in Europe and leaving all nuclear capacity in Belgium, making that way the country, formerly a European pioneer in Atomic energy, nuclear-free.

8 Outlook

Make Europe and the World green again!

A green energy revolution was started exactly with the year 2000. It brought Wind power and Solar PV from a desperate and marginal position for being dear and industrial dwarfs to the dominant power providers in the world of today; they are now recognised in all quarters not only for being clean and safe, but in particular for being the cheapest ones on the markets.

And 20 years later, in 2020 as a second stage of a clean rocket into the future, on top of a green power world, came the turn to Green Hydrogen in view of a broader base of a sustainable green fuel next to the Bio-fuels.

Green power is nowadays so well anchored in the world markets that the task of conquering what is still not met by it today has by and large become a routine. As the fuel market is much larger in size than the power market—and it is the dominant one for years to come—it remains yet a challenge to make our continent CO_2 emission-free by the midst of the century. And it is not yet won.

Hydrogen Utilization in Ships in Line with EU Green Deal Goals

Egemen Sulukan, Alperen Sari, Musa Cenk Özekinci, Doğuş Özkan, and Tanay Sıdkı Uyar

1 Introduction

Since the dawn of civilization, energy and its utilization have been among the most basic human requirements (Sulukan et al. 2020). Energy consumption has increased in proportion to people's demands as the population has grown and technology has advanced from the past to the present. As energy demand soared, so expanded the diversity of energy sources (Qureshy and Dincer 2020). After the industrial revolution, as a result of energy policies based on fossil-fuel technology, not only political and military difficulties, but also economic, ecological, and health concerns began to emerge (Moser 2010).

Figure 1 illustrates a decrease in energy consumption at specific eras owing to economic, political, military, or health-related issues throughout the world. It is

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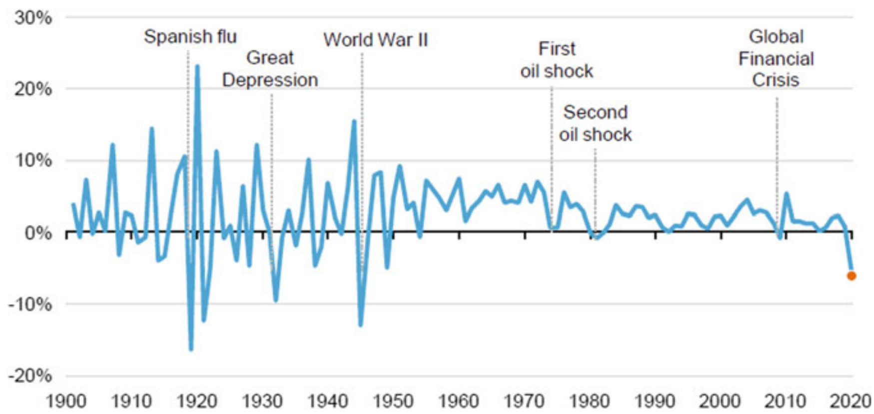

Fig. 1 Rate of change of global primary energy demand, 1900–2020 (IEA, Rate 2021)

expected that there will be an energy scarcity soon, particularly because the production pace of energy resources cannot keep up with the speed of recent technological advances. In this context, it is estimated that various actions should be implemented throughout the world, and the problem may have economic, ecological, health, political, and military implications (Sevim 2011). One of the most noticeable, and arguably the most significant, of these issues is the environmental devastation produced by fossil fuels, as well as the resulting global warming and climate change (Uyar et al. 2019).

1.1 Global Warming and Climate Change Problem

The climate has changed from time to time within the scope of the natural process since the creation of the earth. However, the recent fast increases and reductions in global temperature readings are an indication of the challenge of rapid climate change. To prevent severe effects on human health and environmental events, the CO_2 ratio in the atmosphere should be in the range of 180–350 ppm (Jones 2017). However, according to researches, this level is currently at 410 ppm and is increasing by roughly 3 ppm each year (We and Just 2017). If we do not take action to curb CO_2 emissions, we will suffer severe natural events such as abrupt temperature fluctuations, drought, and flooding (Değişikliği and ve Politikaları Uygulama ve Araştırma Merkezi 2021). The fast climate change problem has evolved into an ecological issue impacting the entire world. When the main source of this problem is investigated, greenhouse gas emissions (GHG) are found to be caused by energy production (Sevim 2011). The majority of the world's energy demands are met by fossil fuels (Sulukan et al. 2021). GHG emitted into the environment as a result of the combustion of fossil fuels damages the ecosystem and ecological equilibrium. When the world's sectors with the greatest GHG emissions are investigated, power generation, industrial, transportation, and residential sectors rise to the top. Many nations, institutions, organizations, and industries throughout the world are taking various actions to prevent global warming and climate change. However, efforts are being made, and advances in high-energy-demanding industries such as marine and aviation remain restricted.

1.2 The Environmental Impact of Maritime Trade and Regulations

Globalization of commerce would not have been feasible without the shipping sector, which has historically been the most useful form of transportation (Sulukan et al. 2018). The price of shipping services has dropped throughout time as a result of the use of larger ships and the growth of the network between the customer, retailer, distributor, carrier, warehouse, supplier, and manufacturer. As a consequence, demand for transportation has risen substantially since the end of the twentieth century. However, the increased shipping supply has a negative impact on the environment. Although environmental impacts are being assessed for all modes of transportation, it is difficult to reach an agreement on international maritime transport regulations (Cullinane and Bergqvist 2014), because a majority of the environmental impacts of maritime transport occur at sea and thus have less perceptible effects on the population.

Almost all emissions from the marine sector are caused by fuel usage. Diesel and fuel oil are used as fuel by nearly all of the world's marine fleet. However, the gasoline used in ships, commonly known as bunker fuel, is of far lesser quality than that used in other modes of transportation (Corbett and Koehler 2003). Because of the poor quality of the fuel used, even the most contemporary ships emit more pollutants per power output and harm the environment than diesel engines used in other sectors. Several strategies to minimize carbon footprint and environmental consequences are still being debated and developed across the world (Sari et al. 2021). The International Maritime Organization is engaged in a global battle to reduce the environmental impacts of the maritime industry (IMO). The IMO serves as a consultancy unit within the United Nations that also deals with administrative and legal issues to encourage and facilitate the overall adoption of the highest standards applicable to marine safety, navigational effectiveness, and the prevention and control of marine pollution from ships.

The IMO has a long history of controlling ship pollution through the International Convention on the Prevention of Pollution from Ships (known as the MARPOL Convention), which is the most important measure that has been enacted to date. MARPOL covers not just intended and unintended oil pollution, but also chemicals, packaged goods, wastewater, garbage, and air pollution. It was ratified in 1973, and the 1978 Protocol came into effect.

Evidence that carbon dioxide (CO_2) concentrations in the atmosphere were increasing was first brought to the agenda by climate experts in the 1960s, and its effects on global warming began to be expressed in the second half of the twentieth century when environmental measures were brought to the agenda. The Kyoto Protocol, which was adopted in Kyoto, Japan in 1997 (Oberthür 2003), is one of these. This protocol is an international agreement associated with the UNFCCC, the most important element of which is the establishment of enforceable objectives for greenhouse gas (GHG) emissions reductions for 37 industrialized nations and the European Union. Greenhouse gases are specified in this protocol as carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydro fluoride carbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6). CO_2 is the heaviest of these gases in terms of mass (Protocol 1997).

Figure 2 shows that CO_2 emissions from the marine sector account for about 3.3% of worldwide energy-related CO_2 emissions and that this rate is growing year after year due to increased demand for maritime transportation.

The Kyoto Protocol also contains rules for reducing greenhouse gas emissions from international aviation and marine transport. Although this protocol compels governments to collaborate with the IMO to reduce greenhouse gas emissions from ships, the IMO published a new protocol in 1997 to address ship air pollution concerns. This protocol was added to MARPOL as Annex VI, and the MARPOL was updated as a result. Since the Kyoto Protocol's validity term will expire in 2020, it has been agreed to sign the Climate Change Agreement (Paris Agreement), which includes the UNFCCC and the Kyoto Protocol, after the 21st Conference of the Parties (COP21) in Paris. The Paris Agreement aims to strengthen the worldwide socioeconomic situation in the context of mitigating climate change in the period

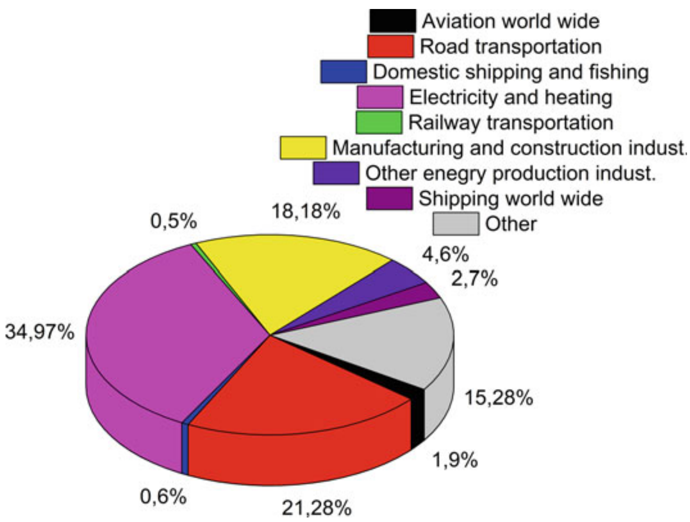

Fig. 2 CO_2 emissions from shipping compared with global total emissions (Dowell and Shah 2012)

after 2020 (Paris agreement. 2015). The Paris Agreement's long-term aim is to limit global temperature rise below 2°C as close to zero as achievable before the industrial revolution, and even less than 1.5 °C (Tschakert 2015). As a result, to reduce and reverse the trend of rising CO_2 emissions, we must cease producing greenhouse gases into the atmosphere.

In this context, the IMO's Marine Environment Protection Committee (MEPC) has placed a strong emphasis on decreasing greenhouse gas emissions from ships, and MEPC.304 (72) on IMO's initial plan for lowering greenhouse gas emissions from ships was approved at MEPC 72 on April 13, 2018 (IMO 2018).

The "Vision" presented in this key "First Strategy" document underlines IMO's commitment to decrease greenhouse gas emissions from international commerce and eliminate them as soon as possible this century. Furthermore, CO_2 emissions from international marine trade are expected to be decreased by 40% by 2030 and 70% by 2050 when compared to 2008 levels for each mode of transport (Chen et al. 2019).

The European Union, on the other hand, plans to lower GHG emissions by 55% by 2030 compared to 1990 and to attain zero GHG emissions by 2050 by updating the Green Deal it established to become the first continent to achieve zero pollution (European Commission et al. 2021).

To achieve these objectives, new energy-efficient ship designs, new machinery, and, most importantly, alternative fuels are necessary, in addition to economic advances. Even though numerous studies have been conducted in this regard all over the world and in Europe, the use of clean fuel appears to be the most pressing issue that must be addressed to realize the zero-emission objective. In the EU's research on alternative fuels, biofuels, methanol, LNG, LPG, and hydrogen came to the fore. However, to meet the 2050 Green Deal objectives, hydrogen stands out as the most suitable of these fuels.

In this context, this chapter aims to offer an overview of the use of hydrogen energy and fuel cells in the marine sector to reach the required environmental conditions soon within the framework of the laws proposed by the European Union under the Green Deal. Therefore, it consists of five sections. The first section contains general information on energy and sustainable energy, global warming and climate change, the influence of marine transport on environmental pollution, and laws in this sector. The second section discusses the European Union's Green Deal and the marine sector's objectives. The following section discusses hydrogen energy, hydrogen fuel cells, utilizing hydrogen energy as a marine fuel, and decreasing emissions from the maritime industry. The fourth section discusses initiatives and applications related to the development of fuel cells and their usage in the marine industry, while the last section provides a conclusion.

2 EU Green Deal and Maritime Transport

Throughout history, maritime transportation has been a resource for economic growth and wealth, as well as for commerce and communication with all European countries.

Sea trade accounts for over 90% of EU imports and exports (Commission et al. 2021). The quality of life on Europe's islands and surrounding maritime regions is directly associated with the availability of maritime transportation services. Overall, the marine sectors contribute significantly to the European economy in terms of jobs and revenue.

The marine industry is not subject to restrictions under climate change agreements, notably the 2015 Paris agreement. The first major move in this direction was taken by IMO in 2018, with the adoption of the first Greenhouse Gas Strategy for International Shipping. Annual total greenhouse gas emissions will be halved by 2050 compared to 2008, and emissions will be eliminated in the longer term.

The European Union has proposed a new roadmap for future carbon-free planning in all sectors. The European Union Green Deal (European Commission et al. 2020), which was designed to reorganize the European Union's (EU) past commitments in a broader and more effective approach in combating climate and environmental issues, is a roadmap set with the goal of making Europe the first carbon-free continent.

Transport accounts for one-quarter of EU greenhouse gas emissions, which are expanding. Figure 3 (Bodewig 2021) shows that maritime transport contributes to 13.4% of CO2 emissions produced by transportation. The EU Green Deal aims to reduce these emissions by 90% by 2050. As a milestone for the marine sector, zero-emission ships will be available for construction in 2030. The EU aims to protect Europe by enforcing highly rigorous safety laws that reduce the environmental effect of maritime trade, as well as by maintaining high shipping standards and a low risk of marine accidents.

Within the framework of the European Green Deal, the EU is focusing on the development and deployment of sustainable alternative transport fuels for all forms

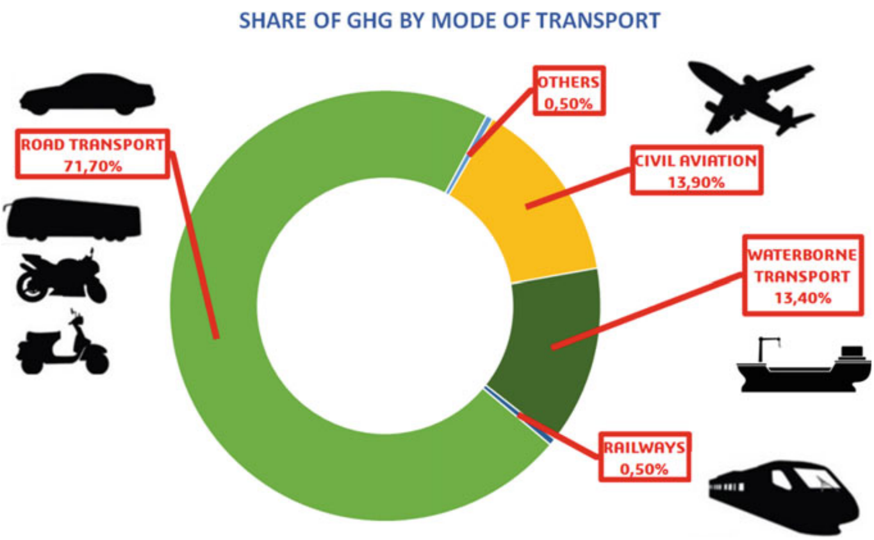

Fig. 3 Share of GHG by mode of transport (Bodewig 2021)

of transportation. It aims to explore the alternative fuels infrastructure directive and the energy taxation directive in this respect, as well as to include the marine sector in the scope of the European emission trade. As the use of alternative fuels in marine transport has some drawbacks within the range of present technology, it can only be used in a limited capacity. Larger fuel tanks are required for clean energy sources to operate aboard ships. Many alternative fuels have a low flash point (below 60 °C), which makes storage and usage hazardous (Dnv 2018).

3 Reducing Emission by Using Hydrogen in the Maritime Sector

The EU Green Deal envisions a carbon-free future for the EU. To achieve this, carbon-free fuels should be favored over the carbon-containing fossil fuels now in use. Figure 4 (Dincer and Rosen 2011) shows the major fuels utilized in the past as well as the C/H ratio. When cutting-edge research and developments on a wide range of alternative fuels are reviewed, hydrogen, ammonia, and methanol stand out as strong possibilities among the fuels now being tested aboard ships.

Fossil fuels, which fulfill the majority of the world's energy demands, are progressively depleting, resulting in severe environmental and air pollution. As an energy carrier, hydrogen can solve these issues (Bicer and Dincer 2018). As a result, substantial research and development on hydrogen energy have been conducted in recent

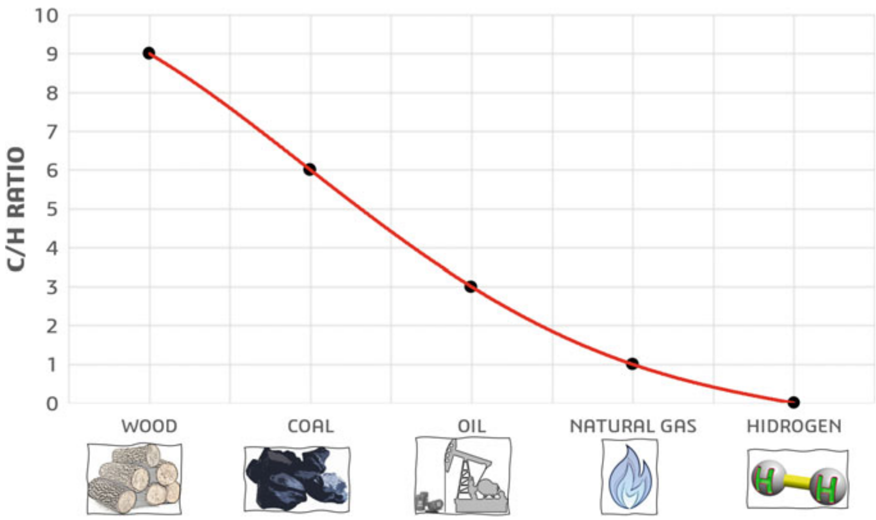

Fig. 4 C/H ratio of energy resources over centuries (Dincer and Rosen 2011)

years. Developed countries are conducting large-scale technical research and development projects in preparation for a future in which clean and renewable hydrogen energy will fulfill the world's rising energy demands (Dinçer 2008).

The transportation industry is the most major user of hydrogen fuel (cars, buses, planes, trains, and other vehicles). In space shuttles and rockets, hydrogen is still utilized as a fuel. Mobile apps (phones, computers, etc.) and built-in applications are also evaluated (backup power units, power requirement in remote locations, etc.).

3.1 Hydrogen Energy System

Recent developments in hydrogen energy point to a future in which hydrogen will replace conventional fuels, particularly in the transportation sector, a trend that has accelerated since 2010. This concept also includes the distribution infrastructure and hydrogen stations needed to transport the hydrogen from diverse production locations to points of usage.

Hydrogen can be generated using several methods and energy sources, and color code nomenclature is often used in this context. Depending on the source of production, hydrogen has color codes of green, blue, and gray. This color-code nomenclature is demonstrated in Fig. 5.

The hydrogen produced from fossil fuels is referred to as "gray hydrogen." Hydrogen can be produced from fossil fuels in two ways: steam methane reformation (SMR) or autothermal reformation (ATR) (Dinçer 2008). Hydrogen derived from fossil fuels contains a significant degree of impurities and must be purified before

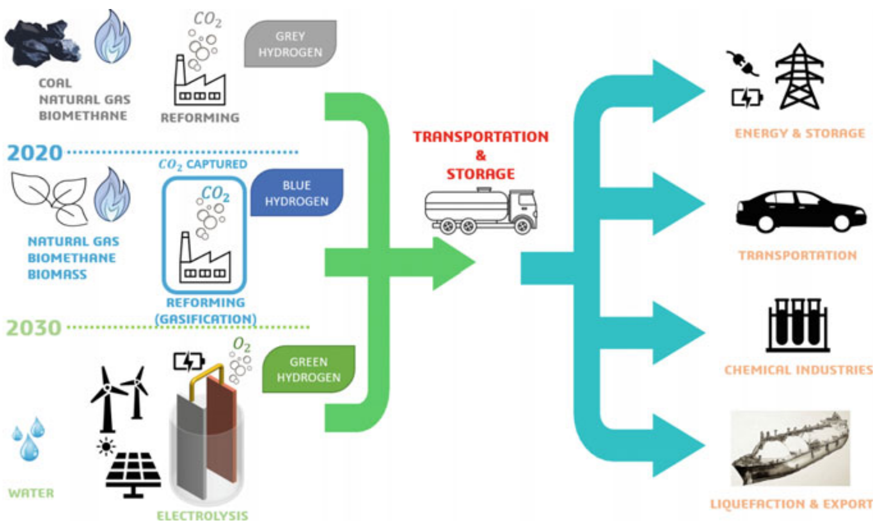

Fig. 5 Hydrogen colors (Gorny 2020)

use. Gray hydrogen releases CO_2, making such hydrogen technologies inappropriate for a path to net-zero emissions.

Blue hydrogen is generated in the same way as gray hydrogen is. However, the goal here is to use Carbon Capture and Storage (CCS) technology to capture and store emissions. However, this technique only allows for the collection of low-level pollutants. In the long run, it does not appear practical to decarbonize the industrial sector with SMR without CCS (Renssen 2020). Natural gas accounts for around 80% of hydrogen production (Salkuyeh et al. 2017). However, the distribution of blue hydrogen has drawbacks such as restricted resource usage, susceptibility to fluctuating fossil fuel prices, and failure to fulfill energy security requirements. Furthermore, blue hydrogen confronts societal acceptability challenges since it incurs additional expenses for CO_2 delivery and storage and necessitates monitoring of stored CO2. Moreover, CCS capture efficiency is estimated to be 85–95% at most, implying that 5–15% of CO2 is still released (Antonini et al. 2020). To summarize, CCS can reduce, but not eliminate, carbon emissions from hydrogen generation. Additionally, these activities require methane, which is a considerably stronger greenhouse gas (GHG) per molecule than CO2. This suggests that while blue hydrogen can reduce CO2 emissions, it does not fulfill the net-zero future criteria. For these reasons, blue hydrogen can only be viewed as a short-term transition to let green hydrogen flourish on the path to net-zero emissions. This, however, makes the procedure extremely complex and costly. SMR with CCS is currently not an industry practice, according to many experts, and does not contribute to commercial growth.

Water electrolysis can also be used to generate hydrogen. If the electric current is generated by a renewable source (such as a solar panel or a wind turbine), the clean hydrogen produced is considered green. During the generation of hydrogen using renewable energy, no hazardous gases are discharged into the atmosphere (Dinçer 2012).

Green hydrogen currently has a few disadvantages that must be overcome. The cost is the most crucial of these. Renewable energy, which is essential for producing green hydrogen via electrolysis, is more expensive to generate, making it more expensive to get (Dincer and Acar 2015). However, the manufacturing of hydrogen in general, and green hydrogen in particular, takes more energy than the production of other fuels. Finally, one of its primary drawbacks is that hydrogen is very volatile and flammable (Hord 1978), requiring extensive safety precautions to prevent leaks and explosions.

Green hydrogen offers advantages as well as drawbacks. Green hydrogen is completely sustainable since it releases no pollutants during combustion or manufacturing. Therefore, hydrogen is simple to store and this enables it to be utilized for various purposes after manufacturing. Compressed hydrogen tanks can store energy for an extended period. It is also more convenient to use than lithium-ion batteries because it is lighter. It is flexible since it can be turned into power or synthetic gas and utilized for household, commercial, industrial, or transportation applications (Midilli et al. 2005). It can be transported at a rate of up to 20% of that of natural gas and can use existing natural gas infrastructure. Increasing this percentage will need the modification of many aspects in current gas infrastructures to make them suitable.

3.2 Hydrogen as a Marine Fuel

Applications that combine renewable energy and hydrogen are considered essential for the marine industry to accomplish the objectives under the EU Green Deal. Although batteries powered by electrical energy can be utilized for short-distance cruises, hydrogen is required for long-distance cruises (McKinlay et al. 2020). Because battery and battery system development is insufficient to fulfill the system's demands. However, in today's technical environment, it is not possible to acquire all of the power a ship will require for long-distance cruises with hydrogen. Thus, battery and battery system development is insufficient to fulfill the system's demands. In this context, it is intended for ships all over the world to employ combustion engines that run on hydrogen and have batteries consisting of hydrogen cells (Dnv 2018).

3.3 The Base of Hydrogen Technologies: Fuel Cells

Fuel cells are electrochemical devices that transform the chemical energy in fuels into electrical energy. Fuel cells are made up of an electrolyte with ionic conductivity, as well as an anode and cathode where various reactions occur (O'hayre et al. 2016). Fuel cells, like batteries, are electrochemical cells; however, there are notable distinctions. The most distinguishing characteristic between fuel cells and batteries is that fuel must be supplied continually from outside. While traditional batteries serve as "energy storage devices," fuel cells (batteries) serve as energy generation/conversion systems (Winter and Broad 2004). Fuel cells have a high potential for energy generation since they generate electricity from hydrogen (Ehteshami and Chan 2014). As far as power generation capacity is considered, fuel cells can be manufactured in a variety of sizes. Because of their extensive usage and application possibilities, from automobiles to home and industrial applications, they must be built in a variety of sizes (Edwards et al. 2008). As a result, these systems may be developed with capacities able to produce enough electricity to fulfill the demands of mobile phones or a city.

Fuel cells are a type of energy technology that is clean, sustainable, and efficient. The water electrolysis experiment may simply explain the functioning mechanism of fuel cells. Water is separated into hydrogen and oxygen in the water electrolysis experiment by passing a direct current across it. In fuel cells, the reverse process is carried out (Ogawa et al. 2018). In other words, during water dissolution, electrical current is applied and water separation occurs, while electrical energy is obtained as a result of the interaction of hydrogen and oxygen. As seen in Fig. 6, the fuel cell transforms the energy of the fuel directly into electrical energy via an electrochemical process.

Fuel cells, which are limitless and never need to be recharged, use electrochemistry to transform the energy of the fuel directly into electrical energy. The fuel cells operate as a continuous battery when the anode provides fuelling and cathode oxidation. This

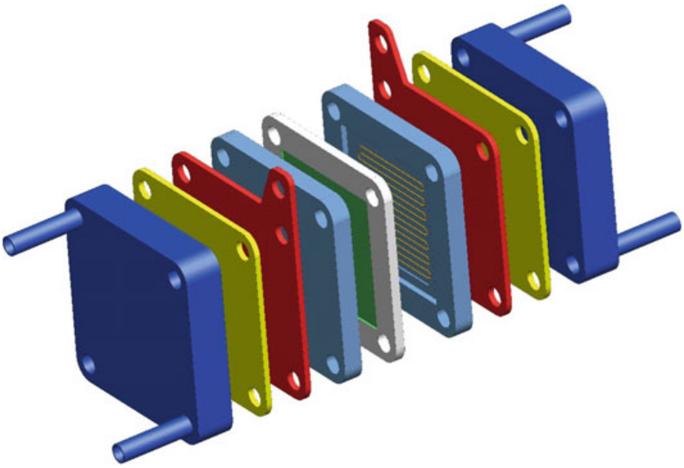

Fig. 6 Fuel cell (Hortal and Miranda 2005)

gains to it, as quiet and unmoving as a battery. It varies from the battery, however, in two respects. It contains no harmful chemicals and can be recycled without polluting the environment. Therefore, it is utilized as a source of energy.

The fuel cell requires hydrogen–oxygen or hydrogen-air to operate (Cook 2002). Temperature, heat, water vapor, and electric current from the flow of electrons from the anode to the cathode are by-products of this electrochemical process due to the great efficiency in fuel usage, as illustrated in Fig. 7 (Abdalla et al. 2018). Fuel cells obtain their energy from actual combustion first. They transform this energy

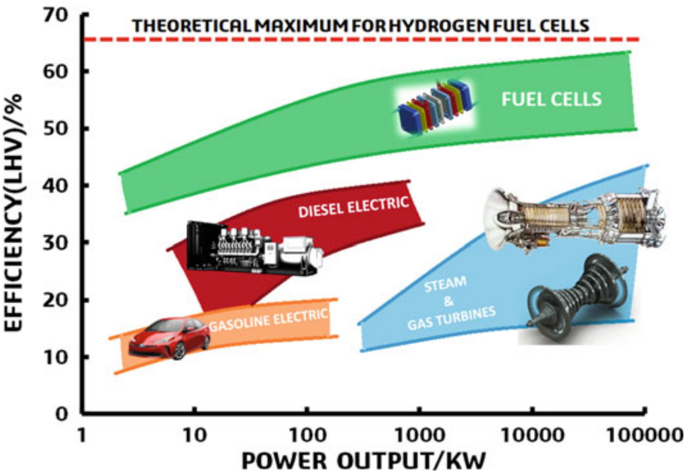

Fig. 7 Comparison of the efficiency achieved with the output power of different fuel sources (Abdalla et al. 2018)

into mechanical (motion) energy using the turbine. Finally, they use a dynamo to transform mechanical energy into electrical energy. Fuel cells; By chemically mixing the fuel and the oxidizing agent without burning, it minimizes energy losses in conventional combustion and does not pollute the environment.

3.4 Hydrogen Fuel Cell Types

Fuel cells, which are still under development, are one of the most investigated energy technologies. Even at this beginning period, a broad range of fuel cell types have been developed. These various fuel cells differ in terms of use, economic value, and market potential. In terms of application and commercial potential, some fuel cells are more beneficial than others. In any case, the fuel cells themselves have a considerable diversity. Polymer electrolyte membrane fuel cells (PEMFC), Direct methanol fuel cells (DMFC), Alkaline fuel cells (AFC), Phosphoric acid fuel cells (PAFC), Molten carbonate fuel cells (MCFC), and Solid oxide fuel cells (SOFC) are the most often investigated fuel cells nowadays (Evrin and Dincer 2019). The method fuel is delivered to the fuel cell and the operating temperature of the fuel cell varies across different types of fuel cells. Figure 8 shows a high-level overview of various types of fuel cell technology.

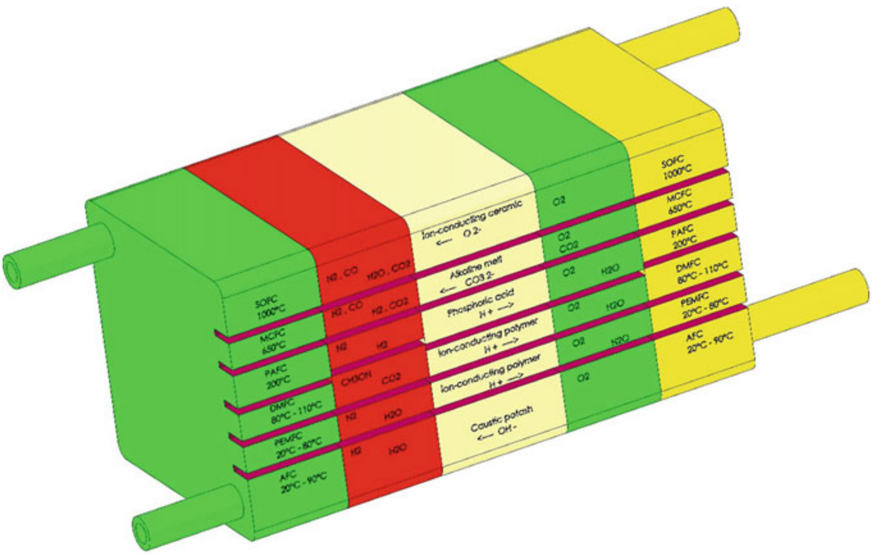

Fig. 8 Overview of the various types of fuel cell technology (Benz et al. 2003)

3.4.1 Alkaline Fuel Cells (AFC)

The research on alkaline fuel cells done by Francis Thomas Bacon is regarded to be the most important study that has brought the fuel cell to its current position. The Pratt and Whitney firm, which recognizes the significance of this innovation, licensed it and allowed it to be utilized in NASA projects. Alkaline fuel cells were one of the earliest fuel cell technologies to be invented, and they were also the first form of fuel cell utilized by NASA in spacecraft (Yılmaz et al. 2017).

The efficiency of a fuel cell can reach up to 70% while operating at temperatures ranging from 20 to 90 °C. Ni catalysts are utilized in the anode of the alkali fuel cell, whereas Ag catalysts are used in the cathode. For this reason, power generation is limited, which is a disadvantage. The oxidizing capabilities of the components in the alkaline fuel cell's body are relatively sensitive to the carbon dioxide in the fuel. Because carbon dioxide mixes with potassium hydroxide in the electrolyte owing to its chemical property, a chemical reaction ensues that consumes the electrolyte and negatively affects the electrodes through which the current flows more than necessary (Andújar and Segura 2009). The usage of pure hydrogen and oxygen is required in this circumstance therefore, it is not often used in the marine industry or on ships.

3.4.2 Polymer Electrolyte Membrane Fuel Cells (PEMFC)

In terms of design and function, the proton exchange membrane fuel cell (PEM) is the most elegant. It was initially developed for spacecraft in the 1960s by PEM General Electric. A solid polymer electrolyte membrane is sandwiched between two platinum-catalyzed porous electrolytes in this case. A fuel cell is another name for a polymer electrolyte membrane (membrane). When compared to other fuel cells, it has a higher power density, a smaller volume, and lighter weight. The electrolyte in the fuel cell is a thin polymer membrane. The proton-permeable membrane has a thickness of microns. Operating temperatures are usually in the 60–80 °C range (Gasteiger and Yan 2004), and are less than 100 °C. The use of noble metals (often platinum) as a catalyst raises the price. The high carbon monoxide sensitivity of platinum catalysts requires the separation of any carbon dioxide contained in the fuel which adds to the processing and cost. To address this issue, several designs employ platinum/ruthenium catalysts with extremely low carbon monoxide sensitivity.

The European Maritime Safety Agency (EMSA) investigated 23 ships utilizing fuel cells in its report on the deployment of fuel cells in ships. It was discovered that 15 of these ships employed PEM fuel cells. PEM fuel cells are favored in the marine industry because of their smaller size, high efficiency, minimal maintenance costs, and extended life (Tronstad et al. 2017).

3.4.3 Direct Methanol Fuel Cells (DMFC)

When hydrogen is used directly in fuel cells, very high efficiencies are attained. However, due to hydrogen's extremely low volumetric energy density, it is difficult to use this gas in tiny electronic devices (Kamarudin et al. 2009). Hydrogen, despite its great energy density, is difficult to store. Due to its high liquid state under air circumstances and high volumetric energy density, methanol has an advantage over hydrogen and expands the application fields of fuel cells (Adamson and Pearson 2000). The Direct Methanol Fed Fuel Cell is a type of proton exchange membrane fuel cell. The most important feature that separates this fuel cell type from others is that it uses liquid methanol as fuel. The following are the benefits of using this fuel: Storage is simple, the cost is low, and the energy density is great. Aside from these benefits, the high cost of key components, such as catalysts, is the most major obstacle to the commercialization of DMFC. Other drawbacks of the methanol transition and the slow rate of methanol oxidation in the anode, in addition to its high cost, include low power density and electrical efficiency (Hamnett 2010). The working temperature of DMFC is between 80 and 110 °C, and it is primarily utilized in electrical equipment. DMFC is not utilized to meet the ship's energy requirements.

3.4.4 Phosphoric Acid Fuel Cells (PAFC)

In a phosphoric acid fuel cell, phosphoric acid is used as an electrolyte and in the early 1990s, these fuel cells were commercially accessible (Lee 2021). These types of fuel cells are more suited for stationary power generation systems in which electrodes, porous carbon electrodes with a platinum catalyst layer are employed. When compared to other types of fuel cells, the efficiency of electricity generation in phosphoric acid fuel cells is lower. At low temperatures, phosphoric acid has a lower conductivity. As a result, these systems should be run at high temperatures. One of the most significant issues reducing efficiency is CO poisoning of the Pt catalyst in the anode. The slow kinetics of the oxygen reduction process have an impact on the performance of these fuel cells. When compared to acid electrolytes, this kinetics is faster in alkaline electrolytes (Sammes et al. 2004). Although PAFC is one of the fuel cells used in ships, its utilization rate is lower than that of other fuel cells due to its disadvantage in terms of a lifetime when compared to other fuel cells.

3.4.5 Molten Carbonate Fuel Cells (MCFC)

This type of fuel cell's electrolyte is made up of a mixture of lithium, sodium, and potassium carbonates. Natural gas whose operating temperature is around 650 °C, is mostly utilized as a fuel and is favored in power plants, industrial applications, and military purposes (Dicks 2004). Because the ionic conductivity of the high-temperature electrolyte is quite high, noble metals are required as catalysts Under normal conditions, their efficiency is approximately 60%, but in the case of cogenerative applications, it can reach up to 80%. The absence of an external fuel processor, which is necessary for conventional fuel cells, is an important feature of the molten carbonate fuel cell. Because of the high operating temperature, fuels can be converted into hydrogen via the cell's internal fuel conversion mechanism. This has a beneficial impact on processes and costs. The combination of carbon monoxide and carbon dioxide in the fuel does not affect the performance of a molten carbonate fuel cell. The most significant drawbacks are their insecurity. Operating at high temperatures reduces fuel cell life due to performance degradation caused by corrosive electrolytes and corrosion formation (Randström et al. 2006). Although the usage of traditional marine fuels makes MCFCs appealing for maritime applications, SOFC and PEMFC are expected to be used for the carbon-free future envisioned by the EU Green Deal.

3.4.6 Solid Oxide Fuel Cells (SOFC)

SOFCs with ceramic electrolytes are a type of fuel cell that can function at extremely high temperatures, such as 1000 °C. Evaporation and electrolyte leakage do not occur since the electrolyte used in the fuel cell with an efficiency of up to 60% is solid. As a result, an issue like the completion of the depleted electrolyte never happens (Brandon et al. 2013). They are utilized in applications that require a huge amount of power, such as continuous power and heat generating. Furthermore, SOFC is used in the transportation industry to produce supplementary power in commercial vehicles, as well as in military projects, night vision equipment, global positioning systems, and target determiners (Singhal 2002).

SOFCs offer greater energy production efficiency, easier industrial application, higher mechanical strength and thermal stability of the ceramic cell employed as a solid electrolyte, more industrial application areas, and so on. Because of their characteristics, SOFCs have a wide range of applications. Nevertheless, when considering industrial applications in other nations, it is clear that the usage of SOFC type cells, rather than all fuel cell cells, is more common, particularly in power production facilities. For all of these reasons, SOFCs are also being used in the marine sector. However, with today's technology, SOFCs are not only made using clean fuels but also use fossil fuels. As a consequence, the EU is no longer well-positioned to achieve the Green Deal's objectives.

4 Fuel Cell Projects in Shipping

Fuel cell technologies were first used in the marine industry in the early 2000s. The first ship built in this area is the small passenger transport boat "Hydra" built-in Germany (Xing et al. 2021). The Hydra ship is especially significant since it is approved by Germanischer Lloyd. The use of fuel cells in the marine industry, which began with Hydra, was expanded for use in short-distance passenger transportation

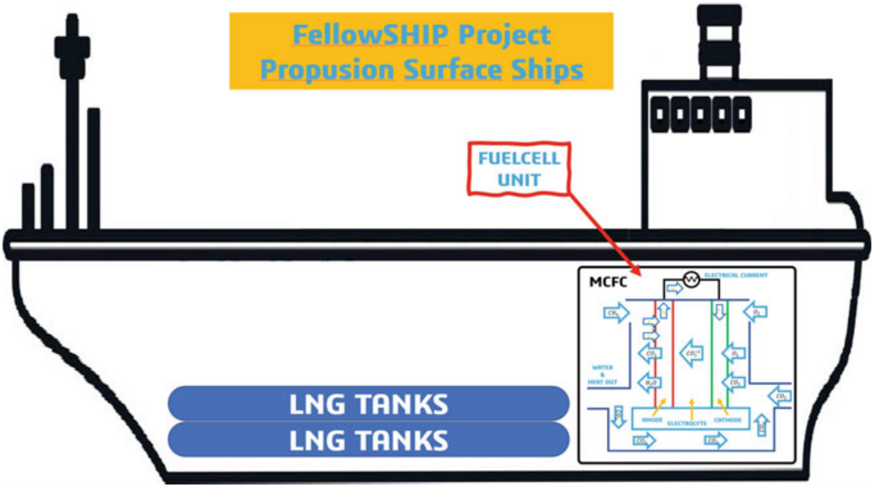

Fig. 9 Viking lady prototype (Winkler 2010)

in other European nations. In 2006, the German military built a hydrogen fuel cell submarine for the first time, elevating the work done in this field to a new level.

Under the leadership of Europe, Norway, and Germany, the FellowSHIP project was launched in 2003 to investigate the application of battery, hybrid, and fuel cell technologies in the marine sector. This project also resulted in the development of classification standards, with DNV establishing the first worldwide classification rule in this sector (Dnv 2018).

The first fuel cell developed as part of the FellowSHIP project was installed aboard the ship Viking Lady, which was built in Turkey's Torlak Shipyard, and the learning phase was carried out by executing the project (de-Troya Jet al. 2016). However, the fact that the Viking Lady's LNG-powered fuel cells represent an important step toward a carbon-free future is inadequate. Figure 9 (Winkler 2010) is a prototype image of the Viking Lady utilizing MCFC and SOFC developed by the German company MTU.

The E4Ships project is another German project involving the use of fuel cells in other ships. The German government is financially supporting this project as part of the hydrogen and fuel cell innovation program. Two separate fuel cells were placed on two different ships as part of the experiment. A 100 kW PEMFC powered by methanol was installed aboard Viking Line's MS Mariella, while a 60 kW diesel fuel SOFC was installed on the MS Forester cargo ship (Dnv 2018).

The FCSHIP project was started by the EU as part of the framework programs (FP 5) for research and technical development (Meek-Hansen 2002). The NEW-H-SHIP project, which was established later, used this project's knowledge to identify technological hurdles (demonstrative barriers) for fuel cell and hydrogen aboard ships. The route to hydrogen propulsion aboard ships will be charted, and recommendations for future research and development will be made by creating a reference list of fuel

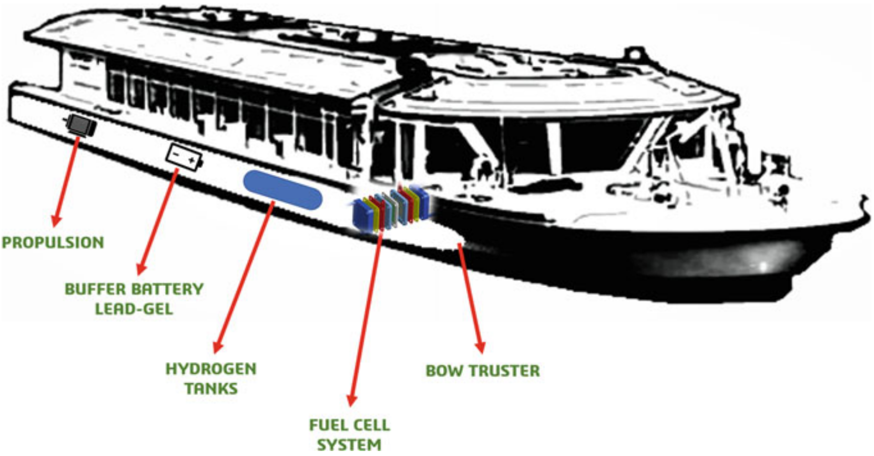

Fig. 10 FCS Alsterwasser (Schneider and Dirk 2010)

cell and hydrogen research and development efforts. The project was launched to find prospective European partners and supporting European initiatives in the field of hydrogen and fuel cells in marine applications (Dall'Armi et al. 2021).

At the end of this project, it was discovered that hydrogen storage is the most difficult problem in ships used for international transportation, although fuel cells can be utilized for short-distance and inland transportation. Another emerging issue is the infrastructure for bunkering. Furthermore, one of the benefits is the requirement for worldwide class regulation.

The zero-emission ship (Zemship) project was established in 2006 to utilize hydrogen energy in a passenger ship for passenger transportation on the Alster river in Hamburg, Germany. 100 kW of PEMFC were developed and used in this project, which was funded by the European Union. This research was carried out on FCS Alsterwasser, as illustrated in Fig. 10 (Schneider and Dirk 2010).

The FELICITAS project was one of several fuel cell research and development projects conducted in Europe between 2005 and 2008 (Dnv 2018). This project was created to conduct research and development on fuel cells that can be utilized not only in maritime transportation but also in road and rail transportation. The project is divided into four parts, with the first focusing on the needs and theoretical research of the application of fuel cells to heavy vehicles. The focus in the second phase was on meeting the demands for Auxiliary Power Unit (APU) with 250 kW SOFC in the marine industry. PEMFC was used in the third stage to evaluate its applicability in all heavy transport industries. The most forward-thinking research at FELICITAS was focused on directly connecting SOFC and PEMFC systems by combining the advantages of SOFC and PEMFC technologies. This technique, which focuses on the fourth phase, can be defined as a particular reform technology for the PEMFC masses. The utilization of not just pure hydrogen but also various hydrocarbon-based fuels in most heavy-duty applications is a precondition for FELICITAS' major research

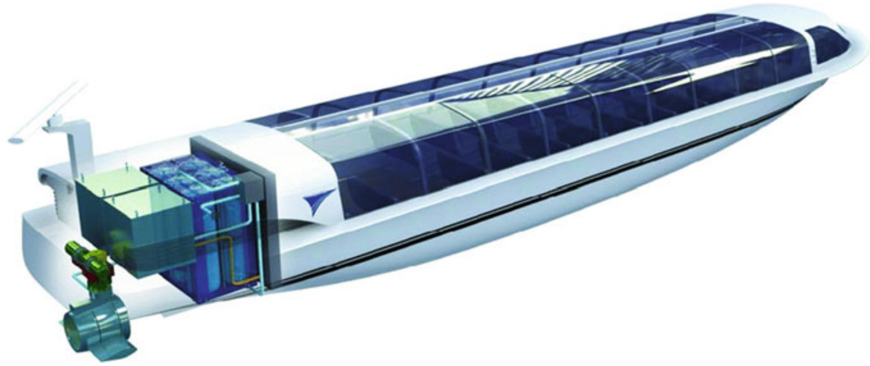

Fig. 11 Fuel cell boat NEMO H2 (Chakraborty et al. 2013)

subject. The primary objective of FELICITAS was to develop fuel cell drive trains for road, rail, and marine applications that can meet the needs of heavy-duty transport.

However, neither the produced SOFC nor the developed PEMFC was sufficient for the main propulsion system of road-rail and marine vehicles in the studies. But, it is understood that the SOFC technology can be modernized and used in the maritime sector (Commission 2017).

Holland participated engaged in hydrogen fuel cell project development in 2009. On cruises utilizing PEMFC with 60 KW electricity, Nemo H2 can travel for roughly 9 h at a speed of 9 knots. With an estimated 125 trips per day on Amsterdam's canals, it was hoped to expand the number of passenger ships by generating a budget for fuel cell research and development in the marine industry by charging 50 euros extra each trip on Nemo H2 cruises (Chakraborty et al. 2013) (Fig. 11).

Hydrogenesis was developed as a proof-of-concept model to demonstrate the availability of hydrogen fuel cell technology. The vessel serves as the foundation for long-term hydrogen fuel cell-powered activities in Bristol's harbor. Hydrogenesis can travel with 12 guests and 2 crew members utilizing 12 kW of PEMFC (Dnv 2018). Today, after the EU Green Deal, a European hydrogen strategy has been developed, and efforts have been made to reduce emissions in the marine industry, particularly in domestic transportation.

5 Result and Conclusions

Almost the majority of the energy used in the marine sector today comes from fossil fuels. The marine sector's energy demand is rapidly growing in direct proportion to population expansion, industrialization, and new demands portfolio. On the other hand, there has been no increase in fossil resources, which are the primary energy source in today's world; in other words, we are approaching a point when supplies are insufficient to satisfy demand. Furthermore, the fossil fuels utilized send hazardous emissions into the environment, contributing to global warming and climate change. The EU Green Deal aims to achieve a zero-emission objective by 2050 in the context of combatting global warming and climate change. All of these factors need the development of new energy sources in Europe's marine sector. It is also critical that these energy sources be innovative, renewable, clean, and long-lasting. In conclusion, hydrogen is extremely appealing among alternative energy sources due to its current global potential, recyclability, reliability, and availability, as well as qualities such as not causing environmental concerns. However, several issues, including production costs, storage issues, and explosion, restrict its application.

Hydrogen fuel cells are regarded as one of the most promising technologies for reducing and eliminating greenhouse gas emissions in the maritime industry. The usage of fuel cells and hydrogen energy in the marine industry following the EU Green Deal goals in the context of mitigating global warming and climate change is investigated in this chapter. To meet the EU Green Deal targets, hydrogen must be utilized directly as fuel or in the primary propulsion system of ships, with hydrogen obtained from renewable sources. Although fuel cells have been developed by consortiums organized in various European nations since the early 2000s, no fuel cell has been produced to fulfill the energy demands of ships involved in long-distance transport. As a consequence, in terms of meeting the 2030 EU Green Deal objectives, hydrogen for fuel cells must be produced from lower-emission fuels, and fuel cell technologies must be developed. After 2030, to meet the EU Green Deal's zero-emission objective in all sectors, hydrogen must be utilized directly or green hydrogen must be used in fuel cells used in the marine sector.

Three fuel cells stand out when the fuel cells used in ships are evaluated. There are three of them: DMFC, SOFC, and PEMFC. Only PEMFC use hydrogen as the primary fuel in their fuel cells. Recent studies in the marine industry show that SOFC and PEMFC fuel cells are preferred due to their high energy output. Although PEMFC stands out due to its ability to use hydrogen as the primary fuel and its capacity to fulfill high energy demands, it is thought that improving it by combining it with the advantages of other fuel cells can help the EU accomplish the Green Deal 2050 objective.

To become the first carbon-free continent under the EU Green Deal, Europe must take a comprehensive strategy that considers the role of the entire marine cluster, including fixtures, ports, and energy suppliers. For hydrogen to be used in the maritime sector and aboard ships, all leading companies, including fuel providers and marine operations, must collaborate. One of the critical shortcomings that must be addressed is the establishment of a fuel standard as a requirement for fuel providers, in addition to the emission limits imposed on the marine sector and ships. Following this, it is important to establish a standardization of hydrogens such as conventional fuels and LNG by overcoming the inadequacies in transportation, storage, bunkering, and security on a global scale. It is also critical to develop and make worldwide accepted class regulations for the use of fuel cells aboard ships.

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Biomass Value—Production of H_2 as an Energy Carrier

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1 Introduction

The advancements of human life, the expansion of the global economy, population growth, industrialization, and urbanization have all resulted in a rise in energy demand. As a modern world necessity, one of our most basic needs is to be able to produce sufficient energy to utilize in our daily lives. Today, approximately 81.4% of

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the primary energy needs in the world are compensated through fossil fuels whereas biomass accounts for only 9.7% of total energy demand. Energy production using fossil fuel resources has led to serious environmental problems such as air pollution and global warming. Thus, the economic and environmental consequences of using fossil fuels in energy production are tremendous. As a result, renewable energy sources are becoming more popular as an alternative. For example, biofuels obtained from biomass, have been used as a transportation fuel in large-scale applications (Safarian et al. 2019; Sahin et al. 2020).

Environmental concerns and the need for environmental-friendly means of energy production forced mankind towards fossil fuel-independent alternatives. Hydrogen is a viable energy source for the clean production of power and heat from a wide range of sources (Acar and Dincer 2014). Furthermore, as a sustainable energy source with minimum or zero use of hydrocarbons and high-energy yield (122 MJ/kg), hydrogen is a promising alternative to fossil fuels (Rifkin 2002).

The transportation industry accounts for 20% of all carbon emissions. As a result, alternative fuels and the utilization of renewable energies have become vital to address the environmental issues that this industry has produced. Hydrogen is closely linked to the transport and fuel industry and can be used as a "clean" fuel. Apart from this, it can be used in crude oil refining, ammonia production, and methanol production. It is predicted that by 2050, hydrogen production will increase with a growth of approximately 10%, marking significant changes in the hydrogen market (Lepage et al. 2021).

Hydrogen is a synthetic fuel that can be produced from various raw materials such as, fossil fuels, water, biomass, and bio-waste. Hydrogen is an important energy carrier that can be stored easily. It is considered a clean and intensive energy source that can be produced via clean processes that do not harm the environment. The production of hydrogen energy is the cleanest among alternative energy sources and produces water as the only combustion by-product, which enables it to truly achieve "zero-emission" of pollutants (Li et al. 2018; Yiin et al. 2018). Hydrogen has higher calorific value than conventional fossil fuels (Acar and Dincer 2018). Thus, due to its cleanliness, abundance, and environmentally friendly nature it can serve as an ideal candidate to replace fossil fuels in the future. It is crucial to use clean energy and material for the generation of hydrogen. Various clean and continuous energy sources can be utilized for hydrogen production, such as solar, hydro, wind, ocean, and biomass. Several methods can be used for its production, such as biological, electrical, photonic, and thermal (Acar and Dincer 2019; Aydin et al. 2021).

Biomass is a renewable, sustainable energy source that offers a substantial reduction in pollution compared to fossil fuel resources. For example, hydrogen production utilizing biomass sources has lower carbon dioxide emissions compared to fossil fuel-based hydrogen production. The conversion of biomass to energy is generally carried out by thermochemical and biochemical methods (Ren et al. 2020). Biomass has a lot of potential as a source of hydrogen, which could be the energy of the future. Hydrogen can be produced from different types of biomass using different processes. The production methods of hydrogen from biomass are; combustion, pyrolysis, gasification, anaerobic digestion, biomethanization, and fermentation. The incorporation of H_2 energy into the energy sector is environmentally advantageous and hydrogen production can take place in sustainable ways.

Research on hydrogen production from biomass is increasing day by day. Although studies on hydrogen production from biomass seem to focus more on thermal processes (Peng et al. 2017; Hamad et al. 2016; Li et al. 2019; AlNouss et al. 2020), hydrogen production using biochemical methods are also the focus of research (Kumar et al. 2018; Safari and Dincer 2019; Basak et al. 2020). In biochemical processes such as fermentation, biomass is converted into biofuels by the breakdown of living organisms. However, in thermochemical processes biomass is converted into biofuels, gases, and chemicals by applying heat and /or pressure. Thermochemical methods can economically transform more biomass types compared to biochemical methods (Safarian et al. 2019).

This study extensively investigates the techniques used in hydrogen production from biomass. It highlights the current approaches, related methods, technologies, and resources being adopted for hydrogen production. Thermochemical and biochemical methods used in the production of hydrogen from biomass have been extensively discussed in light of the current research trend and the latest emerging technologies. The effects of important factors and parameters on hydrogen yield have also been extensively investigated. The literature confirms that the hydrogen obtained from biomass has high energy efficiency and the potential to reduce greenhouse gases and therefore deserves versatile applications in the upcoming period. It has been determined that hydrogen can be a sustainable strategic alternative to fossil fuels, especially in the field of land and air transportations. Thus, the focus of the research would be on hydrogen production from biomass, and this chapter overviews the thermochemical and biochemical methods used for the transition of biomass to hydrogen. Advantages, disadvantages, and important improvements of each process are also presented.

2 Biomass

Wood, agricultural product wastes and by-product, animal wastes, municipal solid wastes, sewage sludge from wastewater treatment plants, wastes from food processing, aquatic plants, and algae are the most important sources of biomass (Karabag et al. 2021). Biomass includes agricultural or forestry products and is composed of materials that can all or partially be used to recover energy and utilized as fuel. Biomass is considered a strategic energy source because it contributes to environmental protection, can be used for electricity production, chemicals, and especially fuel for vehicles. Biomass resources can be classified as forest wastes, sawdust wastes, chemical recovery fuels, agricultural wastes, city trees and green space wastes, energy forests, and energy crops (Ren et al. 2020; Tolay and Waterschoot 2018).

Biomass can be defined as “recent organic matter originally derived from plants as a result of the photosynthetic conversion process, or from animals, to be utilized as chemical energy to provide heat, electricity, or fuel for vehicles" (Ruggeri et al. 2015).

It is expected that chemical and fuel production of biomass and bioenergy will play a vital role in the future of the global energy scenario for heat and power generation. In recent years, bioenergy has received special attention with decreasing fossil fuel resources and increasing environmental concerns. In addition, bioenergy falls among the energy resources that make the most important contribution to the global renewable energy supply and contributes to poverty reduction in developing countries. Bioenergy can provide the necessary energy without expensive processes, complex energy conversion, and its environmentally friendly at all times. Hence, it is considered the best alternative fuel available that can supply energy requirements of the future (Sahin et al. 2020; Hosseini et al. 2015; Avcıoğlu et al. 2019).

3 Hydrogen Production Methods from Biomass

Hydrogen is one of the simplest and most abundant elements in nature that can be produced from many substances such as coal, biomass, and water. Hydrogen gas can be obtained from both renewable energy sources and fossil fuels. The preferred method for hydrogen production determines whether the energy released is environmentally friendly (Acar and Dincer 2015).

Energy obtained from biomass fuels is called biomass energy. This type of energy does not harm the environment, can be regenerated quickly, and is a safe energy source that can be used for a long time (Tolay and Waterschoot 2018). Hydrogen can be produced from different biomass types such as animal, forestry, industrial and municipal waste, agricultural and industrial products. Gasification technology, thermochemical and biochemical processes, are commonly used technologies to produce biomass hydrogen (Acar and Dincer 2015). The incorporation of H_2 energy into the energy sector is environmentally advantageous and hydrogen production can take place in sustainable ways. Generating hydrogen energy from biomass is one of these sustainable ways. Hydrogen, as an alternative energy source, has the advantage of reducing greenhouse gas emissions.

3.1 Thermochemical Methods

There are three main thermochemical biomass conversion technologies for hydrogen production from biomass. These technologies are combustion, pyrolysis, and gasification.

3.1.1 Combustion

Vegetables, animals, or organic materials containing carbon are called biomass, and biomass resources are classified as vegetable waste, animal waste, urban, and industrial waste. Energy can be obtained by burning biomass (Acar and Dincer 2015). Biomass releases the energy it stores during the combustion process. The combustion process is a traditionally used process that can generate heat and electricity but can also generate large amounts of pollutant emissions (Ren et al. 2020). Energy production by burning organic materials is almost as old as human history. The combustion of organic substances can be defined as the chemical reaction of oxygen with flammable elements. Since high amounts of oxygen are used during combustion, fly ash, metal oxides, particulate matter, and emissions that are difficult to control such as SO_x, NO_x, CO occur in high quantity (Varank et al. 2021). Hydrogen production by the combustion process can provide high efficiency compared to other clean technologies, but it is not an environmentally friendly technology (Safarian et al. 2019). The combustion process is the chemical reaction of organic materials with oxygen, resulting in oxidized components, flame, and heat. Combustion is carried out for hygienic disposal of waste, reduction of waste volume, and energy generation.

The advantages and disadvantages of the combustion process are given in Table 1.

As indicated in Table 10, energy production by biomass combustion has high efficiency. However, serious pollution occurs with the combustion of biomass. For this reason, it is important to turn to cleaner technologies for the production of hydrogen (Ren et al. 2020).

Energy production by directly burning biomass is one of the oldest known methods. Biomass is an environmentally friendly renewable energy source with low ash and sulfur content. In addition, NOx, SOx, and polyaromatic hydrocarbon emissions during biomass combustion are lower when compared to emissions generated by burning conventional fuels. The energy obtained by burning biomass can be used to generate heat and electricity. Plant efficiency varies between 20 and 40% (Birinci 2019). Wastes from incineration such as ash can be disposed of through melting and solidification, chemical stabilization, and extraction using acids or other solvents.

Table 1 Combustion process advantages and disadvantages

Advantages	Disadvantages
It can generate energy from a wide variety of waste It provides high yield product Organic matter turns into gas and ash in a short time 70–80% by volume and 60–70% by weight are reduced Waste disinfection is provided hygienically Heat energy is used	A high amount of pollutant emissions occur The initial investment and operating costs are high The ash and slag formed are non-biodegradable Inorganic compounds in ash and slag can reach the receiving environment In the case of complete combustion, it may occur in malodorous organic substances

Another method of disposal is to melt at very high temperatures and to solidify by cooling it. Solid wastes from incineration can be laid on the roads as paving stones and used in the improvement of land areas.

3.1.2 Pyrolysis

Numerous methods for producing hydrogen from biomass exist. Pyrolysis is a well-established, old technology used for the production of energy from biomass. Over time, with significant improvements in terms of reactor material, design, operating conditions, and catalyst type it has become one of the advanced technologies used for hydrogen production, (Hosseini et al. 2015; Bridgewater 2004; Pandey et al. 2019). Generally, pyrolysis is the heating of organic/carbonaceous material such as solid biomass in the absence of oxygen or air to convert organic material to liquid fuels, solid coals, and gaseous compounds (Yang et al. 2006). There is no polluting combustion process and it is used to generate both electricity and heat (Kothari et al. 2005; Mueller-Langer et al. 2007). There are several benefits of biomass conversion using the pyrolysis method, such as fewer emissions and reusability of all by-products. Thermochemical processes such as pyrolysis are being studied in detail to determine process performance with different parameters such as cost, energy/energy efficiency, and even life cycle for more than 10 years (Udomsirichakorn et al. 2014; Tock and Maréchal 2012; Cohce et al. 2010; Spath et al. 2003; Abuadala et al. 2010; Carpentieri et al. 2005; Peduzzi et al. 2013; Arena et al. 2015).

The general pyrolysis process of biomass can be considered to consist of the decomposition of polymer chains in biomass macromolecules to produce condensable volatiles (bio-oil), non-condensable gases, and biochar by external heat under an inert atmosphere (Wang et al. 2017; Chintala 2018; Leng et al. 2018). Pyrolysis itself has a wide range of applications and is mostly used to produce liquid fuel. In addition, solid or carbonized products and a gas mixture consisting mainly of CO_2, CO, H_2, and CH_4 are produced during the process (Saletnik et al. 2018; Chaloupková et al. 2018). Pyrolysis requires temperatures up to 400–550 °C, but can also be done at higher temperatures (Uddin et al. 2018). The results of biomass pyrolysis depend largely on the reaction conditions. According to these conditions, pyrolysis can be divided into subcategories; such as slow pyrolysis, fast pyrolysis, and flash pyrolysis. In the slow pyrolysis process, low heating rate and long residence time operating parameters are applied to obtain biochar as the primary product (Kan et al. 2016). At the same time, gas and liquid fuels also emerge as by-products. Fast pyrolysis is of great interest for bio-oil production from biomass. Bio-oil can be produced in a short time (0.5–10 s) by applying a high heating rate of 10–200 K/s (Naik et al. 2010). Flash pyrolysis takes place in less than 0.5 s. In this process, biomass decomposes mainly to produce vapors, aerosols, and a certain amount of coke. Unlike traditional processes, it is an advanced process with carefully controlled parameters to achieve high fluid yields (Bridgwater 2006). Table 2 shows some operating parameters of the three types of pyrolysis processes and yields of the formed products (Uddin et al. 2018; Mota et al. 2015; Silva Mota et al. 2015).

Table 2 Operating parameters of different pyrolysis processes and yield of products

Process	Time (s)	Rate (K/s)	Size (mm)	Heat (K)	Oil yield (%)	Char yield (%)	Gas yield (%)
Slow	450–550	0.1–1	5–50	550–950	30	35	35
Fast	0.5–10	10–200	<1	850–1250	50	20	30
Flash	<0.5	>1000	<0.2	1050–1300	75	12	13

It is reported that varying operating conditions such as reaction temperature, heating rate, and residence time are important parameters for controlling different product yield content (Pandey et al. 2019). High heating rates and longer residence time at high temperatures are favorable conditions for better hydrogen production efficiency. Furthermore, hydrogen gas yield increases with increasing the pyrolysis reaction temperature (Li et al. 2017a; Valliyappan et al. 2008).

Hydrogen production by the pyrolysis method is affected by tar formation. For this reason, catalysts are used to minimize tar formation and increase the quality of bio-oil. It is reported that the use of a suitable catalyst such as Ni/Al_2O_3, CaO may increase hydrogen production by reducing tar formation (Kaewpanha et al. 2015). Similarly, various catalyst types such as FeO, Al_2O_3, MnO, Cr_2O_3, and CuO are investigated and reported to enrich hydrogen production by reducing tar formation (Chen et al. 2011). The catalyst not only improves gas production but also increases the production rate. It is reported that the production of hydrogen, which is 13.8 g H_2/kg biomass at 900 °C in the absence of catalyst, reaches a value of 33.6 g H_2/kg biomass at 450 °C in the presence of catalyst (Yang et al. 2006).

Co-pyrolysis of materials such as coal, plastic, rubber, and sludge with biomass is frequently studied due to its advantages such as high energy density, low price, recycling, high hydrogen, and carbon content. Comparing pure pine sawdust pyrolysis with pine sawdust and waste polystyrene foam co-pyrolysis; showed that co-pyrolysis of pine sawdust with waste polystyrene foam produced a higher efficiency bio-oil and the heating value of the produced bio-oil increased from 17.81 to 39.65 MJ/kg (Nguyen et al. 2019). It is suggested that the co-pyrolysis bio-oil yield increases as the proportion of rubber in co-pyrolysis of sugarcane pulp and tires increases (Ahmed et al. 2018).

The bio-oil liquid product obtained from biomass by the pyrolysis method has a higher energy density than biomass. In the pyrolysis method, bio-oil production is generally higher in percentage than hydrogen production. Therefore, studies are conducted on the conversion of bio-oil to hydrogen using various methods such as steam reforming and in-line reforming (Abdalla et al. 2018). A schematic representation of steam reforming and in-line reforming processes are presented in Figs. 1 and 2, respectively. As a result of steam reforming, the highest bio-oil conversion was 0.245 g H_2/g bio-oil with an H_2 yield above 95% (Renny et al. 2016). Various studies are conducted on hydrogen production by in-line reforming and it is observed that the use of catalysts in this process helps increase hydrogen production (Arregi et al. 2018; Barbarias et al. 2018, 2016). Since the products are fed directly into

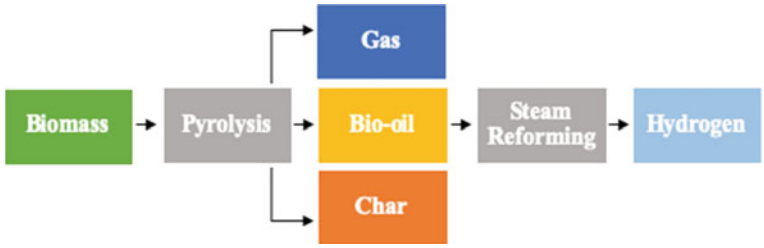

Fig. 1 Schematic presentation of the steam reforming process

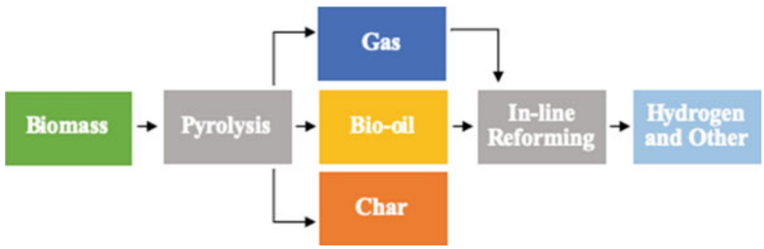

Fig. 2 Schematic presentation of the in-line reforming process

the conversion reactor in the in-line reforming process, the thermal energy of the pyrolyzed product is used during the conversion process. Also, tar production is reduced, which is the most important advantage over the conventional gasification method (Pandey et al. 2019).

The advantages and disadvantages of pyrolysis processes used for hydrogen production from biomass are summarized in Table 3 (Pandey et al. 2019; Dincer and Acar 2015a, b; Zaker et al. 2019; Joardder et al. 2014).

Recently, the use of new technologies such as Microwave-Assisted Pyrolysis and Solar-Assisted Pyrolysis in biomass pyrolysis has attracted great interest from researchers. The microwave-assisted pyrolysis process converts microwave energy into heat energy through the agitation of molecules in the electromagnetic field, and the generated heat spreads from inside to outside of the materials. Thus, no external temperature field is used to heat the biomass. In a study using gum tree as biomass, it was determined that the performance of the microwave-assisted pyrolysis system was 15% more efficient than the traditional pyrolysis system and produced 120 g H_2/kg gum tree hydrogen (Parvez et al. 2019). Solar-assisted pyrolysis is a relatively new approach to biomass pyrolysis. Compared to traditional biomass pyrolysis, solar-assisted pyrolysis provides clean use of primary energy by converting solar energy directly into thermal energy required for pyrolysis (Wang et al. 2020). In addition, it is cleaner than those produced by other heating methods and provides more gas production with higher heating values per unit of raw material (Weldekidan et al. 2019; Puig-Arnavat et al. 2013).

Table 3 Advantages and disadvantages of biomass pyrolysis processes

Process	Advantages	Disadvantages
Pyrolysis	Does not create the pollution created by the combustion process	Net yield is lower than biochemical processes
Pyrolysis + steam reforming	Does not require oxygen Good H_2/CO ratio	Generating more amount of carbon dioxide
Pyrolysis + ın-line reforming	No need to condense the gas product at the pyrolysis outlet Hydrogen-rich gas does not contain tar	Char obtained during the pyrolysis step does not reform
Microwave-assisted pyrolysis	Pyrolysis reactions occur in a shorter time due to microwave heating Lower thermal inertia and faster response Lower polluting	Accurate measurement of the evolution of temperature profile is difficult
Solar-assisted pyrolysis	With the solar system, the heating cost of the pyrolysis process is reduced Solar energy is added to the chemical energy stored in biomass Cleaner than other heating methods	The initial investment cost is higher compared to conventional pyrolysis

Today, more than 98% of hydrogen production is obtained from fossil sources through steam methane reforming (SMR) of natural gas (76% of global production) or coal gasification (CG) (22%) (Lepage et al. 2021; Suleman et al. 2015). At the same time, only 2% of current hydrogen production is generated from renewable sources. It has been reported that the costs for hydrogen production via pyrolysis from biomass range between 1.25 and 2.20 $/kg (Nikolaidis and Poullikkas 2017). This value appears to be close to each other when compared to the existing SMR or CG (1.34–2.27 $/kg). Hydrogen production from biomass is essentially required to reduce the dependency on fossil fuel-derived hydrogen to fulfill the future energy requirement as well as to protect the climate from pollution (Pandey et al. 2019). For this, the application of the pyrolysis method to various biomass sources should be considered as a good option.

3.1.3 Gasification

Gasification processes are one of the most widely used technologies due to the production of high-efficiency products. It is an efficient and fast process that contributes to the generation of energy from various types of biomass. Large-scale

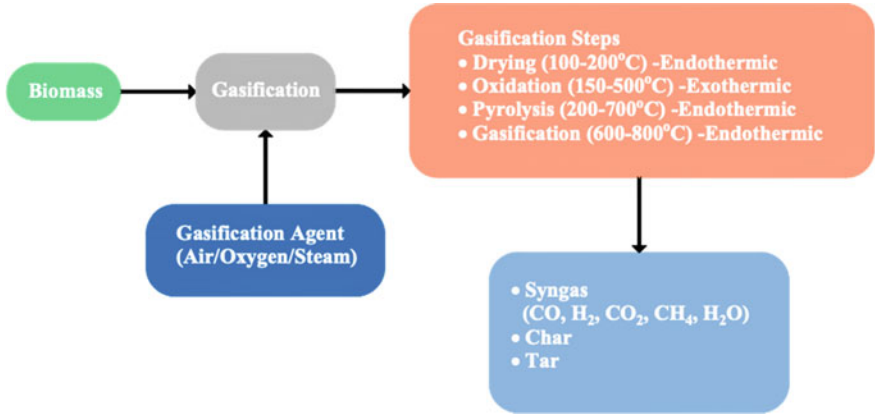

Fig. 3 General flow chart of the gasification method

hydrogen production by gasification of biomass not only supplies the energy demand but also helps reduce the rapidly growing environmental pollution.

Gasification is the degradation of carbonaceous organic materials at high temperatures after undergoing thermochemical transformation using partial oxygen (Varank et al. 2021). In other words, gasification is the process that produces a partially oxidized gas called syngas in an oxygen-deficient environment. Gasification of biomass is generally carried out at temperatures above 700 °C and in the presence of oxidizing agent gas. Biomass types with moisture content below 35% are highly preferred for the gasification process (Couto et al. 2013). Produced syngas is a mixture of CO, H_2, CO_2, CH_4, and H_2O gases (Ongen and Arayici 2015). This gas mixture can be evaluated in the processes following the post-gasification steam reform and the percentage of hydrogen production can be increased by the water gas shift reaction. The gasification process usually takes place following the drying, oxidation, pyrolysis, and finally gasification steps. The basic steps of the gasification process used for hydrogen-rich gas production are detailed in Fig. 3.

An oxidizing agent is used to produce synthesis gas composed of hydrogen, methane, carbon monoxide, nitrogen, and carbon dioxide by gasification (Lepage et al. 2021). The process differs according to the user agent. The gasification process is carried out in the presence of air, oxygen, or steam as an agent. The effect of gasification agents for the production of hydrogen-rich gas from biomass is investigated. It is reported that the percentage of hydrogen production is 30.09% with air, 43.05% with oxygen, and 42.59% with steam (Aydin et al. 2018). The use of oxygen creates a better quality gas, but the cost factor makes it difficult to use oxygen (Ongen and Arayıcı 2014). Two types of biomass (wood and paper) were gasified in another study. It was reported that hydrogen production went from high to low using steam, oxygen, oxygen-enriched air, and air, respectively. (Shayan et al. 2018). Gasification of biomass with steam is seen as the best and inexpensive alternative to gasification with oxygen.

Parameters such as biomass type, the particle size of biomass, temperature, catalyst, and residence time can be optimized to increase hydrogen production efficiency with biomass gasification. Biomass types with high cellulose and lignin increase gaseous products (Safari et al. 2016). Smaller particle size increases hydrogen yield and reduces the tar and coal content (Lepage et al. 2021). Generally, the optimum temperature values are 800–900 °C; above these, the hydrogen yield decreases (Dincer 2012). The most suitable catalysts for the gasification reaction are reported as Ni-based catalysts, alkali metal oxides, olivine, and dolomites (Devi et al. 2005). Longer residence time increases the conversion of biomass to gas.

Studies are still being conducted on the use of Catalytic Gasification for the conversion of biomass to hydrogen. The valuable products formed by this method are not limited to liquids, synthesis gas with high hydrogen content and stable coal can be obtained (Dincer and Acar 2015a). The reactions of catalysts play an important role in obtaining primary products that provide high-quality fuel or chemicals (Kudo et al. 2012; Mohanty et al. 2014). Thus, It is preferable to use a catalyst in thermochemical processes due to the high-quality product obtained. There are many types of catalysts used for enhancing gasification efficiency, such as calcium hydroxide, zirconium phosphate, cement kiln powder, potassium, iron, rubidium-based and nickel-based compounds. Coal and biomass are commonly used as feedstock in catalytic gasification (Hamad et al. 2016; Lv et al. 2007; Ding et al. 2015; Parshetti et al. 2015). Inorganic components of biological wastes such as sewage sludge which act as a "natural catalyst" are also used in increasing the production of desired chemicals and/or fuels by catalytic gasification of biomass.

Plasma Gasification technology is an environmentally friendly technology in terms of the products it releases compared to other thermal methods. During the gasification, heavy metals are melted at the bottom of the reactor and become sludge in the ceramic structure and there are no heavy metals released. Dioxin and furan groups, which are the most problematic groups in combustion technologies, are not formed due to the high temperatures used by this technology (Gomez et al. 2009). This is a serious advantage it offers, compared to traditional gasification methods. In plasma gasification technology, plasma discharge can be with direct current, radiofrequency, or microwave. Microwave plasma is of great interest due to the lack of electrode requirement and lower voltage requirement compared to other methods (Sanlisoy and Carpinlioglu 2017).

Gasification of biomass species with high moisture content (>80% moisture) such as agricultural waste, leather waste, sewage sludge, algae, and fertilizer is very difficult. Supercritical Water Gasification (SWG) as an alternative means of hydrogen production is proposed for this kind of biomass (Cherad et al. 2016; Kang et al. 2016). Since supercritical water conditions are achieved at T > 374 °C and P > 22 MPa, SWG is generally performed at 250–374 °C under a pressure of 4–22 MPa. Under these conditions water is a fluid that is neither a gas nor a liquid, it is in its supercritical state and it may participate in hydrolysis reactions acting as a hydrogen source (Tekin et al. 2014). Studies have shown that almost complete conversion of biomass with SWG can be achieved at temperatures above 700 °C with hydrogen content ranging from 26 to 57% (D'Jesús et al. 2006; Dou et al. 2019). The operating parameters (reaction temperature, pressure, catalyst, etc.) of this process have a significant effect on hydrogen production efficiency. It is observed that the production efficiency increases as the temperature increases in the production of hydrogen with SWG from biomass (Su et al. 2020; Yang et al. 2020). Similarly, it is reported that when a catalyst is used in an SWG process using cotton straw as biomass, hydrogen production efficiency increased by 68.8 times and reached 82.6% (Sun et al. 2020). High hydrogen (50–60% volume) content, low contaminant level, and tar-free syngas production are the major advantages of this method. The calorific value of the produced gas generally ranges between 12 and 18 MJ/Nm^3. Although there are difficulties in operating conditions, the SWG method is a very good option for hydrogen production from biomass types with high moisture content.

Chemical Looping Gasification (CLG) in which oxygen carriers (OCs) are used instead of molecular oxygen and synthesis gas is produced from biomass is a low-cost, new technology. Transition metal oxides such as Fe, Ni, Cu, Mn, and Co are extensively studied as OCs in the CLG process (Wu et al. 2019; Kuo et al. 2018; Keller et al. 2016). Fe is the most commonly used OC. Fe-based oxides are abundant in soil, inexpensive, stable at high temperatures, and environmentally friendly (Lin et al. 2020). As a metal oxide, OC can act as a catalyst for the cracking of coal and tar. This helps to minimize tar yield and carbon build-up. The advantages and disadvantages of gasification technologies used for hydrogen production from biomass are presented in Table 4. (Pandey et al. 2019; Dincer and Acar 2015a, b; Lin et al. 2020; Sarafraz and Christo 2020).

On the contrary to hydrogen, fossil sources can cause serious environmental problems such as air pollution and global warming. Hydrogen should be produced from clean and rich sources such as biomass, using environmentally friendly methods (Karabag et al. 2021). Gasification and its technologies which are one of these methods have an important role in environmental sustainability. It has been reported that the costs for the production of hydrogen by gasification from biomass range between 1.77 and 2.05 $/kg (Nikolaidis and Poullikkas 2017). Comparing this value with the existing SMR or CG (1.34–2.27 $/kg), hydrogen production by gasification from biomass can be a good alternative (Kannah et al. 2020).

3.1.4 Esterification

The esterification or liquefaction process is a thermochemical process similar to pyrolysis. It is a process that converts biomass into liquid. Unlike pyrolysis, biomass is converted into liquid hydrocarbons at lower processing temperatures (500–600 °C) and high process pressures (5–20 MPa). By liquefying biomass, oils can be produced with high energy content, easily stored, and can be used to produce other chemicals and fuels (Birinci 2019; Özay 2014; Yue et al. 2020). The esterification process, whose main goal is to produce liquid products with low efficiency in hydrogen production, is frequently used in biodiesel production. The diesel product formed as

Table 4 Advantages and disadvantages of biomass gasification processes

Process	Advantages	Disadvantages
Air gasification	The maximum conversion of biomass to syngas can be achieved	It is difficult but necessary to remove the tar completely from the syngas
Oxygen gasification	Low content of tar in syngas	Pure oxygen has a high cost
Steam gasification	Lower the operating temperature	Higher CO_2 emission High content of tar in syngas
Catalytic gasification	The use of catalysts results in high-quality products Primary products such as high-quality fuels and chemicals are formed The hydrogen content of the resulting products is high	The catalytic gasification of the hydrogen conversion of biomass is still in the developmental stage
Plasma gasification	It is an environmentally friendly technology in terms of the products it produces compared to other disposal and direct combustion methods Dioxin and furan groups, which are the most important problems of waste combustion technologies, are not produced due to the high temperatures used by this technology No heavy metal formation	Difficulty operating conditions Investment and operating costs are high
Supercritical water gasification	The moisture content of the biomass does not need to be reduced Pressure and temperature can be reduced with the use of catalysts	The high energy input to pump the feedstock High operating costs Corrosion of the reactor
Chemical looping gasification	By using OCs, the cost of oxygen supply can be significantly reduced The heat released by OC restoration can be returned to the fuel reactor along with the OC, supplying the energy demand of the biomass gasification	Difficulty controlling the operating temperature Carbon particles build up on the OCs

a result of the esterification reaction, which can be used in waste biomass such as vegetable and animal oils, can be used as fuel, heating, and greenhouse cultivation.

3.1.5 Carbonization

Carbonization is a process that typically heats biomass feedstock in a kiln or retort (pyrolysis) at temperatures around 400 °C (generally between 300 and 900 °C) in the absence of air. The produced biochar is also known as charcoal, which is a porous, carbon-enriched, grayish-black solid. It can also be produced from torrefaction, gasification, hydrothermal carbonization, etc. (Zhang et al. 2019). Carbonization of coal produces four organic-dominated by-products: coke (thermally stable coal minerals bound by graphitic carbon), coal tar (liquid pyrolytic condensate), soot (solid pyrolytic condensate), and hydrocarbon gases (methane, ethane, acetylene, carbon monoxide, and others) (Emsbo-Mattingly and Stout 2011).

The main objective of the carbonization process is to obtain the maximum attainable fixed carbon, but this comes as a detriment to the product quality which will suffer low energy yield, energy density, and hydrocarbon content. The carbonization process occurs by slowly heating the biomass to high temperatures exceeding 400 °C for several hours. The products from this process are charcoal which is used as fuel, biochar which is used as fertilizer or soil amendments, biocoke for metal extraction, and finally activated carbon when regular charcoal is upgraded for adsorption and purification purposes (Amer and Elwardany 2020). Products formed as a result of carbonization; can be used as a renewable solid fuel source to reduce dependence on fossil fuels, increase soil fertility and crop production efficiency when used in soil, improves water quality and soil quality. The purpose of the carbonization process is to produce more solid products. The hydrogen gas production efficiency of this process is very low. Compared to other thermal processes, it is a less preferred method for hydrogen energy production.

Hydrothermal carbonization, on the other hand, is the transformation of water and high organic content (biomass, organic waste) into valuable products by hydrolysis, dewatering, decarboxylation, aromatization, and re-condensation reactions in closed systems with the effect of pressure and temperature (Birinci 2019). Hydrothermal carbonization gives a high conversion efficiency, requires no pre-drying step of feedstock, and operates at relatively low temperatures compared to other thermochemical processes used to produce biochar (Lee et al. 2019).

It is a thermochemical transformation technique used for synthesizing high-quality carbon-derived materials at low or high temperatures from wood, resin, swamp coal, biomass, or waste biomass as well as model materials such as glucose, cellulose, and lignin (Wang et al. 2018). This process enables the transformation of wet biomass into coal-like products or carbon nanostructured materials under temperature and autogenous pressure in a closed container. One of the biggest advantages of this method compared to thermochemical conversion methods is that the raw material can be used in high moisture content without the need for pre-drying processes. In pyrolysis, gasification, and combustion processes, the raw material is dried before the process, which causes additional energy costs. The advantages and disadvantages of the hydrothermal carbonization process are presented in Table 5.

In the hydrothermal carbonization process, 50–80% solid product, 5–20% liquid product, and 2–5% gas product are formed by weight (Birinci 2019). This process, in which the gas product yield is very low, is a very inefficient process for hydrogen energy generation. The vast majority of gas generated during hydrothermal carbonization is CO_2. Besides, small amounts of CO, CH_4, and H_2 are formed (Funke and Ziegler 2010). In the case studies examined in the literature, it was concluded

Table 5 Hydrothermal carbonization process advantages and disadvantages (Birinci 2019; Lee et al. 2019; Wang et al. 2018)

Advantages	Disadvantages
The raw material does not need pre-drying It can be applied to biomass with high moisture content It is an inexpensive and easy process Low operating costs	Solid, liquid, and gaseous products are formed, but the gaseous product released is less than other thermal conversion systems The calorific value of the gas formed is low. It is not a suitable process for hydrogen production

that the amount of gas formed at increasing reaction temperatures also increased (Basso et al. 2016; Niemann and Whiticar 2017).

3.2 Biochemical Methods

3.2.1 Anaerobic Digestion

Anaerobic digestion (AD) is a method used for converting biomass waste into energy. Microorganisms convert biomass waste into volatile fatty acids and biogas (Zhu et al. 2009). Organic-containing waste/wastewater is separated, stored (oxygen content $< 1\%$), and decomposed under appropriate conditions (Zhu et al. 2011). The organic content decomposes into odorless, colorless biogas that is lighter than air, and the liquid and solid product formed after digestion is used as fertilizer depending on its content. Many parameters (temperature, substrate composition, type/number of microorganisms, pH, alkalinity, nutrients, etc.) affect the yield in anaerobic digestion (Kim et al. 2009). For example, a single or multiple types of substrates can be used for digestion. However, the digestion of different biomass (mixed in appropriate proportions), is desirable due to the availability of high microorganism population, ideal nutrient balance, appropriate C/N ratio, dilution of toxic substances, reduction of inhibitory effects, increased stabilization, and increased methane formation.

In terms of temperature ranges, AD at mesophilic temperature is more common compared to thermophilic temperatures. Decomposition of volatile solids is very slow and occurs in 30–40 days at mesophilic temperatures, however, this temperature range may be optimum for many methane-forming microorganisms (Labatut et al. 2014). Furthermore, mesophilic temperatures require low energy use. Thermophilic temperatures provide higher removal of both infectious animal viruses and bacteriophages. Digestion at thermophilic temperatures has more advantages, however, the main reasons for its limited use are poor process stability, poor upper phase quality, and high operating costs.

One of the most important parameters affecting the performance and stability of this method is the input substrate composition. For example, the high nitrogen (N) content of the raw material, especially under thermophilic conditions, causes high

Table 6 Anaerobic digestion advantages and disadvantages (Elanur, Bitlis Eren Üniversitesi Fen Bilimleri Dergisi)

Process	Advantages	Disadvantages
Mesophilic	Process stability Low operating cost	Lower energy efficiency Sensitive to toxic compounds
Thermophilic	Not sensitive to organic loading Can tolerate wastewater temperature Low foaming problem Ability to work in low reactor volume	Sensitive to toxic compounds Unstable structure Sensitive to temperature change

ammonia and ammonia accumulation and in turn, causes the accumulation of volatile fatty acids (VFA), which adversely affects the system (Hamad et al. 2016).

Anaerobic digestion advantages and disadvantages are given in Table 6.

Table 7 shows the type of organisms commonly used for H_2 production depending on the processes applied.

Studies on bio-hydrogen production using different methods such as bio-photolysis and bio-methanization were reported in the literatüre (Dar et al. 2021; Kwietniewska and Tys 2014; Kapdan and Kargi 2006; Grimalt-Alemany et al. 2018). Nonetheless, when these studies were examined, it was seen that although the efficiency of hydrogen production with bio-methanization methods was calculated in theory, it was not supported by laboratory studies. In the biophotolysis method, bio-hydrogen production studies are carried out by eliminating the sensitivity to oxygen (Kapdan and Kargi 2006; Winkler et al. 2002; Melis et al. 2000; Tamagnini et al. 2002). While in biomethanization method, methane is produced during the process and this suppresses hydrogen production (Kwietniewska and Tys 2014). Studies targeting the prevention of methane production are carried out to improve the biohydrogen production process.

3.2.2 Biomethanization

Biomethanization is one of the biological methods that can separate waste into biogas, and other substances, including recalcitrant biomass using anaerobic microorganisms. This strategy for the waste-to-gas conversion approach promotes sustainability while decreasing emissions to the extra CO_2 emissions. The biomethane mechanism (methane fermentation) has four distinct steps: hydrolysis, acetogenesis, acetate production, and methanation (Grimalt-Alemany et al. 2018).

Several factors such as temperature, pH, nutrients, ammonia, and volatile fatty acids affect the performance of this process. For the growth of microorganisms, a delicate balance between nutrients and environments is essential. Thus, maintaining the essential factors within the appropriate range is critical for Biomethanization's

Table 7 Biochemical process and organisms

Process	Feedstock	Organism	H_2 Yield	References
Photofermentation	Corn stover	HAU-M1/enterobacter aerogenes	90.13 ml H_2/g raw material	Zhang et al. (2020)
	Acetate	R. capsulatus	0.2- 3.2 mol H_2/mole acetate	Azwar et al. (2014), Liu et al. (2009), Ren et al. (2009), Tian et al. (2010), Lee et al. (2011), Xie et al. (2012, 2013)
	Succinate	R. sphaeroides	2.3–3.7 mol H_2/mole succinate	Azwar et al. (2014), Kim et al. (2013), Kim and Kim (2012)
	Platanus orientalis leaves	*HAU-M1*	64.10 ml H_2/g raw material	Zhang et al. (2020), Lee et al. (2011)
	Glucose	*R.sphaeroides O.U.001*	1.52–1.72 mol/mole acetic acid	Mishra et al. (2019), Pandu and Joseph (2012)
Dark fermentation	Corn stover	Enterobacter aerogenes	36.08 ml H_2/g raw material	Zhang et al. (2020)
	Glucose	Anaerobic sludge	1.03–1.9 mol H_2/mole glucose	Azwar et al. (2014), Chaganti et al. (2013)
	Glucose	*E.cloacae* strain DM11	1.86–5.5 mol H_2/mole glucose	Mishra et al. (2019), Pandu and Joseph (2012), Chittibabu et al. (2006), Nath et al. (2006), Kumar and Das (2000)
Thermophilic Anaerobic digestion	Sucrose	T.thermosaccharolyticum PSU-2	2.53 mol H_2/mole substrate	Chong et al. (2009)
	Glucose	T. Maritima DSM3109	1.67 mol H_2/mole substrate	Chong et al. (2009)

Table 8 Advantages and disadvantages of hydrogen production by biophotolysis method (Kapdan and Kargi 2006; Winkler et al. 2002; Melis et al. 2000; Tamagnini et al. 2002; Nagakawa et al. 2019)

Process	Advantages	Disadvantages
Direct bio-photolysis	Hydrogen production occurs directly using water and light	Oxygen build-up around the oxygen-sensitive hydrogenase enzyme
	Theoretical H_2 production yield is high	The hydrogenase enzyme is sensitive to oxygen
	Hydrogen production without substrate addition	Inhibition due to oxygen
		Low energy conversion of light used in hydrogen production
Indirect bio-photolysis	Hydrogen is produced using microalgae and cyanobacteria species	Inhibition due to oxygen low
	Water is used as a hydrogen source The process is easy to set up and operate and inexpensive	Large space requirement due to intense light requirement Hydrogen production efficiency
	Microorganism growth occurs even in the presence of simple minerals	High cost due to large space requirement

long-term success. The results suggest that variations in the temperature have a great impact on the growth of bacteria, which thus, contribute to fluctuations in foam formation. This should have a notable impact on the amount of biogas (Dar et al. 2021). While mesophilic (35–45 °C) and thermophilic (55–80 °C) temperatures are also appropriate, the temperature to be used is at (60–70 °C) and biomethanization studies showed that a pH range of 5–8.5 is optimum the ideal pH value for the specific microbe to optimize performance and growth (Grimalt-Alemany et al. 2018).

A significant disadvantage of anaerobic digestion is that it is more susceptible to toxicants than aerobic. Heavy metals, salinity, chlorophenols, halogenated aliphatics directly affect this process, while ammonia, long-chain fatty acids, sulfur, and humic acid indirectly affect this process. Food waste and livestock manure are generally used as feedstock (Kwietniewska and Tys 2014).

3.2.3 Bio-photolysis

Biophotolysis is another method used in the production of hydrogen from biomass. It is divided into direct biophotolysis and indirect biophotolysis. Direct biophotolysis is a biological process that produces hydrogen directly from water by converting solar energy to chemical energy in the form of hydrogen through the photosynthesis of microalgae. Like photosynthetic plants, cyanobacteria can use radiation in the range of 400–700 nm (Nagakawa et al. 2019). In this process, the hydrogenase enzyme is the main enzyme responsible for hydrogen production and decreases in the presence of oxygen. This is because electrodes that are released during the aerobic breakdown of water molecules tend to reduce carbon dioxide (Winkler et al. 2002). Researchers found that some microalgae species (e.g. Chlamydomonas reinwardtii) do not produce oxygen but produce hydrogen under bright non-sulfur conditions (Melis et al. 2000). The indirect biophotolysis process consists of two stages separated; oxygen and hydrogen formation reactions. In the presence of hydrogenase enzyme, hydrogen production is continued under oxygen-free conditions (Tamagnini et al. 2002).

This process has the disadvantages of having a higher cost and lower hydrogen production efficiency compared to the direct biophotolysis process. Nevertheless, studies have shown that using both methods, the hydrogen production efficiency cannot exceed approximately 10% according to the biomass ratio (Kapdan and Kargi 2006; Łukajtis et al. 2018). However, the use of water as a substrate and sunlight as energy in hydrogen production shows that this process can be developed in hydrogen production and wide-ranging applications can be made.

3.2.4 Fermentative Processes

One of the methods used in biological hydrogen production is fermentation. Fermentation methods are divided into two; dark fermentation and photo fermentation. The dark fermentation method is the most understandable among the biological hydrogen production methods, it's net energy ratio of 1:9 is advantageous compared to other methods (Manish and Banerjee 2008).

Hydrogen is present during the metabolism of many bacteria and it is one of the important reasons why anaerobic bacteria increase efficiency during hydrogen production in the dark fermentation method (Hallenbeck 2005; Rittmann and Herwig 2012). In this method, hydrogen molecules use electrons obtained from hydrogen oxidation by microorganisms. The Hydrogenase enzyme plays a key role in facilitating the process (Rittmann and Herwig 2012; Kalia et al. 2003; Kalia and Purohit 2008). The efficiency of the process is affected by many factors such as the inoculation used, type and amount of substrate, type of reactor, metal ions in the environment, temperature, pH, inorganic nutrients, and working conditions (Mona et al. 2020; Shanmugam et al. 2020). For example, when utilizing the fermentation process, batch reactors are used, and starch is more often employed as the substrate.

Hydrogen production by fermentation method is done using various biomass. Hence, for industrial-scale hydrogen production, it is very important to choose the appropriate substrate in terms of cost and efficiency (Herbel et al. 2010; Panagiotopoulos et al. 2009; Antonopoulou et al. 2007; Ntaikou et al. 2008; Eriksen et al. 2011). In studies conducted, the most preferred carbon sources in terms of efficiency in hydrogen production by dark fermentation are monosaccharides and disaccharides (Łukajtis et al. 2018; Hallenbeck 2012; Bartacek et al. 2007; Hawkes et al. 2002). Other sources used include whey, olive wastewater, organic municipal waste (from households, restaurants), and sewage sludge.

Studies with anaerobic bacteria, facultative bacteria, and thermophilic bacteria for hydrogen production by dark fermentation were investigated as well. It was recorded in the findings that mixed culture is preferred instead of pure culture due to its advantages such as ease of operation and stability of the system (Kumar and Das 2000). Thermophilic bacteria 6–70 °C, facultative bacteria 6–38 °C, and anaerobic bacteria 5–35 °C are used in the rectors. The maximum hydrogen production efficiency (L H_2/g raw material) was acquired using facultative bacteria which had higher hydrogen production efficiency than other bacterial species (Łukajtis et al. 2018).

The pH effect on hydrogenase enzyme activity is significant in terms of how much hydrogen can bacteria produce (Usman et al. 2021). Changes in pH may have a direct impact on the amount of available hydrogen and the composition of soluble metabolites. It is possible to say that the initial pH establishes a delicate balance between the high hydrogen production rate and the desired conversion efficiency. In addition, pH may negatively impact the metabolism of microorganisms, limiting hydrogen production and triggering a change in the microbial community (Srivastava et al. 2020). Most studies have found the optimum pH level between 6 and 8 to be suitable for H_2 processing. Other experiments reported that the greatest performance was at a pH of 4.2 and a concentration of acetic acid was found. The optimum pH for hydrogen yield is 5.2, but the median pH value is 6. Studies show that the maximum hydrogen supply is at 6 according to the literature (Sinha and Pandey 2011; Li and Fang 2007; Özkan 2009; Şentürk and Büyükgüngör 2015).

There must be enough nutrients for hydrogen-producing bacteria to thrive. Nitrogen is the most often used in this context. Hydrogen-consuming bacteria can thus benefit from the addition of the appropriate amount of nitrogen (Jayalakshmi et al. 2009). Phosphorus is rich in important nutrients and has such a large buffering capability, it is needed for the production of hydrogen (Elbeshbishy et al. 2011). Nitrogen and phosphorus improve productivity. However, there is a correlation between amount and production. Hydrogen gas (H_2) production needs a proper C/N and C/P ratio however, according to the experimental results, it was not possible to find optimal C:N:P ratios (Hwang et al. 2011; Yasin et al. 2013).

Excessive metal ion concentration affects fermentative H_2 output, even at low levels. Metal ion concentrations have been extensively researched for fermentative H_2 production because the hydrogenase enzyme requires elements like Na, Mg, Zn, and Fe. Thus, they have an impact on H_2 metabolism (Zhao et al. 2012).

Hydraulic retention time (HRT) is a factor that can affect the rate at which hydrogen is produced and/or the reliability of continuously operating reactors (Şentürk and Büyükgüngör 2015). During the fermentation phase, HRT affects the substrate however, the best way to manage it varies from one system to the next, depending on a variety of factors (reactor shape, substrate used, specific microorganisms, or microbial communities) (Baghchehsaraee 2009). The HRT dose required allows the bacteria to increase their hydrogen supply. The risks associated with operating at a high HRT level are significant. An increase in the amount of volatile acidity can inhibit the development of hydrogen because of fat accumulation (Ntaikou et al. 2010). Dark fermentation process advantages and disadvantages are summarized in Table 9 (Bolatkhan et al. 2019).

The ability to use a variety of carbon sources encourages the use of the dark fermentation process for biohydrogen production. In addition, it is a method for biohydrogen production with extensive study data in the literature due to the lack of light and oxygen requirements. However, studies show that biohydrogen cannot be produced without the presence of CH_4 and H_2S.

Photo-fermentation, in contrast to dark fermentation, uses volatile fatty acids as a substrate in the presence of light. The process uses photosynthetic non-sulfur bacteria (PNS) that can convert volatile fatty acids to hydrogen gas (Sampath et al. 2020).

These bacteria, which are frequently used in photofermentation, can also use glucose and sucrose as carbon sources (Wang et al. 2019). Photo fermentation, unlike other processes, occurs in the presence of oxygen and is suitable for the production of hydrogen from agricultural and industrial wastes. Despite these benefits, due to the low efficiency of hydrogen production, the optimum values of the variables affecting the process should be thoroughly investigated (Azwar et al. 2014; Redwood et al. 2009; Hallenbeck and Ghosh 2009). In one of the photo-fermentation studies, the effect of pre-treatment of agricultural wastes on hydrogen production efficiency was investigated. Another study looked at the impact of various carbon sources on hydrogen production efficiency and acetate was found to be an effective carbon source (Bolatkhan et al. 2019; Sampath et al. 2020). Although the hydrogen production efficiency of the dark fermentation method is high in the studies, it is seen that the photo fermentation method is more efficient in laboratory studies. Hydrogen production efficiency can be increased depending on the biomass source. For example, when corn stover was used as a biomass source, hydrogen production efficiency was high in both photo fermentation and dark fermentation.

Biohydrogen production cost with dark fermentation method is between 1 and 4 USD/kg (Lepage et al. 2021; Kannah et al. 2020; Parthasarathy and Narayanan 2014; Martınez-Merino et al. 2013; Han et al. 2016a, 2016b) and the cost of biohydrogen production with photo fermentation method is 2.83–3.89 USD/kg (Kannah et al. 2020; Parthasarathy and Narayanan 2014; Martınez-Merino et al. 2013). These cost estimates are highly dependent on the biomass source used, for example, the cost of biohydrogen production using food waste as a waste source in dark fermentation is 1 USD/kg (Han et al. 2016b) while using Molasses costs 2.7 USD/kg (Han et al. 2016a).

Table 9 Dark fermentation process advantages and disadvantages (Bolatkhan et al. 2019)

Advantages	Disadvantages
Requires no illumination Working without oxygen (anaerobic process) It generates waste materials containing commercially valuable organic acids Carbon sources are diverse	Pure hydrogen gas cannot be produced in the process (include in CH_4 and H_2S) The residue after fermentation must be treated

Table 10 Photofermentation process advantages and disadvantages (Bolatkhan et al. 2019)

Advantages	Disadvantages
There is no O_2 evolution in the process Capability to use a long range of light Ability to consume a variety of substrates derived from organic waste	Low conversion efficiency of solar energy Large area needs to benefit from sunlight with high efficiency Light is critical for the process

Photo fermentation, dark fermentation, and dark-photo fermentation methods were used to produce hydrogen from corn stover. According to the findings, while photo fermentation had the highest energy conversion, dark fermentation had the lowest energy conversion. Furthermore, in a different study by the same team, Platanus Orientalis leaves were used as a source. Although the energy conversion efficiency is lower than corn stover, the photo fermentation method had higher efficiency than the dark fermentation method. It was reported in the study that the energy conversion is low because the use of different raw materials affects bacteria (Zhang et al. 2020).

Although the hydrogen production efficiency in photo-fermentation depends on the light intensity, it has a high hydrogen production efficiency depending on the carbon source. Optimum conditions of light intensity should be determined according to different PNS bacteria species (Mishra et al. 2019). Photofermentation process advantages and disadvantages are presented in Table 10.

Unlike dark fermentation, the need to use light in the photo fermentation process and the low conversion efficiency of solar energy are its disadvantages. However, its ability to consume different substrates and use a wide spectrum of light enables biohydrogen production.

4 Conclusions

In this section, the production of hydrogen gas, which is the subject of intensive research on a global scale, both as an environmentalist and as the most intense energy carrier, in meeting energy needs from biomass, which is one of the renewable energy sources, has been examined. In this context, the current level of the technologies in question and their hydrogen production potential is determined, the advantages and disadvantages of the processes are presented, and current techniques in the literature are compiled and presented. As hydrogen can be produced from fossil fuels, it can also be obtained from renewable sources such as biomass today, where the transition to 100% renewable energy sources is based. It is accepted as the most preferred approach to meet the future energy needs sustainably, without polluting nature, by protecting resources, and by using technologies that can help to take effective steps in the fight against global warming. In line with this goal, researchers are trying to develop biochemical and/or thermochemical methods that can provide high-efficiency hydrogen production from biomass. Pyrolysis and gasification are two basic zero waste approaches with a wide range of applications. Pyrolysis in-line reforming is considered as one of the promising alternative methods in biomass gasification and the bio-oil cycle. The minimum tar content of the hydrogen obtained during this process ensures that tar-based problems are controlled on a large scale throughout the process. In particular, a wide variety of studies are carried out to remove tar from produced gas, and significant progress has been made to improve gas quality. In particular, basic raw material properties such as biomass character, moisture content, and size stand out as the main parameters affecting the process efficiency. Studies have shown that more intensive hydrogen production is provided during gasification compared to pyrolysis and this efficiency can be increased with increasing temperature (>700 °C). In the studies examined, it is stated that the use of catalysts generally supports hydrogen production, and it is an important finding that the reactions taking place on the catalyst surface during the reactions can adversely affect the catalyst yield. Another important consideration is the choice of gasification agent. Dry air, pure oxygen, and water vapor are the gases used for this purpose, they are the focus of the researches, both with their effects on system efficiency and their costs. While water vapor provides ease of application, it supports the production of hydrogen gas, but it also causes tar formation in the system. Pure oxygen is one of the agents that increase the efficiency compared to dry air, however, their costs increase in real-scale systems. The choice of an agent directly affects the cost as well as the process efficiency.

Pyrolysis and Gasification, in general, although the initial investment costs of the processes are high because they are zero waste technologies, the products produced can be recycled as an added value. Hence, when their inputs and outputs are considered as a whole, they are applicable for hydrogen production and will be able to compete with traditional methods in the near future.

Another hydrogen production technology with intensive research is biochemical hydrogen production methods. These methods use the ability of microorganisms to consume biomass, digest, and release hydrogen, however, one of the main problems reported in these methods is low hydrogen production. Depending on the method applied and the biomass used, the potential of industrial-scale systems that can provide medium to long-term hydrogen production at different levels is considered as one of the promising developments expected with this technology.

In systems based on fermentation, microorganisms break down organic matter to produce hydrogen. Organic matter can be raw biomass sources such as sugar, corn residues, and even wastewater. When light is not required, these methods are sometimes referred to as “dark fermentation” methods. Fermentation has been used as an industrial technology for producing biofuels and other products. Researchers are working extensively on issues where fermentation systems experience fundamental problems, such as increasing the rate of hydrogen production and producing more hydrogen from the same amount of organic matter.

The general trend in the literature shows that both thermochemical and biochemical processes have both advantageous and competitive potential when compared to the current technology used for hydrogen production. There are some fundamental difficulties in producing hydrogen from biomass with various technologies. Especially, efforts to reduce the initial investment cost gain importance at this point. The financial problems encountered in terms of reactor structures, equipment used, costs associated with raw materials, training of qualified personnel, and compliance with legal processes are of significance. Today, efforts to minimize the system cost are primarily aimed at adapting the appropriate technology. An example is the adaptation of membrane separation technologies to ensure the use of pure oxygen in gasification systems. Developing appropriate technologies to separate and purify hydrogen from the produced gas stream with higher efficiency, combining multiple steps in the processes to create more compact systems are some of the technology-based cost reduction studies.

With improved agricultural practices and efforts to grow raw materials, enables the increase of biomass reserves and their use as an alternative fuel source in a controlled manner. Energy sources include short-rotation woody crops, herbaceous wood crops, park and garden waste, starch crops, and sugar crops. An integrated management mechanism can be created in which both low-cost and sustainable resource management can be adapted.

Global warming is one of the biggest environmental problems of today, and approaches to combat it are discussed internationally. The reduction of CO_2 emissions is one of the important strategies at the center of the struggle. In this context, it was stated as an important result that fermentative processes have lower effects in terms of carbon footprint. In the light of the studies carried out, it is observed that there is a need for more comprehensive life cycle analysis studies at the point of evaluating the carbon footprint for the production of hydrogen-rich synthesis gas by thermochemical means.

As a result, the lessons learned from commercial applications, as well as the laboratory and/or pilot-scale applications carried out, are the potential of these conversion technologies to be used as a cost-competitive, sustainable and convenient way for hydrogen production, both according to the type of biomass and the form and type of the product to be obtained will be decisive.

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Comparative Hazard and Environmental Assessment for Hydrogen and Formic Acid Production, Storage, and Utilization for Renewables

Nour Mardini and Yusuf Bicer

1 Introduction

Alternative fuels are derived from different sources. However, if produced from renewable sources, they can be considered clean fuels in which they have considerably less pollution than conventional fuels such as gasoline or diesel. Biodiesel, for example, is a renewable fuel that can be made from vegetable oils and animal fats. Ethanol is a widely used renewable fuel made from corn and other plant materials. As Fig. 1 shows, the volumetric energy density of hydrogen (H_2) is lower than formic acid, methanol, and ethanol. H_2 is potentially emissions-free alternative fuel.

Formic acid produces less carbon dioxide (CO_2), directly decreasing greenhouse gas emissions, as shown in Fig. 2. It makes formic acid bear fewer emissions than methanol, diesel, methane, and ethylene.

Petroleum-based diesel will produce more emissions than diesel derived from vegetable oils and animal fats. Electric vehicles (EV) have recently become quite popular for powering vehicles with electricity, which does not cause any tailpipe emissions. However, generating electricity from various fossil resources such as coal and natural gas can have significant environmental consequences, including substantial CO_2 emissions when complete life cycles are considered. Harmful air pollutants from the transportation sector can be decreased by fuel cell-powered vehicles with H_2. However, H_2 has transportation, distribution, and storage problems due to its thermophysical properties.

The Environmental Impact Assessment (EIA) aims to evaluate the environmental impacts of the proposed development and protect the environment by

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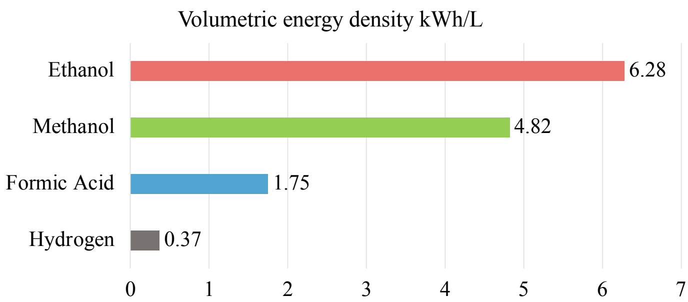

Fig. 1 Volumetric energy densities of H_2, formic acid, methanol, and ethanol (data from Williams et al. (1978))

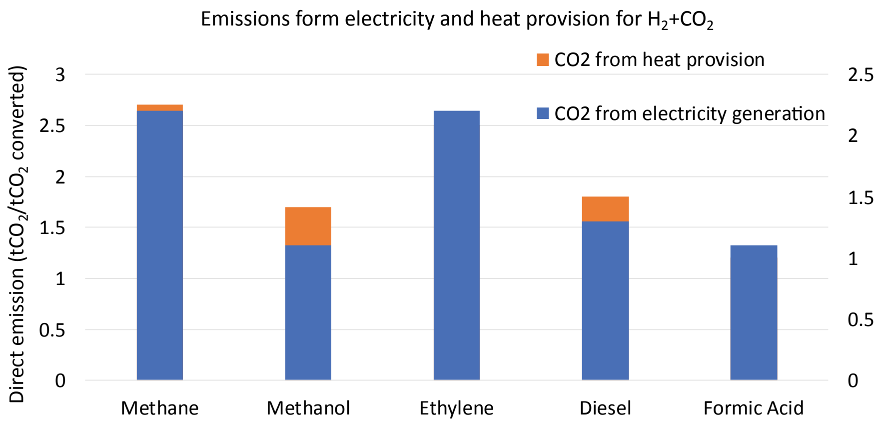

Fig. 2 Emissions from electricity and heat provision for different fuels (data from Bennett et al. (2014))

ensuring that a local planning authority inter-relates both beneficial and adverse socio-economic, cultural, and human-health impacts (Environmental Impact Assessment—an overview|ScienceDirect Topics 2020). EIA contributes to several stages like screening, scoping, preparing, planning, and decision-making. In EIA, in the screening stage, a project is determined whether it falls within regulation. Finding the project's extent is part of the scoping stage. The later stage entails preparing the required environmental statements for the assessment. EIA as a planning tool provides methodologies and strategies for defining, forecasting, and assessing possible environmental effects of projects at both the planning and decision-making levels. Reduction of environmental risks and helping promotion of environmentally sound projects are among the benefits of EIA.

H_2 is the most common element in the universe and essential elements for sustaining life on earth. H_2 is in high demand as a clean and green energy carrier for transportation and other energy-related applications for various reasons. The H_2 fuel cells turn H_2 from the vehicle's fuel tanks into electricity, driving the vehicle's electric motor and providing a similar range to conventional vehicles like trucks, buses, boats, motorcycles, and bicycles other kinds of vehicles. Since water is the only direct byproduct during energy production, it could dramatically reduce air pollution and carbon emissions.

The primary source of H_2 is natural gas in the world. Other materials, most notably water vapor and non-hydrocarbon elements known as impurities, are present in the world's extracted raw natural gas. H_2S, O_2, CO_2, N_2, and other rare gases are among these elements. As a result, such polluted gas must be treated before converted into H_2. It is common knowledge that fossil fuels, such as oil, coal, and natural gas, are nonrenewable resources. This will only last a few decades before CO_2 levels in the atmosphere rise drastically, resulting in global warming. Accordingly, fossil fuels should be replaced with substitute renewable fuels like H_2 (Petrescu et al. 2020). H_2 storage will continue to be in high demand as a stable and clean energy carrier for transportation and other energy-related applications in the future (Khan 2019). Chemical hydrides, methanol, ammonia, and formic acid are among the H_2 storage options (Müller et al. 2017). Electricity cannot be stored in large quantities for long periods, unlike H_2, which can be stored chemically. As a result, H_2 generated on a commercial scale will be critical in the clean energy transition. Industrial-scale H_2 production may be critical in the energy transition. As a result, H_2 can be stored in large quantities for long periods. As a cleaner energy carrier than conventional fuels, formic acid can play a role in the H_2 economy (Andersson and Grönkvist 2019) since pure H_2 storage poses a significant heat transfer challenge. Formic acid emerges as an alternative H_2-storage material (Khan 2019).

1.1 Hazards

Formic acid has several hazard statements as listed in Table 1: Combustible liquid, corrosive to metals, toxic if inhaled, causes severe skin burns and eye damage. On the other hand, H_2 has two hazards being extremely flammable gas and containing high-pressure gas. If the temperature increases, gas is likely to explode. The associated risks affect health and the environment in different ways, which are discussed below.

1.2 Health

H_2 is a colorless gas with no odor, and it is not toxic. It does not impose a direct negative impact on health. Nevertheless, H_2 is an asphyxiant if it displaces oxygen reduced it to below 18% in the atmosphere. The concentrations at which flammable or explosive mixtures form are much lower than the concentrations at which a substantial risk of asphyxiation exists. Formic acid is non-toxic; however, if inhaled, it will

Table 1 Comparison of formic acid and H_2 in different hazard statements with mitigation measures

Identification	Formic acid	H_2
Chemical formula	CH_2O_2	H_2
Uses	The agent that reduces the amount of something. In dyeing quick wool colors, it is used as a decalcifier and reducer. It is used in dehairing and plumping hides, rubber latex coagulation and regeneration, electroplating, and chemical analysis (FA safety sheet.pdf 2020) Used as fuel	Test gas/calibration gas Laboratory use Chemical reaction/synthesis Used as fuel Shield gas for welding processes Use for the manufacture of electronic/photovoltaic components (Hydrogen gas h2 safety data sheet-sds.pdf 2020)
Hazard statements	H227: combustible liquid H290: corrosive to metals H302: harmful if swallowed H314: causes severe skin burns and eye damage H318: causes serious eye damage (Safety and FA. pdf 2020)	H220: extremely flammable gas H280: gas under pressure; if heated, it can explode (Sheet and for Hydrogen 2020)
Hazards Health	Inhaled: people who were exposed to 15 ppm of a formic-acetic acid mixture complained of nausea Ingestion of fewer than 150 g can be fatal or cause serious health problems for the person While skin contact is not considered to be harmful to one's health, the substance could still cause harm if it enters the body through wounds The substance causes severe ocular lesions in the eye (Petrescu et al. 2020)	H_2 is not toxic by any route. Asphyxia may result if the oxygen concentration is reduced to below 18% by displacement The immediate health hazard is that it may cause thermal burns (Bennett et al. 2014)

(continued)

negatively affect health. It will cause respiratory tract irritation due to acidic corrosives properties. Repeated or prolonged exposure to formic acid without using safety equipment may result in frequent bronchial pneumonia attacks (Safety and FA. pdf 2020).

Table 1 (continued)

Identification	Formic acid	H_2
Hazards environmental	In the atmosphere, formic acid reacts with photochemically produced hydroxyl radicals Formic acid is highly soluble in water Leaches into some soils where it is expected to be biodegradable (Müller et al. 2017)	Extremely flammable gas When combined with air and oxygen, it creates volatile mixtures Air mixtures containing between 4 and 74% H_2 by volume are explosive (Sheet and for Hydrogen H2 (2020)
Handling and storage	Keep your items in their initial containers Keep containers tightly closed Refrigerate or store at room temperature. Temperatures above 35 °C should be avoided At low temperatures, polyethylene and polypropylene can be used to store 85% formic acid. Formic acid is not a problem for polyfluoroethylene (FormicAcid store.pdf 2020)	Contains a pressurized gas CGA P-1, safe handling of compressed gases in containers, local building and fire codes, and other related legislation should all be followed when storing cylinders For storage, materials should be separated according to the hazards they pose Store where the temperature will not rise above 52 °C (Hydrogen_compressed-SE_ENG.pdf 2020) Direct sunlight, precipitation, mechanical damage, and temperatures above 55 °C should all be avoided
Ecological information	Hazardous to the aquatic environment if the concentration of formic acid exceeds 130 mg/L, effects to fish above 365 mg/L, and effects to aquatic invertebrates and algae over 1240 mg/L (Safety and FA. Pdf 2020)	No ecological damage caused by using H_2
Mitigation measure	In warehouses and enclosed storage areas, have sufficient ventilation (Safety and FA. pdf 2020)	Provide H_2 control system to prevent metal water reactions Use acceptable accident sequences (Recommendation 2020)

1.3 Environmental

H_2 is flammable and can combine with air to create flammable or explosive mixtures. When combined with oxidizers such as air, oxygen, and halogens, H_2 can react violently, unlike formic acid, low flammability (Eppinger and Huang 2017). Recent technological advancements aid increased demand for formic acid, which can be used in fuel cells and renewable energy storage applications. It can also be a carbon–neutral solution to reducing global warming is used in a closed-loop.

1.4 Handling and Storage

Chemical hydrides, methanol, ammonia, and formic acid are among the H_2 storage options (Müller et al. 2017). At normal handling conditions (8.4–100.8 °C), formic acid's ability to store H_2 has been defined in several studies as a non-toxic and simple-to-store chemical (Singh et al. 2016). The energy efficiency of hydrogenation and dehydrogenation is usually lower than that of chemical storage. Since polyethylene and polypropylene are resistant to formic acid, containers made of polyethylene and polypropylene can be used to store 85% formic acid at low temperatures (Müller et al. 2017).

1.5 Ecological Information

Formic acid is not classified as hazardous to the aquatic environment, although it is highly soluble in water. It will affect fish, aquatic invertebrates, and algae if the formic acid value exceeds 130 mg/L, 365 mg/L, and 1240 mg/L, respectively. So, it should not be spilled into drains or watercourses. In contrast, no serious ecological damage is caused by H_2 (Safety and FA. Pdf 2020).

1.6 Mitigation Measures

Provision of sufficient ventilation in warehouses and enclosed storage areas are needed to eliminate and monitor the hazards of formic acid. If the exposure is severe, a PVC protective suit may be required. The critical problem with using H_2 is that metal water reactions can occur if the H_2 content is greater than 75% (active fuel cladding) without compromising containment structural integrity. As a result, it must oversee a system capable of handling an equal volume of H_2 while still maintaining safe accident sequences.

2 Environmental Impact Assessment of Formic Acid Formation Using CO_2 and CO

2.1 Producing Formic Acid by Methyl Formate

The carbonylation of methanol and subsequent hydrolysis of the methyl formate are involved in this process. The first stage of the process, in which carbon monoxide (CO) and methanol are compressed and converted to methyl formate in a reactor as depicted in Fig. 3. To compensate for methanol losses in the process, a catalyst (sodium methoxide, CH_3NaO) is fed to a reactor along with methanol. The reaction occurs at a pressure of 4 MPa and a temperature of 80 °C (Hietala et al. 2016). The methyl formate column is flushed and injected with the reactor discharge. In the recycle column, the distillate is separated into methyl formate and methanol to aid formic acid growth. In the water and methyl formate distillation column, the reactor's waste gas is burned. The obtained methyl formate reacts with water in the second step. At around 120 °C and 9 bar, this stage takes place. The tertiary amine is added as an auxiliary chemical to the reactor due to the unfavorable equilibrium (Hao et al. 2011).

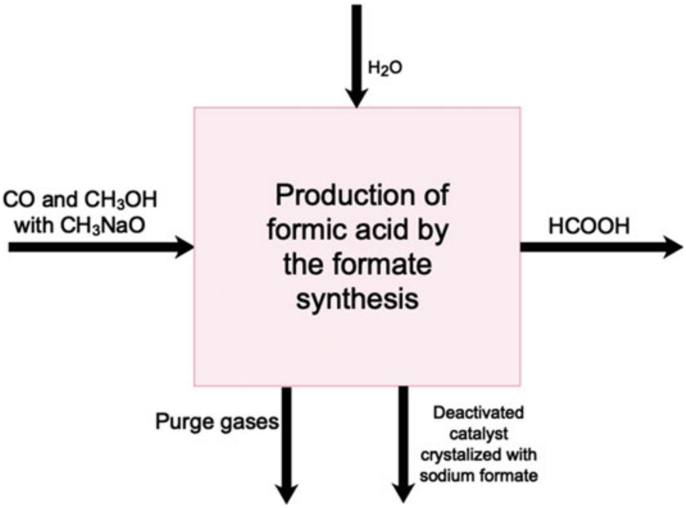

Fig. 3 Flow diagram of formic acid production by the formate synthesis

2.2 Producing Formic Acid by CO_2 and H_2

To enhance conversion, the method for producing formic acid from CO_2 uses heterogeneous catalysis. Although the formic acid synthesis from CO_2 promotes CO_2 recovery and use, it is still limited to the laboratory due to unfavorable thermodynamics (Chu et al. 2009). The thermodynamics of converting gaseous H_2 and CO_2 into liquid formic acid is unfavorable. Gibbs free energy is positive because the formation of formic acid from CO_2 and H_2 requires electricity or heat to proceed, or reaction coupling, which necessitates neutralizing the acid formed with a weak organic base (nonspontaneous reaction) (Chu et al. 2009). The response takes place at a temperature of 50 °C and pressure of 150 bars as per the below equation:

$$CO_2 + H_2 \rightarrow HCOOH \quad (1)$$

As shown in Fig. 4, a heterogeneous ruthenium catalyst catalyzes the reaction. A phosphonium ionic liquid supporter is paired with motivation to increase formic acid yield. It is easy to separate the ionic liquid because it is highly viscous (Chu et al. 2009).

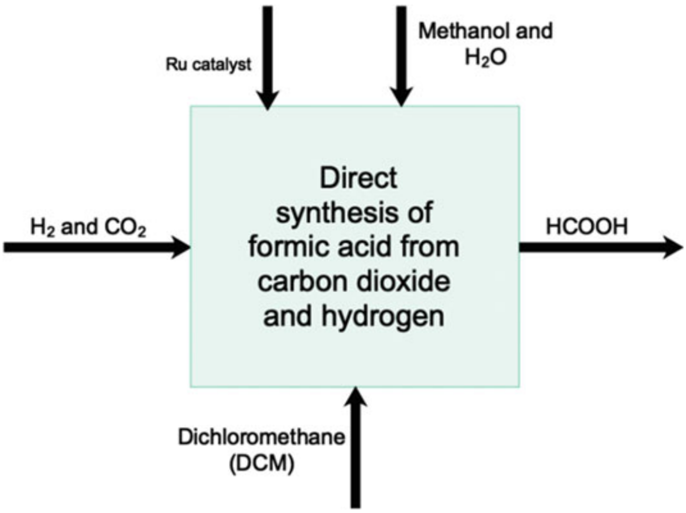

Fig. 4 Flow diagram of producing formic acid from CO_2

3 Comparison of Methods

Table 2 shows the comparison for both ways of producing formic acid depending on side-products, waste, emissions, risks, solvents, auxiliary chemicals, and catalyst reusability. These parameters were suggested in conjunction with the Twelve Green Chemistry Principles (Anastas and Warner 2000). In terms of green chemistry standards, preventing waste until it forms is preferable to handling or cleaning up waste after it has developed. Even though formic acid consumption emits CO_2, it can be recycled to a formic acid reactor to produce formic acid again. However, the formic acid synthesis using CO will make waste such as sodium methoxide (CH_3NaO) used as an inactivated catalyst, and small amounts of unreacted CH_3OH and CO. CH_3NaO has some health and safety issues, which must be taken care of in the safety plan. Unreacted CH_3OH and CO are recycled or burnt for energy.

In contrast, the formic acid synthesis using CO_2 can negatively impact health due to the used catalyst of ruthenium trichloride, which requires additional washing chemicals and processes. All ruthenium compounds should be regarded as highly toxic and carcinogenic (Ruthenium (Ru) 2020). The use of CO in formic acid synthesis has a detrimental effect on health. Since more hazardous components to human health are used in the synthesis of formic acid using CO_2, the amount of raw materials used to achieve the same ability is noticeably higher. As a consequence, using CO to synthesize formic acid has a more significant adverse effect on the ecosystem. CO and methanol are more harmful as feedstocks than CO_2 and H_2. Since hydrocarbons have some dangerous consequences, they have a slightly higher environmental

Table 2 Comparison of formic acid synthesis using CO_2 and CO (Saavalainen et al. 2017)

Process description	Formic acid production using CO (Method A)	Formic acid production using CO_2 (Method B)
Side-products	CH_3OH, the majority of which is recycled back into the process, with the remainder being burned for energy	Hydrocarbons, acetic acid, methanol, $HCOOCH_3$ CO_2 and H_2 can be reused in the manufacturing process
Waste/emissions/waste water	CH_3NaO is an inactive catalyst. The majority of the unreacted CH_3OH and CO is recycled or burned for energy	No
Higher risk case of an accident	CO puts people at risk in the event of an accident	In the event of an accident, H_2 increases the risks
Solvents and auxiliary chemicals	To inactivate the catalyst, use sodium formate to crystallize it	Phosphonium ionic liquid is promoted using dichloromethane (DCM), methanol, and water
Catalyst reusability	There is no need for recycling since part of the catalyst is recycled, and part is substituted with a new catalyst	Reusable, washing with methanol

Table 3 SAT total points for formic acid production using CO_2 and CO (Saavalainen et al. 2017)

Sustainability scores of cases	Using CO (Method A)	Using CO_2 (Method B)
Environmental	20.56	23
Social	13.48	10.12
Economic	22.46	22.46
Health	12.78	18.89
Total	69.29	75.9

impact. Even if it uses more volatile auxiliary chemicals, formic acid synthesis using CO has a significantly higher ecological effect than the two-stage reaction route because it uses fewer ancillary indicators.

Table 3 summarizes some of the questions in the Sustainability Assessment of Technologies (SAT). SAT educates and informs about a wide range of environmental, economic, health, social, and safety issues. Waste reduction, material quality, raw materials product by design, less auxiliaries, energy efficiency, danger and threat, and management are discussed in these issues. SAT assists in comparing a variety of design choices and selecting the most promising one. However, since the SAT's data quality is its weakest point, the findings can be deceptive if the information is inaccurate (Saavalainen et al. 2017). As given in Table 3, the synthesis of formic acid using CO and CO_2 has a total score of 69.28 and 75.97, respectively. This finding suggests that the synthesis of formic acid using CO is currently more sustainable. Synthesis of formic acid using CO_2 is very competitive in raw material selection, but it scores poorly on all other metrics such as social and health. Some of the specifics of the formic acid synthesis process using CO_2 are still ambiguous, which might affect the accuracy of the results. In economic concern, both methods have the exact total score of 22.46. Formic acid synthesis using CO is an economic production path that has been developed decades ago. Comparing the two approaches has the benefit of concentrating on the sustainability metrics that must be improved to compete with commercial methods. Even though formic acid synthesis with CO_2 is more environmentally friendly due to the renewable raw materials used, the process needs to be improved to be more sustainable, especially in production and auxiliaries used (Saavalainen et al. 2017).

4 Risk Assessment

Compared between Methods A and B, the total score for Method B is higher than Method A. The main difference in score between the two results is in environmental and health effects. Producing formic acid from CO_2 will affect more in the environment and health. That is simply due to using the carcinogenic auxiliary substance as dichloromethane (DCM), methanol and water, phosphonium ionic liquid. According

Table 4 Comparison between two methods of producing formic acid

Features	Using CO (Method A)	Using CO_2 (Method B)
CF values (kg of CO_2 per kg of formic acid)	2.2 kg/kg (Rumayor et al. 2018)	0.16 kg/kg (Rumayor et al. 2018)
Consumption of energy (kWh/kmol HCOOH produced)	18.6 (Saavalainen et al. 2017)	71 (Saavalainen et al. 2017)
Separation units consumption (kWh/kmol HCOOH)	25.6 (Saavalainen et al. 2017)	19.2 (Saavalainen et al. 2017)

to the report, Method A, the commercial production of formic acid, which was developed decades ago, is more sustainable. While producing formic acid with CO_2, there are several improvements in material quality needed. In terms of raw material selection, Route B, on the other hand, is very competitive. The key benefit of contrasting the planned path to the economic path is that it highlights the sustainability metrics that need to be improved in order to compete with commercial routes. Even though the raw materials used in Method B are renewable and more sustainable, the process must be significantly changed in terms of chemical ancillaries used in order to be more sustainable.

Table 4 shows a comparison in terms of carbon footprints (CF) and energy consumption for both methods. Method A consists of a two-stage process: In the first stage, methanol is carbonylated with CO, and in the second stage, methyl formate is hydrolyzed to formic acid and methanol. The CF of CO_2 per kg of formic acid produced is 2.2 kg/kg. While Method B has a lower CF value of 0.16 kg/kg due to several reasons: The first H_2, which feeds the process, is supplied by water electrolysis, and the CO_2 use and capture plants are at the same site (no transport is needed). On the other hand, the energy consumption of producing formic acid in Method B has a higher value than Method A. This action demonstrates that creating formic acid from CO_2 need higher energy than CO. However, the separating stage needs more power in Method A, which formic acid needs the energy to separate formic acid from other byproducts.

As mentioned before, producing formic acid from CO_2 needs to be developed to make it a commercial route. By using CO_2 to produce formic acid, the raw material is derived from a waste emission and it is more environmentally friendly considering the complete carbon cycle. It is also proposed to generate formic acid by adding renewable sourced- heat to reduce the environmental effects of using catalysts. Energy consumption is one of the significant drawbacks of producing formic acid from CO_2 and H_2. Another fundamental solution to reaching an even carbon cycle is using renewable energy for the complete phases.

5 Conclusions

H_2 storage in the form of formic acid can help to deploy the H_2 economy. Unlike electricity, H_2 storage allows vast quantities of energy to be stored for long periods of time. Formic acid is used as H_2 carrier for a variety of purposes. Since it is the simplest carboxylic acid, it is easily biodegradable. As a result, it is environmentally friendly and a non-toxic, ecologically benign, and low-flammable liquid. Both H_2 and formic acid are non-toxic and have no adverse effects on health; however, formic acid, if inhaled, has a detrimental impact on health. Because of its low flammability, formic acid is safe to use in the field. H_2 is a highly flammable gas, which can explode if mixed with oxygen. Formic acid is simple to store and can be kept in its original container under normal conditions. Containers can be made of polyethylene and polypropylene at low temperatures due to their acidic properties. If both H_2 and formic acid are being used to eliminate and monitor hazards, mitigation measures should be considered. Two formic acid production methods are compared based on the Sustainability Assessment of Technologies (SAT) in this study. The cumulative scores for the synthesis of formic acid using CO and CO_2 are 69.28 and 75.97, respectively. This finding indicates that the synthesis of formic acid with CO is currently more sustainable. Furthermore, due to the thermodynamically unfavorable forming reaction, producing formic acid from CO_2 and H_2 as raw materials requires more studies. Finally, formic acid synthesis from CO_2 and H_2 has the potential to be one of the future CO_2 abatement solutions, requiring less fossil fuel consumption and providing an electricity storage system.

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