Green Energy and Technology

Jacqueline A. Stagner
David S.-K. Ting *Editors*

Sustaining Resources for Tomorrow

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Green Energy and Technology

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To those who strive to preserve resources for the next generations.

Preface

Ralph Marston rightly put it, “What you do today can improve all your tomorrows.” The time to make sure there are life-supporting resources for tomorrow is today. If tomorrow is the day after today, then renewable alone will not make it, and thus, the opening question chapter (“Energy, Renewables Alone?”) by Reader, Energy, Renewable Alone? Water is definitely one key resource for sustaining tomorrow’s generations. Its use, along with energy utilization, provide an indicator more than just economic development. Expósito et al. apply the southern Spain context in chapter “Exploring EKCs in Urban Water and Energy Use Patterns and Its Interconnections: A Case Study in Southern Spain” to capitalize on water and energy usage data to forge policies to ensure sustainable management of these resources beyond today. The scarce life- and/or plant-sustaining phosphate—is an indispensable resource. To mitigate the rapidly diminishing phosphate, Mukherjee et al. detail ways to recover this vital ingredient from phosphate-rich wastewater in chapter “Mining Phosphate from Wastewater: Treatment and Reuse”. For vegetarians and omnivores alike, sustainable living literally equals sustainable agriculture. In chapter “Toward Sustainable Agriculture: Net-Houses Instead of Greenhouses for Saving Energy and Water in Arid Regions,” Abdel-Ghany and Al-Helal explicate the advantages of net-houses instead of greenhouses. In arid regions, this transition implies serious water and energy savings. No food means no future. Thus, sustainable food for thought is disseminated in chapter “Sustainable Food for Thought” by Ting and Stagner. Moving toward a more plant-based diet entails both a healthier and more sustainable tomorrow. As countries develop, their populations spend more time indoors. As such, green buildings are the way forward. Sua et al. disclose a multi-criteria assessment methodology to properly deduce the optimum natural insulation option in chapter “Tomorrow’s Green Buildings: Optimum Natural Insulation Material Modeling”. Other than the building’s insulation, the entire building must be accurately evaluated for its environmental impacts over its lifetime, as detailed by Hoxha in chapter “Improving the Uncertainties of Building’s Lifetime in the Evaluation of Environmental Impacts”. Sustainable buildings must be complemented by sustainable living. It is impossible to use a couple of sentences to describe the philosophical chapter, Sustainable Living? Biodigital Future! by Estévez; therefore, chapter "Sustainable Living? Biodigital Future!" is completely left for the reader to savor. Every being needs energy to thrive. To ensure energy security for tomorrow, Gökgöz and Güvercin emphasize the need to invest in renewable energy, solar, geothermal and ocean technologies, in particular, in chapter "Energy Security and Efficiency Analysis of Renewable Technologies". Large wind is by and large mature, not so for small wind. A timely review of challenges and opportunities of small wind is spelled out by Vilar et al. in chapter "Small Wind: A Review of Challenges and Opportunities". Energy storage is a given, especially as more intermittent renewable is to be realized. Abbate et al. provide the state-of-the-art of supercapacitors for high power storage. With the interplay of ever varied systems, it is necessary to "smarten" the grid. Nikolaidis and Poullikkas enlighten us on Sustainable Services to Enhance Flexibility in The Upcoming Smart Grids in chapter "Supercapacitor for Future Energy Storage". As hinted by the opening chapter by Reader, we still need fossil fuels into tomorrow. The associated challenges must thus be continuously and hastenedly mitigated. This book ends with Carbon Storage and Utilization as A Local Response to Use Fossil Fuels in A Sustainable Manner by Llamas et al. "Even if I knew that tomorrow the world would go to pieces, I would still plant my apple tree."—Martin Luther King, Jr.

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“Energy, Renewables Alone?”

Graham T. Reader

Abstract At the dawn of the twenty-second century, the grandchildren of those born at the start of the twenty-first century will be having their own children and the global population could have reached 11.2 billion. At such levels, the world’s energy demands could be 124% higher than in 2017. How can this increased demand be met? It is highly unlikely that traditional fossil fuels will be able to meet these future wants and needs because of their continuing depletion rates. Moreover, the accumulative amounts of carbon dioxide produced, since the start of the British Industrial Revolution in the eighteenth century, by the burning of such fuels can be correlated with increasing rises in global surface temperatures. It is these rises which have led to the growing public concerns about the detrimental impact of anthropogenic activity on climate change. Consequently, although fossil fuels provide almost 90% of today’s energy demand, additional forms of energy will be required for the future. But what will these be? A study by the Stanford University group, based on the energy scenarios of 139 countries, predicted that all their energy needs could be met by renewable forms by 2050. Whatever the accuracy of such predictions, the underlying assumption that all countries will buy into the wholly renewable scenario is highly optimistic. The World Energy Council, in their ‘hard-rock’ energy transition scenario for 2060, has suggested that the availability of local resources and the concomitant political pressures will prevent global collaboration on energy use and climate change issues. Thus, while the eventual transition away from the dominance of fossil fuel energy is inevitable, exactly how and when this will happen to remain matters of conjecture. The current development emphasis on alternative energy sources that are considered to be sustainable and renewable will likely continue. However, will such sources ever be able to meet 100% of the future global energy needs in the absence of carbon-based fuels, let alone the increasing demand for energy? In this chapter, the candidate energy sources, which are considered by some, if not all, to be renewable, are discussed against a background of the growing

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This chapter is, in part, based on a keynote presentation given by the author at the University of Windsor’s 2019 Energy for Tomorrow Symposium June 20–21, 2019.

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acceptance of climate change, government and regional energy policies, and associated incentives in an attempt to address the question, ‘Renewables Alone,’ at least for the remainder of this century.

1 Introduction

At the dawn of the twenty-second century, the grandchildren of those born at the start of the twenty-first century will be having their own children and the global population could have reached 11.2 billion. For although birthrates are decreasing universally, these are more than compensated by increases in life expectancy and the total population could be 48% higher, Fig. 1, than it is today [1]. At such levels, the world’s energy demands could be 124% higher than in 2017, Fig. 2 [2]. How can this increased demand be met? It is highly unlikely that the traditional fossil fuels, which presently provide almost 90% of global energy needs, will be able to meet these future needs because of their continuing depletion rates [3]. Moreover, the accumulative amounts of carbon dioxide produced, since the start of the British Industrial Revolution in the eighteenth century, by the burning of such fuels can be correlated with increasing rises in surface temperatures which, in turn, has led to the growing public concerns about the detrimental impact of anthropogenic activity on climate change [4]. Subsequently, those alive at the end of this century could experience harmful increases in the global mean surface temperature (GMST), the degree of harm depending upon the global ability and commitment to achieving

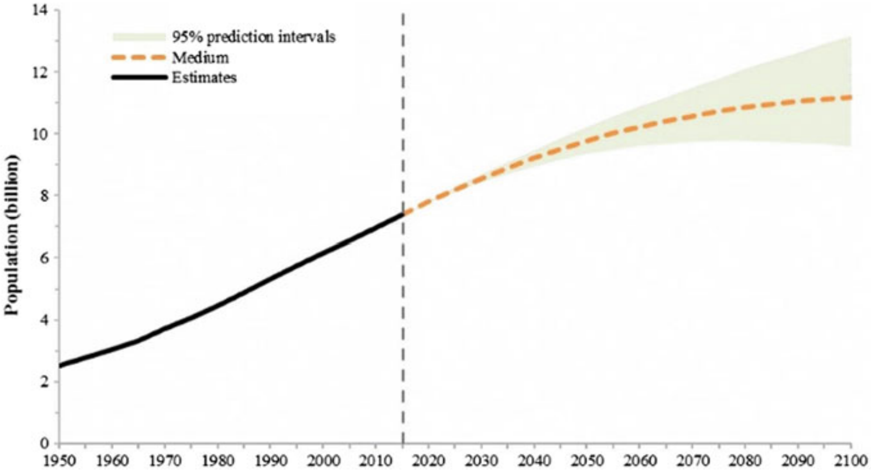

Fig. 1 United Nations World Population Prospects to 2100 [1]

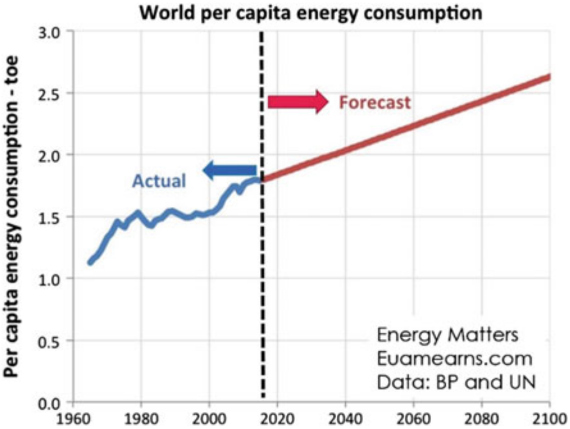

Fig. 2 Global energy demand to 2100 [2]

'Net Zero'[1] anthropogenic CO_2 emissions [5]. So, to meet future energy demands additional forms of energy will be required to at least compensate for the shortfalls in fossil fuel resources, but also to address the effects of anthropogenic climate change [6]. But what will these be? The current development emphasis on alternative energy sources that are considered to be sustainable and renewable will likely continue and may provide the desired solutions. However, will such sources ever be able to meet 100% of the future global energy needs in the absence of carbon-based fuels, let alone the increasing demand for energy? Yes, according to the Stanford University group led by the civil and environmental engineer, Mark Z. Jacobsen [7]. In 2009, they published a plan for a complete global transition to renewable energies by 2030 [8]. More recently, the group and its collaborators have used their intricately sophisticated climate modeling techniques to demonstrate that wind, water, and solar (WWP) renewable power sources could provide 100% of the energy needs for the 50 states of the USA, and at least 138 other countries, by 2050–2055 [9–11].

Projections by other groups and agencies are not as optimistic in terms of percentage renewables in future energy mixes, for example, the annual authoritative BP energy output reports [3, 12] in 2018 and 2019 forecast that about 25% of all power generation will be by renewables by 2040, Fig. 3 [12]. Additionally not all entirely agree with the Jacobsen group's hypotheses or their modelling techniques and conclusions, including some of the group's Stanford colleagues [13]. Such clashes of opinion and disagreements are not uncommon, and they are often considered to be part of the 'scientific process,' but in this case, the differences led to a civil lawsuit for defamation being launched although this was subsequently withdrawn [14]. However, as with all forecasts about future events, they are invariably based on hypothetical models, especially in the scientific world where the models will, or should be, tested against empirical evidence or validated past data. When future energy transitions are based solely on anthropogenic climate change models, the methodologies used

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[1] Net zero carbon dioxide (CO_2) emissions are achieved when anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period [4].

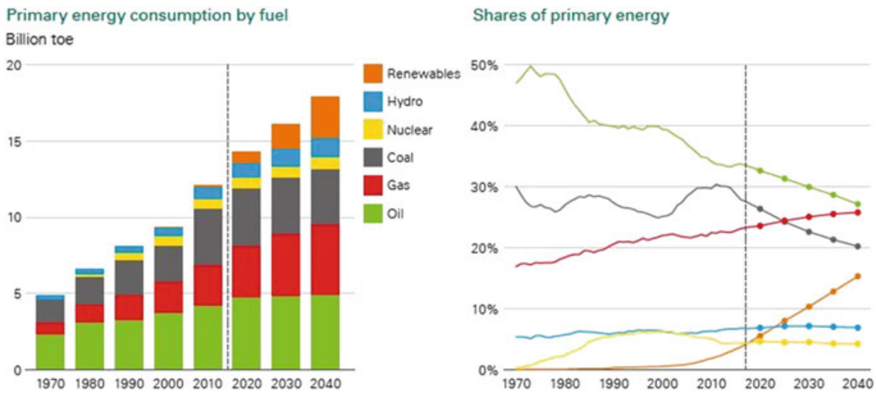

Fig. 3 BP 2018/2019 Annual Energy Outlook Forecasts [12]

to verify past data, especially before 1880, are the topic of some debate. Yet, even in the scientific world, there have been a number cases where the 'evidence-based theories' have been proven to be wrong, but the predictions have proved to be correct [15]. This has not been the case with predictions about when natural resources such as fossil fuels will be finally exhausted [16].

1.1 Fallible Predictions—The Demise of Fossil Fuels

Using fossil oil as an example, a significant problem with 'the end of predictions' is that they are usually based on 'proven reserves,' which is not a measure of actual known quantities, but is a technology-business-economics definition [17]. There are variants of the definition, but the one used in the oil industry being: 'Proven reserves are classified as having a 90% or greater likelihood of being present and economically viable for extraction in current conditions' [18]. Such economically based 'proven reserves' definitions can be applied to all natural resources not just oil. A non-fossil example would be the UK's Cornish Tin resources. Tin mining in Cornwall dates back some four millennia—at least—and activity peaked 150 years ago, but the last mine closed in 1998. However, 'the closure of the tin mines in Cornwall was never about running out of resources, it was in response to competition from cheaper tin from abroad' [19]. Yet, three years ago, in 2016, the Canadian company Strongbow Exploration announced they had acquired the mining rights to the 'famous' Cornish South Crofty[2] tin mine and preparatory engineering work began—and continues—with a view to starting operations in 2021 [20]. The main reasons being that price of tin has increased fourfold since the 1998 closure and more efficient and environmentally friendly extraction and processing technologies have rapidly advanced over the past decade.

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[2] Featured on the BBC–PBS TV series 'Poldark.'

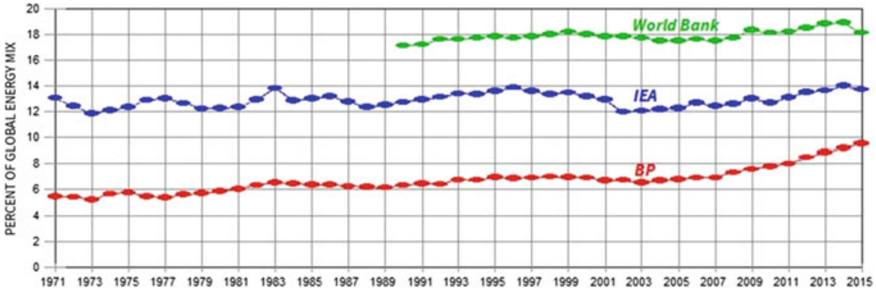

Fig. 4 Three estimates of renewables in the energy mix 1971–2015 [23]

Consequently, the amounts of a particular natural resource and the proven reserves of that resource can be quite different. For fossil fuels, the difference between the amounts of ‘resources’ and ‘proven reserves’ is a factor of 2.8–4 for oil, 4–58 for natural gas, and 14–23.5 for coal [21]. Depending upon the actual amount of fossil energy resources and the rate of extraction of the proven reserves could mean their longevity of use will be far longer than the current savants suggest. Nevertheless, regardless of whether there are sufficient fossil fuel resources for decades, centuries, or millennia, as a former long-serving Saudi Arabian Minister of Oil, Sheik Ahmed Zahi Yamani, is quoted as stating, ‘The stone age came to an end, not for lack of stones, and the oil age will end, but not for lack of oil.[3]’ So will the demise of the age of oil, let us say all fossil fuels, be brought about by the fear generated by the somewhat overstated ‘end of fossil energy’ scenarios? It seems more likely that the anxieties surrounding the pervasive climate change scenarios will result in alternative energy sources being exploited, especially those that are environmentally friendly, sustainable, and renewable.[4] However, such epithets are open to interpretation [22] so exactly what constitutes a renewable energy source varies as discussed in Sect. 2.

Depending upon the source of the energy data and how ‘renewable energy’ is defined, or at least categorized, such energies account for between 7 and 18% of global power generation, Fig. 4 [23]. This is a significant variation and it would be wise to neither exaggerate nor underestimate the global contributions of renewable energies particularly as in recent years other descriptions for renewable energies have been used, like ‘Alternative Energy, Clean Energy, Green Energy,’ and so on. The use of such depictions can lead to the number of types of renewable energies being increased, but also decreased, since not all renewable sources are considered to be clean or green and not all clean and green energies are renewable. Notwithstanding such issues, the literature indicates that many international organizations categorize 5 particular energy sources as renewable, but some identify 6, 7, and sometimes 11 categories [24–26]. Nevertheless, regardless of definitions and interpretations, the use of ‘renewable’ energy or non-fossil energy sources is on the rise and it is evident

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[3] Op. cit Reference [17], EME 831[6].

[4] Op. cit Reference [4].

that this increase, as a proportion of the global energy production and consumption, will continue.

1.2 Renewables and Climate Change

Usually, the main reason for switching from one form of energy to another is economics, i.e., costs to the producers and the users, and particularly 'national financial well-being' as measured by the Gross National Income (GNI) [27]. Numerous analyses have been developed in attempts to clarify the possible economic viability and potential advantages of global energy transitions to renewable sources. These determinations are invariably based, wholly or partially, on some form of life-cycle analysis (LCA), such as the levelized cost of energy (LCOE) [28] and the energy return on investment (EROI) [29]. In the first case, over a specified time period, the actual costs of energy production are calculated for a particular energy source, whereas in the second case, the amount of energy that has to be expended to produce a certain amount of energy is determined. These two forms of energy source comparators, while simple in concept, are notoriously difficult to apply in practice, and there is considerable variation in the results produced from such analyses as each country and region uses different methodologies in their calculation processes [30, 31]. The data that have been published indicate that conventional methods of energy/electricity production are still less expensive than other methods, but the LCOEs for utility-scale renewable wind and solar have dramatically decreased over the past ten years and both are becoming increasingly cost competitive. However, the economic basis for a transition away from conventional energy production and transmission has not as yet been fully established. What is clear is that financial incentives and penalties applied to the various sources have significant impacts especially on LCOE calculations [32].

Without significant demonstrable cost benefits, governments of the day must have enforceable policies that play key roles in energy switches or transitions and convince the voting public of the need for such policies. We live in a world where that public is fast becoming more politically aware and unrelenting in their demands for more accountability of their governments' decisions, such as the ratification of the non-binding UN's 2015 Paris Climate Agreement [33]. Of the 197 countries and 'parties' who have 'signed' the agreement, 185 have ratified it as of May 12, 2019 [34]. The USA withdrew from the agreement in 2017, but intimated they could rejoin in the future. The agreement came 'into force' in 2016 and its '*central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below* 2 °C *above pre-industrial levels and to pursue efforts to limit the temperature increase even further to* 1.5 °C." To achieve these aims, it has been determined by numerous scientific studies that the carbon dioxide generated by fossil fuel usage, past and present, is the main reason that global surface temperatures are rising. Thus, to prevent irreversible environmental damage, future carbon dioxide emissions need to be wholly eliminated or at least severely mitigated. Even if all such emissions were to stop today (literally), because of carbon dioxide's longevity in the atmosphere, and the ostensible delay in subsequent air temperature rises, it will be at least 40 years before global temperatures start to stabilize and at somewhat higher levels than at present [35]. To avoid the forecast harmful effects of climate change, including further sea level rises, it has been predicted that the maximum incremental temperature rise must be 2 °C or less by the end of the century, as embodied in the Paris Agreement.

So if governments are to fulfill their commitment to the Paris Agreement, they will need to ensure that at least 90% of the current energy sources are replaced by alternatives which, at the very least, do not emit carbon dioxide and can be available instantly, or as soon as possible. The latter scenario is more realistic. Nuclear energy should be an obvious candidate if reducing carbon dioxide is the singular aim, but for the majority of potential users, it is a politically and socially unacceptable solution. The favored alternative sources are the 'renewable' energies that are considered by the majority of scientists and politicians to be the panacea for the fossil fuel problems. But not all agree with the results of the calculations on which the elimination–mitigation timelines are based, or with the underlying assumptions and mathematical techniques used to make the predictive calculations [36]. Other scientists and media commentators have cast doubts on the climate change rationale for wholly transitioning to renewable energies, going so far as to label it a 'fraud' [37]. Indeed, since the publication of the now famous, or infamous, depending on your perspective, 'hockey-stick [38]' graph [39, 40] by the IPCC[5] in their third assessment report [41], doom-laden and equally forceful contradictory viewpoints have led to the ongoing so-called, Climate Wars. The climate change discussions have become increasingly politicized and polarized, especially in the USA. Most of the disagreements concern the carbon dioxide—average global temperature 'predictions'—for the time before temperature instrumentation became available. In more modern times, the lack of temperature measurement stations in the southern hemisphere compared to the northern hemisphere has led to queries regarding 'average' global data. The topic that dominates the debates is whether climate change is influenced more, if at all, by anthropogenic activity than natural forces.

Intuitively, with the extraordinary increase in global population over the last two centuries, is it not reasonable to surmise that human influences impact global change along with natural causes? The 'modeled' anthropogenic influences [42] are shown in Fig. 5 in comparison with the observed global temperature increases. Of the four identified influences, the main driver is the increase in the amounts of, the unfortunately named [43], greenhouse gases (GHG), of which carbon dioxide has been determined to be the largest contributor to the 'greenhouse effect' mainly for the reasons previously mentioned, i.e., because of its retained longevity in the atmosphere compared with the other principal GHGs and its high annual emissions [44]. However, its ability to absorb energy per unit mass, its 'radiative efficiency,' is less than other GHGs [45, 46].

Jurisdictions, local, national, and international have largely accepted that the underlying scientific basis of climate change model predictions, i.e., the rise of global

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[5] IPCC—Intergovernmental Panel on Climate Change.

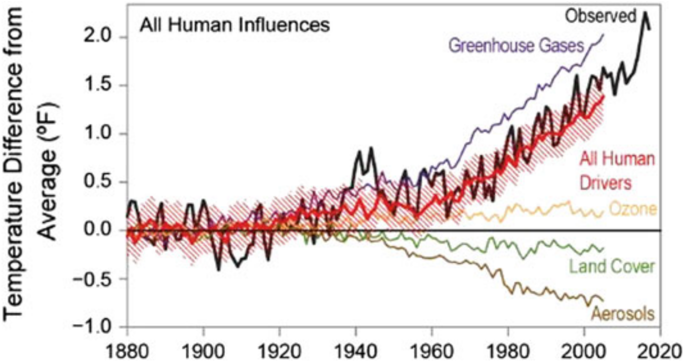

Fig. 5 Human influence on observed global temperatures [32]

air temperatures, is sound. But what is this scientific basis and why does it attract criticism from some quarters? The basic science behind the causes of climate change models has its origins in the early twentieth-century work of the Norwegian physicist and meteorologist, Vilhem Bjerknes, who developed a graphical means to predict weather based on a set of seven partial differential equations and the 'accepted physics' of the time [47]. The work was further extended after the two world wars of the 'killing' twentieth century largely because of the arrival of electronic computation, which enabled numerical methods to be applied to the solution of the seven core equations for weather predictions and produce forecasts much faster. An American meteorologist, Jule Gregory Charney, was the originator of the use of computers and he went on to play a significant role in devising increasingly sophisticated mathematical models of the atmosphere until his untimely early death in 1981, less than two years after his report on 'Carbon Dioxide and Climate' [48] set the stage for acceptance of anthropogenic global warming and the role of carbon dioxide in the warming [49]. This connection was enunciated in the many publications [50] by the noted climate scientist and activist, James Hansen, and in his 1988 testimony to the US Congress, which was instrumental in bringing the issue 'Global Warming' [51] into the political arena.

The work of Charney and Hansen has led to ever more sophisticated mathematical models and scientific hypotheses, and at the same time, actual measurements of air and ground temperatures and GHG concentrations are becoming increasingly trustworthy, providing benchmarks against which the various models can be tested. Even so, there appears to be growing concerns about the underlying science of the models, in particular the 'radiative' heat transfer[6] aspects along with the weighting of so-called Climate *Feedbacks, Forcings, Sensitivities and Response Times*[7] [52]. Time will tell if the concerns are justified and if the climate models are accurate predictors, especially with regard to the role played by carbon dioxide, the other

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[6] Author comment, essentially the basis for 'Greenhouse' effect.

[7] Op. cit. Reference [52].

identified greenhouse gases, clouds, and especially the oceans. Whatever the outcome of the ongoing, at times acrimonious, discussions and disagreements about 'Global Warming,' which is now typically referred to as 'Climate Change,' it would be surely negligent not to consider what other sources of energy will and could be available in the 'three-generation' future and beyond.

2 Renewable Energy 'Candidates'

As previously mentioned, exactly what constitutes a renewable energy source is open to various interpretations in the literature, a few examples of which are given in Table 1.

A common theme is that renewable energy sources are being constantly renewed and 'simply cannot run out' [57], 'they will not be depleted' [58], *[they]* are inexhaustible [59]. If such phrases were to be pedantically applied, then there are no sources of renewable energy. The sun has already used 50% of its hydrogen fuel and will eventually engulf and destroy the earth [60], but that will be in a few billion years. However, long before the final extinction takes place, as the sun gets brighter [61], the Earth will become uninhabitable for humans, but once again the timeframe will be in the hundreds of millions, or even a billion years and other natural apocalyptic incidents[8] could occur before then, although unlikely.[9] So it is not an overreach to consider that solar sources are renewable for as long as humans survive on the Earth. As wind and water energy sources are also derived from the sun's transmitted solar energy, then these too can be considered as 'renewable' sources within the basic premise of the renewable definition. Nonetheless, this longevity may not be true for all forms of identified 'renewable' energy. To acknowledge these limitations, many of the definitions include caveats such as, 'naturally replenished on a human timescale' [62], 'sources that will not be used up in our lifetimes' [63], 'can be replenished within a human's lifetime.'[10] While these provisos have been made with good intentions, they can be open to misapplication. So, for this discussion of renewable energy sources for the twenty-first century, the definition[11] given in the IPPC's 'Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN)' will be used as a general guideline:

> Renewable energy (RE) is any form of energy from solar, geophysical or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use. Renewable energy is obtained from the continuing or repetitive flows of energy occurring in the natural environment and includes low-carbon technologies such as solar energy, hydropower, wind, tide and waves and ocean thermal energy, as well as renewable fuels such as biomass.

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[8] Such as asteroid collisions, super-volcanic eruptions, cascading earthquakes, etc.

[9] Op. cit. Reference [68].

[10] Op. cit. Reference [55].

[11] Op. cit. Reference [28] p. 958.

Table 1 Examples of 'renewable' definitions

Definition	Source
Renewable energy, often referred to as clean energy, comes from natural sources or processes that are constantly replenished	https://www.nrdc.org/stories/renewable-energy-clean-facts#sec-whatis [53]
Renewable energy is energy from sources that are naturally replenishing but flow-limited. They are virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time	https://www.eia.gov/energyexplained/?page=renewable_home [54]
Renewable energy is energy produced from sources that do not deplete or can be replenished within a human's lifetime	https://www.studentenergy.org/topics/renewable-energy [55]
Renewable energy sources are sources of energy that are constantly replenished through natural processes … Fossil fuels produce energy but their supply is limited because they don't naturally replenish on a short enough timescale for humans to use	https://news.energysage.com/five-types-of-renewable-energy-sources/ [56]

Obviously, nuclear and fossil fuel energy sources are not included in the IPCC definition although in the latter case it appears they can naturally replenish [64] but not on a short enough timescale for humans to use. While it is becoming apparent that the origin of 'fossil' fuel deposits may not be as well understood as previously supposed [65] they still produce carbon dioxide when combusted. On the other hand, nuclear power is the second largest source of low-carbon power, generates over 10% of global electricity, 20% of the USA's [66], and according to the International Energy Agency's World Energy Outlook (2018) [67] this proportion will remain constant until 2040, and the more optimistic World Nuclear Association's 'Harmony' program [68] has a goal of providing 25% of global electricity by 2050. If the reduction in global emissions of carbon dioxide advocated by the IPCC is to be met by mid-twenty-first century, and nuclear power is to play a role then, as stated by the IPCC, '*Continued use and expansion of nuclear energy worldwide as a response to climate change mitigation require greater efforts to address the safety, economics, uranium utilization, waste management, and proliferation concerns of nuclear energy use*' [69]. The latter concerns were addressed in a paper by Jacobsen [70] ranking energy-related solutions to global warming and which concluded that the large-scale expansion of nuclear energy would '*further increase the risk of nuclear war and terrorism*' and that if a limited nuclear war occurred in 'megacities' over the next 30 years (2038)[12] up to 16.7 million could be killed and result in short-to-medium time cooling due to soot emissions while the burning of combustibles would generate CO_2 emissions '*[that] would cause long-term warming,*' and thus, nuclear was ranked ninth of the 12 global warming solutions reviewed. If nuclear energy were not to be part of the carbon dioxide mitigation tapestry and indeed was wholly

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[12] The Jacobsen paper [81] was originally published online in 2008, so thirty years hence is 2038.

eliminated,[13] then renewables or other alternative energy sources would need to fill the consequent energy gap. This is what Germany intends to do as part of the country’s official *Energiewende* (Energy Transition) policy [71] and is set to phase out nuclear energy. By 2022, approaches favored by 81% of Germans [72].

So having discounted nuclear and fossil energy as renewable energy, are the only renewables those identified by the IPPC’s special report?[14] What does the rest of the open literature identify as renewable energy sources? A Google™ Scholar article search[15] for ‘renewable energy’ listed about 2.16 million reports, papers and books, 375,000[16] from the years 2015 to 2018. Such a database of information would probably take several lifetimes to digest let alone analyze. To circumvent such a task, the 1088 page IPCC’s SSREN report is a worthy starting point, as this was the result of a review compiled by 122 lead authors, 25 review editors, and 132 contributing authors and subjected to further external reviews by more than 350 experts.[17] IPCC identified six specific renewable energy sources and technologies, and other leading energy agencies have also identified analogous if not wholly identical renewable sources.[18] For example, BP does not consider hydropower to be a renewable energy source, especially large-scale hydropower, as is the case with California Energy Commission. However, all categorize solar, wind, geothermal, and ‘bioenergy–biomass–biofuels’ as renewable sources with hydropower being included by four of the agencies, three without caveats, see Table 2. The present and predicted uses of these sources are discussed in the next section.

3 Present and Future Use of Renewable Energies

An encyclopedic survey of the favored and agreed renewable energy sources is outside the much narrower scope of this paper. However, as the theme of this chapter paper has been set against the time period used by the Paris Agreement, i.e., 2100, perhaps a good indicator of the renewables that can be expected to play an increasing role in the future use of such energy sources is the amount of financial investments that are being made in particular technologies? If only global totals are used this could result in a skewed portrayal of likely renewable developments, both current and future. For example, although new investments over the past decade in geothermal energy are much lower than for most other renewable sources, especially in 2017 [75], Fig. 6, 25% of Iceland’s electricity is produced by geothermal sources along with heating for 90% of its buildings. Moreover, its electricity is a third cheaper than

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[13] Germany is phasing out nuclear energy by about 2022 as part of its *Energiewende* policy.

[14] Op. cit Reference [28].

[15] Last accessed 6-2-2019.

[16] A climate change scholarly article search for 2015–2018 listed 576,000.

[17] Op. cit [28], page ix.

[18] In addition, the California State Government also includes battery storage, but this is more of a zero-carbon source than a renewable source.

Table 2 Renewables as listed by state/international organizations

IPCC-SSREN Renewable[a]	International Renewable Energy Agency (IRENA) [73]	British Petroleum (BP) 2018 and 2019 Energy Outlook[b]	US Energy Information Administration (EIA)[c]	California Senate Bill 100[d] [74]
Direct solar energy	Solar	Solar	Solar	Solar
Wind energy	Wind	Wind	Wind	Wind
Hydropower	Hydropower		Hydropower[e]	Small hydro[f]
Geothermal energy	Geothermal	Geothermal	Geothermal	Geothermal
Ocean energy	Ocean			
Bioenergy	Biomass	Biomass	Biomass	
		Biofuels		Biofuels

[a] Op. cit. Reference [24]
[b] Op. cit. References [3] and [12]
[c] Op. cit. Reference [54]
[d] Also known as the 'The 100% Clean Energy Act of 2018'
[e] Includes Tidal and Wave Energy and Ocean Thermal Energy Conversion
[f] Only hydropower plants producing less than 30 MW qualify under California's Renewable Portfolio Program (RPS)

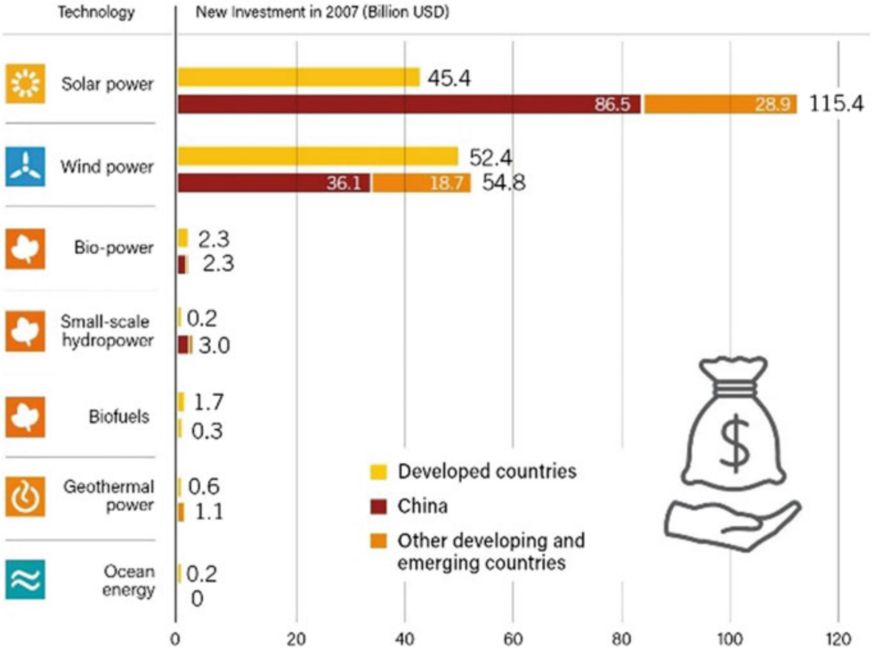

Fig. 6 2017 new investments in renewable energies (2007 US $) [75]

in countries like the UK [76]. The Iceland–UK cost comparison is an illustration of how a particular choice of renewable energy works better for some countries than others. In general, the choice of which renewable sources to develop depends upon a multitude of factors: physical, political, and philosophical.

3.1 Geothermal

Iceland is not among the top five geothermal users [77]. Indeed, the top user of geothermal energy is the USA, which has more than five times the present capacity of the Icelandic facilities and almost a third of global geothermal energy production [78]. But what exactly is geothermal energy?

Geothermal energy comes from the natural generation of heat energy largely due to the decay of naturally occurring radioactive isotopes of uranium, thorium, and potassium [79] in the Earth’s crust. It has been used for millennia for heating purposes (direct use) and commercial activities since the fourteenth century [80]. So why is geothermal energy not a major contributor to energy production, in general, and the renewable energy tapestry, in particular? The primary reasons have been cost (especially compared to fossil fuel power generation) and geographic location. The Earth’s geothermal gradient is on average about 25–30 °C/km, and in Iceland, this gradient is 200 °C/km as a result of the island being close to tectonic plate boundaries. For locations close to such boundaries, and normally their higher geothermal gradients, makes geothermal energy more attractive since for electricity production the technology requires that temperatures of the water heated by geothermal activity are at least above 150 °C and preferably above 200 °C, making geothermal plants in the Pacific ‘ring-of-fire’ especially attractive. The higher thermal gradient also lessens the depth that drilling is required to utilize the heat energy of the ‘hot rocks.’ However, improving technologies are now making geothermal energy appealing for other geographic locations for the purposes of district heating and cooling as well as electricity generation.

One such location is Switzerland [81], where after a few false starts the government is set to increase feed-in tariffs for geothermal energy generation [82] to encourage development. The main reason for the false starts has been the public reaction to the increased seismic activity resulting from the drilling (fracking) operations. On occasion induced or triggered ‘earthquakes’ of Richter magnitudes up to 3.9 have resulted from such operations which, although they very rarely cause human injury or infrastructure damage, are disconcerting, especially to those who do not have prior experience of such phenomena [83]. Nevertheless, a number of countries such as Switzerland and the USA [84] have developed drilling protocols for the ‘seismicity’ associated with geothermal systems to avoid such occurrences. However, some scientists argue that the 5.5 magnitude earthquake at Pohang, South Korea, on November 2017, which resulted in injuries to 60 and damages estimated at US $50M, was the result of geothermal drilling, but others disagree [85]. The work being done on ropes made of the ‘wonder’ material graphene, being used as

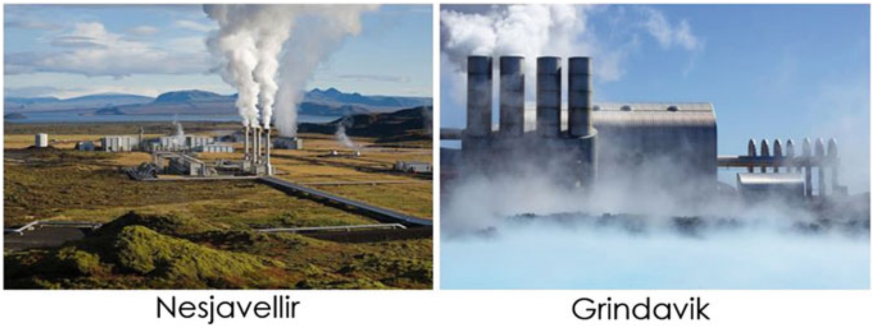

Fig. 7 Icelandic geothermal plants [87]

energy transfer devices in geothermal systems, may lead to the elimination, or at least an amelioration, of the induced seismic activity concerns [86], but for the moment issues associated with cost, location, and seismic activity along with some GHG and other toxic emissions need to be overcome to the thorough satisfaction of users, producers, and investors—including governments—before geothermal energy becomes a major factor in the expected journey to a renewable energy future. Interestingly, when photographs of geothermal installations are shown in the media, Fig. 7, e.g., [87], producing steam they are not cited as being indicative of pollution as are similar pictures of fossil-fueled power generation plants!

3.2 *Hydropower*

It is not only media reporting that can lead to public misunderstandings. International, national, and regional definitions of exactly what are clean, sustainable, and renewable energy sources often add to such confusions. For example, at the start of this millennium, hydropower, which produced almost 40% of the USA's electrical power in the last century and now only contributes 6%, appeared to be one of the major methods of producing carbon-free renewable energy to replace fossil fuel sources and mitigate the effects of 'global warming,' but this is no longer the case. Today, in many global jurisdictions, hydropower is only considered renewable if the existing installation produces less than 30–40 MW of electrical power. In the US states of Michigan and Missouri, hydropower is termed a non-renewable energy source if new dam construction is required. This relatively recent aversion to hydropower is because of a litany of issues involving habitat degradation, destruction of fish stocks, natural water flow disruption, generation of methane and carbon dioxide emissions, and displacement of human population. In the latter case, the impact of the world's largest power station plant at 22.5 GW, i.e., the Chinese 'Three Gorges' hydroelectric dam, is said to have displaced at least 1.2 M people. This level of displacement would seem to be a colossal number to all nations, other than India. For China, it represents

0.086% of its population. The amount of energy generated by the Three Gorges power station could power the whole of Norway with sufficient power remaining to meet the annual total energy needs of Cuba, Uruguay, and Sri Lanka [88, 89], combined. Surely, for a single non-fossil-fueled power plant to meet the whole of the energy needs for over 41 M people would be impressive, but some[19] believe that

> Hydropower is dirty energy, and should be regarded just like fossil fuel. And environmentalists, far from embracing it, should be battling to shut down hydropower plants and block the arrival of new ones just as vigorously as we work to close and prevent construction of dirty coal plants. [90]

Yet, it is not passionate environmentalists alone that are against utilizing water power, especially hydropower, and for at least two decades, publications in scientific journals have warned about the negative environmental and climate change impacts of hydropower. So, while it is somewhat nonsensical to not describe hydropower as a renewable source, the claimed scale of the generation of methane and carbon dioxide, two of the major greenhouse gases, from reservoirs and dams, is a principal player in the assertions that hydropower is a 'dirty' energy source and should not be counted in renewable inventories. The fact that bodies of water such as reservoirs and dams [91] can emit methane and carbon dioxide is valid. This happens when such bodies of water are created by 'flooding' an area without clearing the site of vegetation, e.g., trees, beforehand or are located close to significant agricultural activities. The carbon dioxide is generated by the rotting vegetation (underwater biomass), and also, some of the methane produced at the bottom of the reservoirs can be oxidized to carbon dioxide as it rises to the surface of the reservoir [92]. The methane is produced by bacteria living in reservoirs with oxygen-starved environments. The situation is compounded by the nutrient supply emanating from runoff from farmland. The severe warnings about the scale of methane production largely emanated from Brazil's National Institute for Space Research (INPE) who estimated dams are 'the largest single anthropogenic source of methane, being responsible for 23% of all methane emissions due to human activities [93].'

Not all dams and reservoirs have electrical generation facilities. For instance, there are 91,468 dams in the USA, of which only 7% (~6,400) have hydropower facilities [94]. The average age of US dams is 54 years, so it should be the case for many of the dams and reservoirs that did submerge rotting trees and other vegetation that their decay and consequent production of GHG has long since ended. But has it? A study published in 2014 [95] found that for all global inland waters, e.g., lakes and reservoirs, sunlight (solar radiation) is also a driver of carbon dioxide emissions from such bodies of freshwater, accounting for up to 10% of the total emissions depending on the cloud coverage. Moreover, if inland waters are located close to, or on, agricultural lands or are subject to the effluents from some industrial activities, then part of the methane generation problem will likely be due to untreated wastewater entering the lakes, rivers, dams, and reservoirs. Apparently, these 'water' problems will continue to increase in harmony with rises in global temperatures.

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[19] For example, 'The Waterkeeper Alliance fights for every community's right to drinkable, fishable, swimmable water'.

In their 2013 publication [96] on the physical science basis for climate change, the IPCC included 'freshwater outgassing' in their carbon cycle definition. So, if all hydropower facilities were abandoned and all dams dismantled the inland waters, problems would persist and it is not clear what such drastic actions would achieve. Moreover, hydroelectricity production is not wholly synonymous with all dams, lakes, reservoirs, and rivers.

'Run-of-the-river [97],' hydropower plants, both small and large, Fig. 8, use small ponds [98]. 'Pumped storage' hydroplants, Fig. 9, do not necessarily need reservoirs at all, but usually do globally as such plants are in the range of 1000–1500 MW, being in some instances as large as 2000–3000 MW [99]. The latest innovation, 'conduit or energy-recovery' hydropower attempts, to harness the energy from gravity feed drinking water pipes using micro-turbines in the supply lines, such as the LucidPipe™ power system [100]. The 'conduit' system replaces or greatly lessens the need for the pressure regulating (reducing) valves in the water feed systems [101]. Tidal and wave power are also forms of hydropower, but as of 2018, their contributions to global energy production are negligible. In its many forms, whether considered renewable or not, hydropower provided over 16% of the global electricity production in 2017 [102].

Nevertheless, the mantra '*small-hydro good, large hydro bad*' is afflicting hydropower development especially in many states of the USA and federally [103] because of the focus on the issues of GHG production. To address these issues, researchers at the International Hydropower Association (IHA) in conjunction with researchers in Canada, Norway, and Finland carried out a life-cycle emissions inventory of 498 reservoirs worldwide (178 single purpose + 320 multi-purpose) and reported that the global median intensity was 18.5 gCO_2-eq/kWh with an estimated 75% emitting less than 60 gCO_2-eq/kWh and 84% of reservoirs exhibiting less than

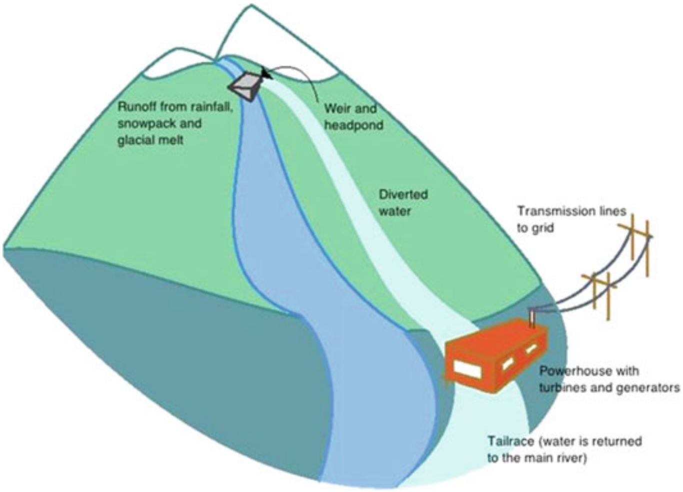

Fig. 8 Run-of-the-river hydro [98]

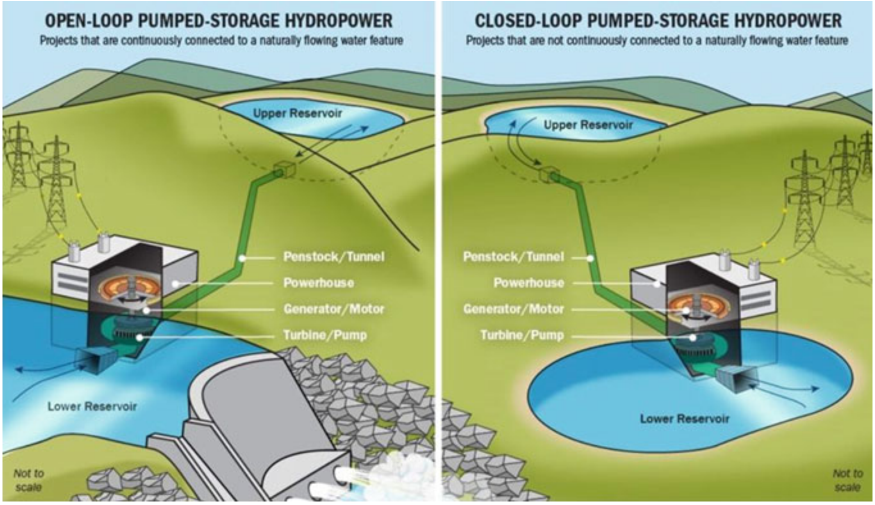

Fig. 9 Pumped storage hydro [99]

100 5 gCO_2-eq/kWh.[20] This median is far less than equivalent measures of CO_2 emissions from coal and gas burning electrical power generators and a factor of between 2.6 less than the life-cycle median emissions of solar PV panels (utility). Similar data on methane emissions have not yet been reported[21] by IHA. Until the methane matter is resolved the future of the accounting of hydropower as a renewable energy will remain contentious in many US states and in other regions because political and organized environmental entities meticulously enforce their definitions of ‘renewable’ and ‘sustainable,’ perhaps unrealistically. That is not to say that global hydropower projects do not continue, some of several GW of energy production, but many will not qualify as renewable as summarized in Table 3.

In some countries, and in many US states, the ‘renewable’ power definitions have as much to do with politics and vested interests as ‘science.’ In the USA, this is largely because of the so-called Renewables Portfolio Standard (RPS), these are legislated targets which specify the percentage of electricity sold by utilities which must come from renewable resources [105]. For many states, if hydropower sizes above the limits indicated in Table 3 were considered to be ‘renewable,’ then they would have already met their RPS targets. This means the further development of renewable sources such as wind and solar would be hard to justify to the taxpayers which largely fund such developments. Although some of the 39 states, four territories and Washington D.C. have cost limitations for RPS and similar schemes, 21 states also have ‘*carve-outs and credit multipliers (renewable energy credits)*’ or both, whereby a specific technology must be used to produce a precise amount of the state’s overall renewable energy target or electricity produced by certain technologies will receive

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[20] Op. cit [127]. The emission data were determined using the IHA-UNESCO tool G-Res.

[21] As of March 2019.

Table 3 Definitions of small hydropower[a]

Country/state	Small hydropower definition (MW)	Sources from[b] except for California [104]
Brazil	≤30	Brazil Government Law, # 9648, May 27, 1998
Canada	≤50	Natural Resources Canada, 2009, http://canmetenergy-canmetenergie.nrcan-mcan.gova.ca/energy/renewables/small_hydropower.html
China	≤50	Jinghe (2005), https://www.ipcc.ch/report/renewable-energy-sources-and-climate-change-mitigation/; Wang (2010), https://www.ipcc.ch/report/renewable-energy-sources-and-climate-change-mitigation/
EU Linking Directive	≤20	EU Linking directive, Directive 2004/101/EC, article 11a (6)
India	≤25	Ministry of New and Renewable Energy, 2010, www.mnre.gov.in
Norway	≤10	Norwegian Ministry of Petroleum and Energy. Facts 2008, Energy and Water Resources, p27
Sweden	≤1.5	European Small Hydro Association, 2010, www.esha.be/index.php?id=13
USA	≤5–100	US National Hydropower Association, 2010, Report on State Renewable Portfolio Standard Program (USRPS)
California	≤30	California Energy Commission, https://www.energy.ca.gov/hydroelectric/ [104]

[a] Op. cit. [24], A. Kumar et al., Chap. 5
[b] As of March 2019

additional renewable energy credits.[22] Needless to say, hydropower is not one of the specific or certain technologies. So, if only a very modest amount of hydropower energy is considered renewable, largely because of the unacceptable 'high' GHG emissions, then why are such emissions highlighted in the overall GHG emission inventories reported each year?

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[22] Ibid. 133.

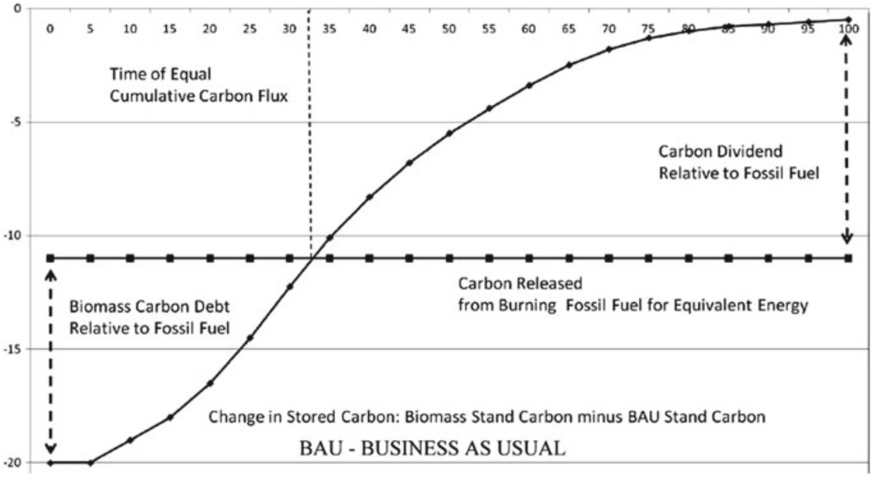

Fig. 10 Biomass carbon debt to dividend (a fuller description of Fig. 13 is given by Manomet [93] p. 6): BAU—Business as Usual

3.3 *Biomass*

Another of the renewable energies, see Table 2, biomass [106] when combusted produces large amounts of GHG emissions, especially CO_2 from wood burning, but biomass is considered to be carbon neutral [107]. Indeed, in some US states the amount of CO_2 produced from biomass can be actually deduced from their emissions inventories [108]. Over 80% of biomass is wood or wood scraps and will release carbon dioxide if burned. So how can these emissions be considered to be carbon neutral? The core justification is that the emissions can be sequestrated through new tree/plant growth as long as the replacement is 100%, a secondary justification for wood wastes, natural and man-made, is that if they were allowed to decay they would emit the same amount of carbon dioxide as if they were combusted.

Trees cannot be grown and reach maturity, or at least be ‘harvest-ready,’ instantaneously, so there is bound to be time lag between the release of the carbon dioxide from the burning process and its complete sequestration. As wood combustion produces significantly more carbon dioxide per unit energy than natural gas and coal,[23] there will be a period of time between wood harvesting and new tree/plant growth when there is a ‘carbon debt’ in comparison with fossil fuel combustion which should then be followed by a ‘carbon advantage’ provided there is sufficient new growth to match, at least, the harvested wood. This scenario is illustrated in Fig. 10,[24] the fossil fuel line is for a mixture of coal and natural gas usage. As can be seen, the increase in atmospheric CO_2 emissions from burning trees for energy will be present for many years. The delay before CO_2 advantages or benefits are achieved is called

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[23] Ibid. [137] p. 21.

[24] A fuller description of Fig. 13 is given by Manomet [118] p. 6.

the ‘carbon payback time’[25] and can be defined as, either ‘*when pre-harvest carbon levels are reached (absolute carbon balance)*,’ or as, ‘*time to carbon parity*’ when comparing carbon levels to a reference case (such as when fossil fuels are burned and the trees remain growing) [109]. The carbon payback time for biomass use depends on many factors and can vary between 1 year and 1000 years [110], for example, harvesting wood for fuel from Norwegian boreal forests can result in a carbon debt that takes 150–230 years [111] to repay. A Canadian study [112] indicated that there is great uncertainty in determining carbon payback and carbon parity timelines and in their modeling of three forest growth scenarios found that 78 years and over were required to achieve carbon parity depending upon which of the fossil fuels was used as the comparator. If wood burning is to contribute to carbon dioxide mitigation from next year and over the crucial next two decades (according to the IPCC 2014 report [44]), then it would appear that burning ‘stand’ wood will be counterproductive. Clearly, although burning biomass is not carbon neutral or particularly environmentally friendly and is not in compliance with the designation of a renewable energy, the acceptances of biomass burning is the result of political choices and cultural choices being made by consumers, industrial corporations, and other vested interests. Moreover, it has been reported that some 2.8 billion people use biomass for cooking [113].

3.4 Solar

The two remaining ‘renewables’ identified in Table 2, wind and solar, appear to meet all the regulatory requirements except during the manufacture and eventual disposal of wind turbines and solar devices, in particular photovoltaic (PV) cells. But can solar- and wind-driven devices be used in all locations? The answer is yes, but locating these devices in places where they can be used most effectively would appear to be obvious. Where are these places? Figure 11 indicates the scale of the global power potential of solar radiation [114].

Interestingly, the top five countries with the most installed solar capacity are not in the areas of maximum potential. Indeed, one of these countries, Germany, who since the start of this millennium have politically committed to being a global leader in solar power, can hardly be described as an especially sun-drenched country. Although solar ‘electricity’ generation especially by photovoltaic panels appears to receive most of the media attention, solar thermal [115] (conversion of light energy to heat energy) and solar chemical (conversion of light energy to stored chemical potential energy) are also increasingly important uses of solar irradiance [116]. In Germany, for example, heating makes up to approximately 40% of all energy consumption compared with about 20% for electricity consumption [117]. However, there has not been the same enthusiasm for adoption of solar heating by the German public

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[25] The measure can be applied to all types of renewable and low-carbon energy sources and technologies.

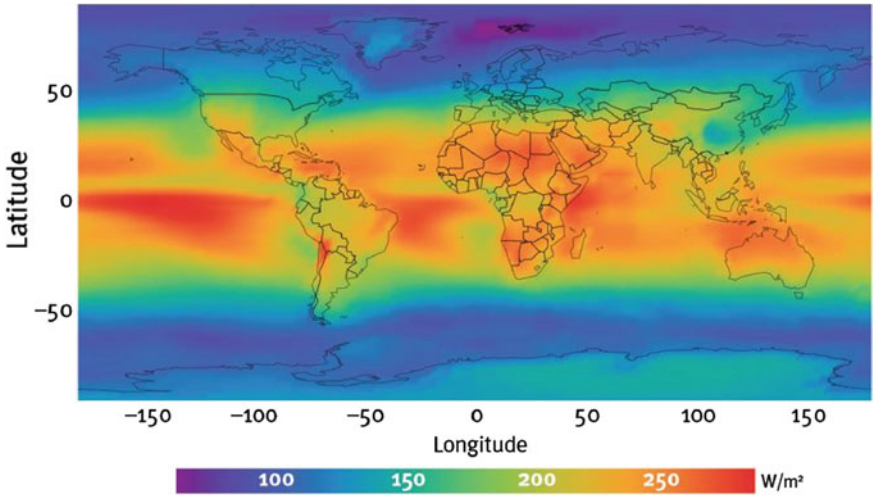

Fig. 11 Distribution of annual average solar irradiance [114, 116]

probably because the Government has not offered feed-in tariffs as they did with solar PV panels.[26]

The rapid growth in the use of solar PV technology and the associated industry in Germany began to slow as the feed-in tariff rate was reduced and far cheaper [118] imported solar panels from China began to flood the German market and caused the German Government to eventually impose import tariffs in 2013, but these had little effect and the antidumping tariffs were eliminated by the European Commission from August 31, 2018. In the meantime, some of the largest German solar panel manufacturers went into insolvency with the loss of thousands of jobs. The arrival of the Chinese solar panels also led to the demise of the sun-tracking solar dish–engine market especially in the USA just as that industry was achieving commercial breakthroughs and companies like Infinia had secured major contracts (MWs) for their free-piston Stirling dish system, Fig. 12 [119], but by 2013, the company had to seek Chap. 13 bankruptcy. The cost of the solar dish collectors and concentrators alone was far higher than the PV panels.

Although research and development on such systems continue in a number of global universities and small technology companies, it is unlikely that the dish–Stirling systems, despite their superior performance, will displace the PV systems. However, the concept of using concentrating solar thermal (CST/CSP) systems, Fig. 13, did survive, and since 2006, this has been growing at an annual rate of 40%, Fig. 14 [120], although still a small portion of overall global renewable energy generation.

There are four main concerns with the use of solar power, especially if used as a utility-scale installation. These are land use, competitive operational costs, waste disposal, and 'curtailment.'

As the energy density of solar power is extremely low, Table 4, the amount of

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[26] Ibid. [150] p. 73.

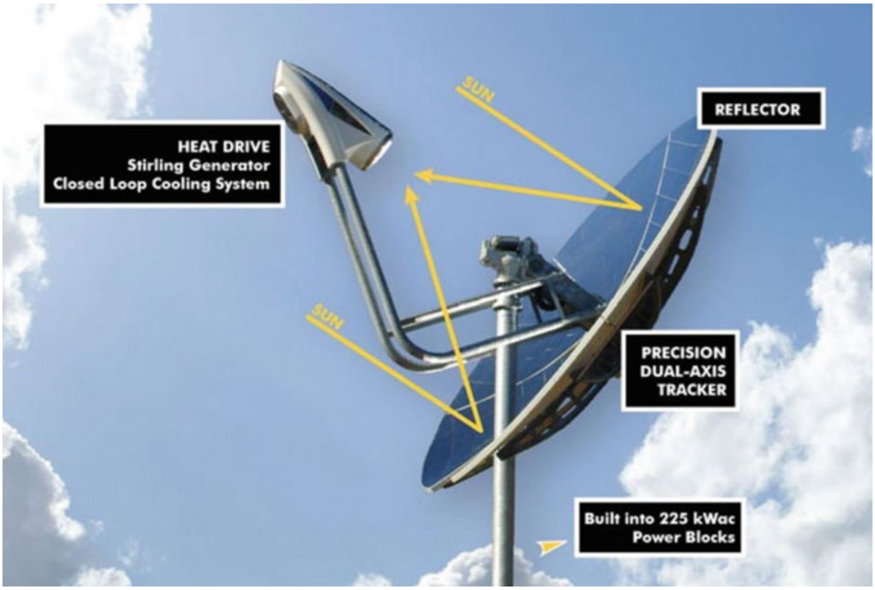

Fig. 12 Infinia™ free-piston solar Stirling system [119]

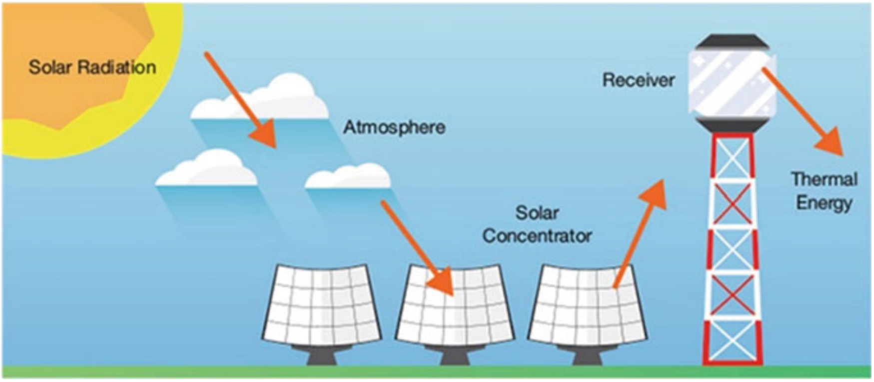

Fig. 13 Basics of solar CST/CSP [120]

land area needed is significant [121], ranging from 1.4 to 6.7 ha per MW, so, for example, it is claimed that as much as 450 times more land would be required for a solar farm (CSP) compared with an equivalent output nuclear system [122]. The USDOE 'Sunshot [123]' initiative for utility-scale solar would require over 2.5 million hectares of land by 2050. However, while this is just a small proportion of the total land area of the USA, direct and indirect environmental impacts from habitat fragmentation to reduced water quality to damaging ecological effects on wildlife could turn public opinion against the use of pristine lands for such purposes

Fig. 14 Growth in CSP since 2006 [120]

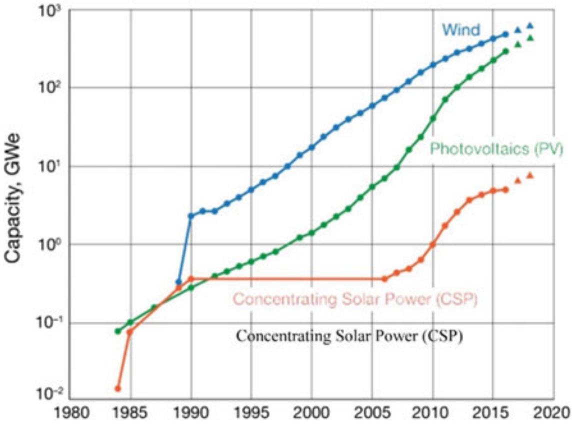

Table 4 Energy densities: [127]

Energy source	Joules per cubic meter
Solar	0.0000015
Wind (5 m/s) Betz Limit	7
Oil	45,000,000,000
Gasoline	10,000,000,000
Natural gas	40,000,000
Nuclear (breeder uranium)	1.54×10^{15}
Geothermal	0.05–0.1
Tidal power	0.5–50

[124]. To address this issue, the potential use of so-called marginal[27] lands is gaining momentum in many US states. The amount of land used would be reduced if the energy conversion efficiency of solar PV panels could be improved. The majority of presently available commercial panels have conversion efficiencies in the 15–17% range although the best panels have ratings as high as 22%, but usually these are more expensive. However, over the last 5 years, the efficiency of some research solar cells has achieved levels up to 46% [125], and a Japanese design team has suggested that efficiencies of over 50% will soon be possible [126].

Potential increases in cell efficiency, at affordable prices, could be instrumental in addressing the second main obstacle to solar power growth, the achievement of competitive power generation costs. This was (and is) the core objective of the previously mentioned ‘Sunshot’ vision whereby solar power could meet 27% of all electricity needs in the USA by 2050 provided that costs could be reduced by 75% between 2010 and 2020, and a further 50% by 2030. It was considered if these levels of LCOE [128] cost reduction could be obtained, and it would encourage further

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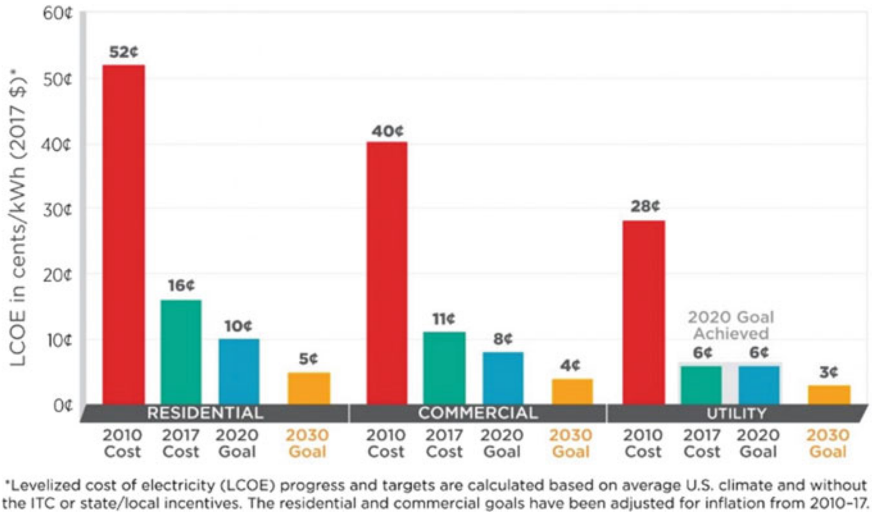
[27] In the USA, these include degraded and contaminated lands, former coal, and mineral mining sites and are defined by the USEPA as ‘Superfund’ or ‘Brownfield’ lands.



*Levelized cost of electricity (LCOE) progress and targets are calculated based on average U.S. climate and without the ITC or state/local incentives. The residential and commercial goals have been adjusted for inflation from 2010-17.

Fig. 15 US 'Sunshot' vision performance measures [129]

market penetration of solar power generation. So what has been achieved to date? The impressive performance of the Sunshot initiative is summarized in Fig. 15 [129].

While these data are only for a single country, the USA by 2017 had the second largest installed global solar PV capacity, even more than Japan and Germany, but some 60% less than China. The USA produces a tremendous amount of publically accessible (and free) data and information on energy use and is therefore a particularly interesting case study.

The average useful life of a solar PV panel is presently estimated at 30 years or less, and many of the early panels are now reaching the end of their life, or have been irreparably damage in severe weather events. Estimates showed that by 2016 between 43,500 and 250,000 tonnes of cumulative PV waste were produced which, because of the unprecedented increase in PV use since the start of this millennium, could rise to between 60 and 79 million tonnes by 2050 [130]. According to a United Nations report between 60 and 90% of all electronic waste is illegally traded and dumped in poor nations and a loophole in the regulations allow used solar panels to be legally exported from developed to developing countries [131]. The glass used in PV panels usually contains cadmium, lead, plastics, and other impurities which make recycling expensive. So who will pay? A number of solar companies have entered bankruptcy because the materials retrieved by recycling, produced revenues which were less than the processing costs. One of the problems is the designation of PV wastes as 'hazardous' as this increases the costs of recycling. But as different materials and manufacturing processes are used in producing PV panels, can they all be labeled as hazardous? This is a matter engaging industry and governments in most of the leading solar countries. Until the issue is resolved, either by lawmakers or by the development of economical recycling processes, there is bound to be a question

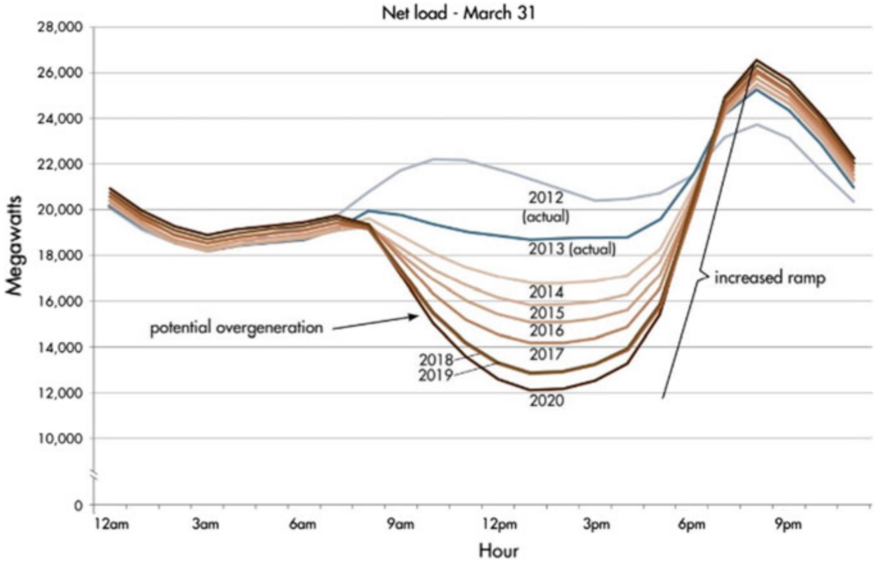


Fig. 16 NREL-CAISO ‘duck curve’ [133]

mark about the rate of growth in solar PV power usage. If recycling is mandated by law, then the increased life-cycle costs of such panels would be passed to producers and consumers with obvious consequences. So it appears that many solar panels will continue to be dumped in landfills, often located outside the country of origin or original use.

In 2008, the US Department of Energy’s National Renewable Energy Laboratory (NREL) published a report [132] dealing with the impact of the increasing use and benefits of solar PV energy on the traditional seasonal hourly power demand-supply requirements for the regions covered by the Western Electricity Coordinating Council (WECC),[28] especially California and Colorado. As the costs of solar PV energy production declined, the California Independent System Operator (CAISO) began to project the impacts of the increased use of solar on net demand loads and published the now well-known ‘duck chart,’ Fig. 16, in 2013, that has been featured in a multitude of publications [133]. The ‘duck’ profile is formed because solar power generation usually peaks around mid-day, and between sunrise and sunset has an approximately sinusoidal power–time profile, Fig. 17.[29] This means that the power required from the existing forms of power generation is reduced during the ‘solar-generation’ time period.

As a consequence, the former reasonably predictable power–time demand curves for the extant power facilities are changed, but how and by how much? The duck

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[28] Op. cit [137, p.5]. In 2008, the US Electrical Power system had three large electrical grids the WECC, the Eastern Connection, and the ERCOT (Texas) grids.

[29] Ibid. [169].

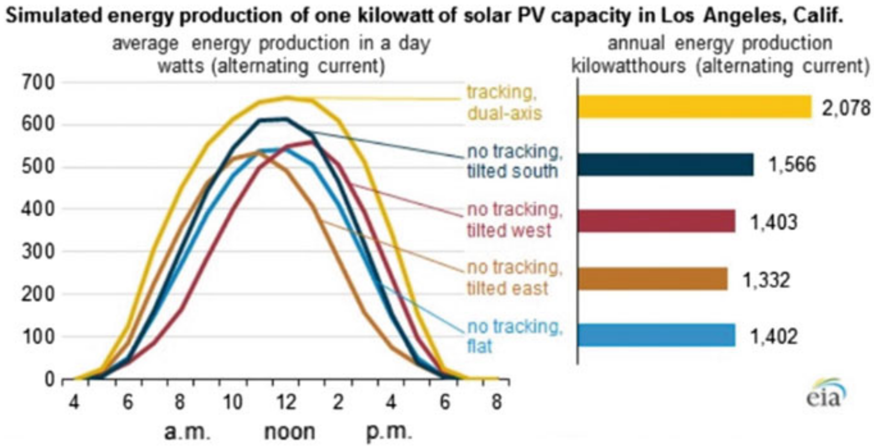

Fig. 17 Sinusoidal solar energy daily profile (ibid. [133])

chart is based on a hypothetical model used to illustrate how the historical electricity demand curves could be impacted by the intermittent power generation of solar PV systems as their contributions increase. As shown in Fig. 16, the greater the amount of solar power available the more the shape of the non-solar demand curve is changed giving a 'duck-like' profile [134] with an increasing 'belly' size. As it is difficult, and expensive, to turn on and off existing utility power generation facilities, there is a possibility of 'over-generation' and to combat this scenario the amount of solar power generation has to be operationally reduced or 'curtailed.' Overall, 'over-generation' and 'curtailment' have a negative impact on electricity production resulting in higher costs and in the loss of amounts of carbon dioxide mitigation possible from the use of solar power. However, the duck curve is hypothetical—what happens in practice? Although far more data and operating experiences are required before any type of definitive pronouncements can be made, the indications are that the duck chart is realistic, as demonstrated by the data produced, Fig. 18, by Independent System Operator (ISO) of New England [135].

This fourth issue is not so much a problem with solar power generation, but more to do with the integration of solar systems into traditional electrical supply grids, and the operation of the different forms of power generation which feed the grids. An overarching solution to these complex problems would be to find an affordable method of storing the energy produced by solar systems; although there are some promising technologies under investigation and development [136], it seems likely that, until these become commercially viable, the rate of growth in utility solar energy use will be somewhat stifled.

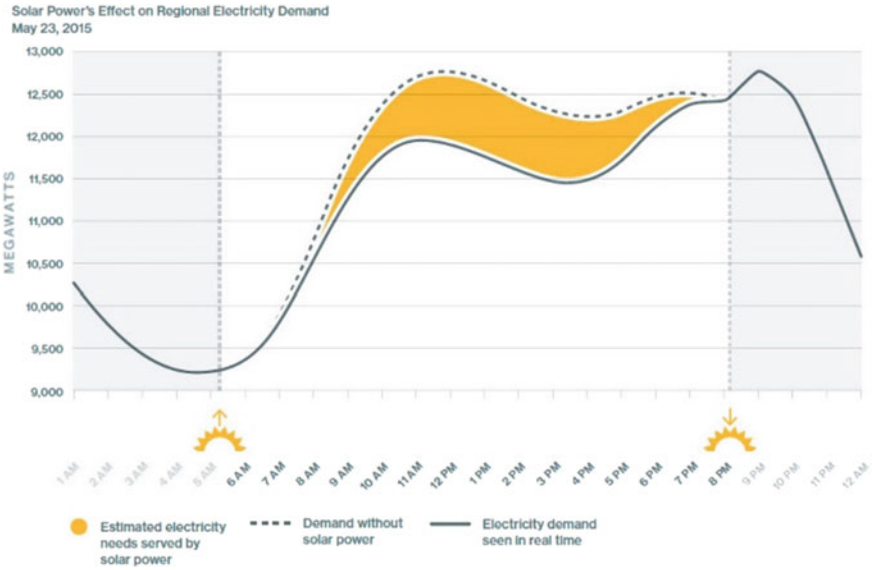

Fig. 18 Impact of solar energy on electricity demand in New England [135]

3.5 *Wind*

Wind, the other 'acceptable' form of renewable energy given in Table 2, is created by air moving high-pressure areas to low-pressure areas, and the main driver of the wind is air temperature differences caused by sunlight unevenly heating different parts of the planet. The global wind map, Fig. 19, is not, however, identical to the solar map in terms of energy potential for a variety of reasons. As can be seen, the

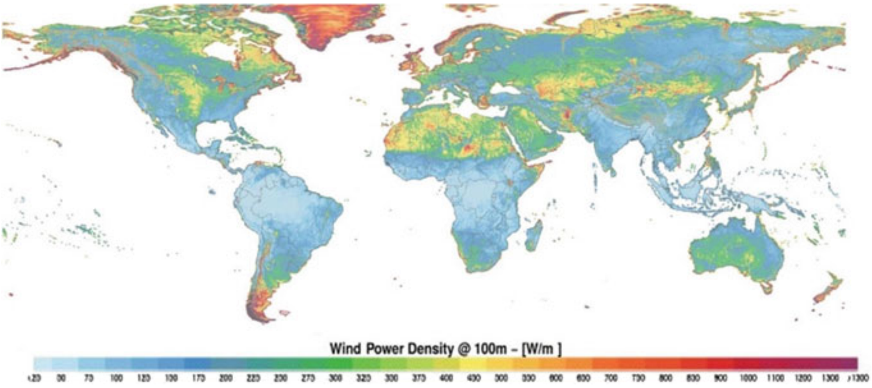

Fig. 19 Global wind power density map (see Footnote 30)

countries developing both onshore and offshore wind power generation, unlike solar power, are usually located in geographic regions with the greatest potential.[30]

Nevertheless, the variability and uncertainty [137] associated with utility wind power is analogous to that encountered with similar solar power use. 'Peak' wind power production does not occur at times of peak electricity demand, and although it is often claimed in the literature that peak wind power occurs at night, when solar irradiance has ceased, this is only true in some geographical locations. In places like the UK—which produced 17% of its total electrical energy from wind in 2017—the peak wind power time curves are similar to the solar–time curves, offset by a couple of hours past mid-day, Fig. 20 [138]. On the same figure, it can be seen that wind power does not peak at the end of the day in Germany, Denmark, and Ireland, but does in France and Spain.

The issues encountered with the increasing growth of wind power, while not identical, are very similar to those encountered with utility-scale solar power, as aptly described in a report prepared for the US Congress [139]. The aesthetics of large wind power farms, and the sounds, are concerns often expressed by members of public when the farms are located close to residential areas. To address the noise issues, many regulators specify a 'setback' which is essentially a space to be created

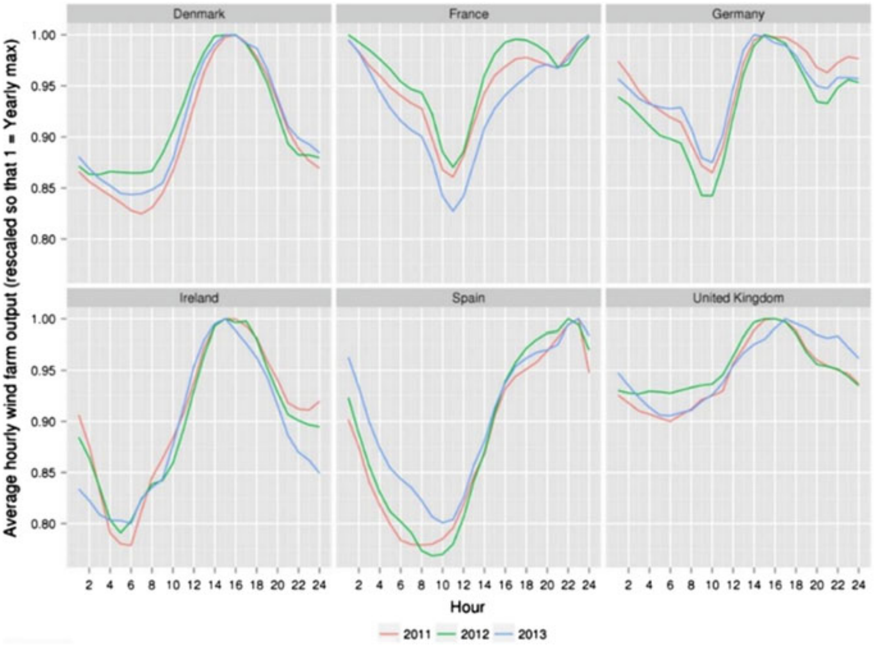

Fig. 20 Average hourly wind farm output for selected European countries [138]

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[30] It is not just the presence of prevailing winds that is important, but the range of the wind speeds as wind power is proportional to the cube of the wind speed.

between the areas of concern and the wind farm. However, there are no agreed national or international definitions of exactly what constitutes a 'setback' [140]. Although wind energy is more energy dense than solar power and most other defined 'renewables,' it is still far below those of fossil and nuclear energies, as illustrated in Table 4. Consequently, wind farms need significant swathes of land and access to that land, which opponents suggest could be put to better use, so wind farms in the future will need to demonstrate that they are the best economic use of the land. But how much land? A study conducted by the US DOE NREL [141] found that on average the amount of land used per MW was 35 ha. However, because of capacity factors (see below) and the need for turbine separation spacing to be equivalent to 15 rotor diameters for optimal operations [142], the land need, according to the 'Industrial Wind Energy Opposition' organization group, could be as high as 300 ha per MW of actual output [143]. With the significant technological advancements over the last decade, a ratio of 40–60 ha per MW (actual) is not uncommon for newer installations.

Regardless of the design of the wind turbine, there is a theoretical limit as to the amount of kinetic energy that can be extracted from open flow wind. This is known as Betz's Law,[31] which basically indicates that only 16/27th (59.26%) of incoming energy can be extracted. The more important technical performance parameter is the 'capacity factor' [144] of wind turbines which depends on wind speed, air density, and turbine swept area. In general, wind speed increases with height above ground level and tends to be steadier, but air density decreases, although at a height of 1000 m air density is still 90% of that at ground level. The greater the turbine swept area, essentially the length of the blades, coupled with increasing the height the blades are above ground level, allows more of the wind's kinetic energy to be harvested and the capacity factor to be increased. Thus, the trend, especially in the USA since wind turbines began to be deployed, has been to 'scale up' the installations [145]. As of October 2018, the tallest onshore wind turbine in the USA is 574 ft (175 m), and in March 2018, General Electric [146] announced that they were developing the world's tallest offshore wind turbine, the 'Haliade-X' at 853 ft (260 m), for installation in 2021, Fig. 21 [147].

There are also concerns about the threat to wildlife, especially birds and bats. Estimates of the global magnitude of the wildlife problem vary widely, but the US government [148] estimates that up to 500,000 birds annually are killed by collisions with wind turbine blades, and this figure could reach 1.4 million per year as the use of wind power is increased. Similarly, it has been estimated [149] that tens to hundreds of thousands of bats die because of such collisions each year in North America alone and because of their impact on insect control and crop pollination the loss of so many bats could be costing the US economy between $3.7B and $53B annually [150]. It must be noted that the birds and bats issues are guesstimates at best, and wind farm location, over which regulators can exercise control, appears to play a key role in providing, at least a partial, solution to this potentially significant ecological obstacle

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[31] Named after German naval engineer and physicists Albert Betz, although the English automotive engineer Frederick Lanchester had derived the 'Law' some 5 years before Betz and the Russian engineer Nikolay Zhukowsky published the same result just before Betz.

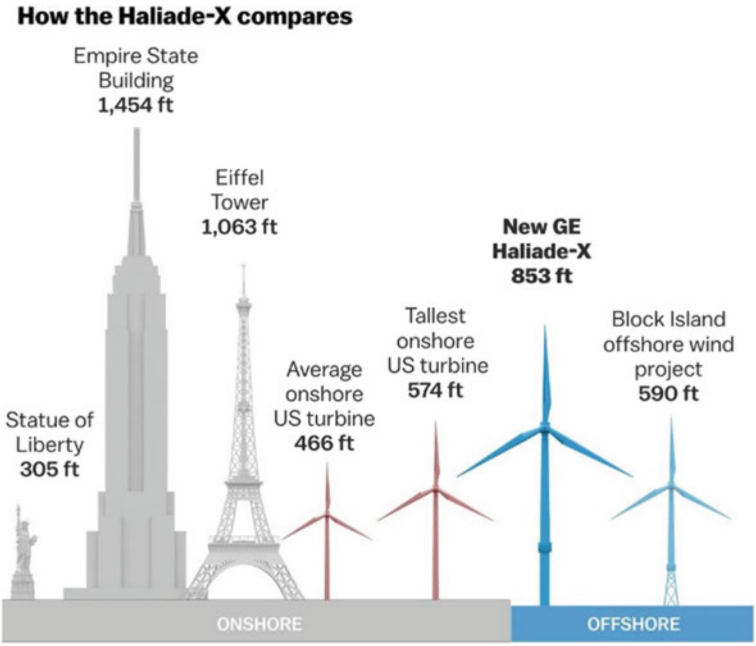

Fig. 21 Increasing height of wind turbines [147]

to wind power use and growth. These types of issues require far more investigation and data gathering especially for wind farms, but utility size concentrated solar plants are also encountering similar problems although on a much smaller scale [151].

The growth of wind turbine power, like some other renewables, has been made possible through financial incentives, tax breaks and feed-in tariff systems. What will happen when these 'subsidies' are removed, partially or wholly, is unclear. However, it is likely to depend upon the eventual cost of wind produced electricity to the consumer and, at least to governments, its beneficial contributions to national and global climate change targets, such as atmospheric reductions in carbon dioxide emissions, and the forecasted lowering of global average surface temperatures. Moreover, like the other favored 'renewable' energy—solar power—the problems with the disposal of end-of-life wind turbines will engage owners, users, and lawmakers. In the USA, compliance with Federal and State laws and regulations make it more difficult to use public lands to construct wind (and solar) power facilities and so at present most of the installed capacity is on private lands, which in many instances provides an additional revenue stream (license fees) for landowners such as farmers.

So will solar and wind power be widely adopted and met the increasing global energy demands of '*tomorrow's world*' as defined at the start of this paper? Obviously, as these are intermittent and variable sources of energy some energy backups will be required, but maybe all that is needed is energy storage? The USA, for example, has 431 MWh of electricity storage available [152], of which pumped hydroelectric

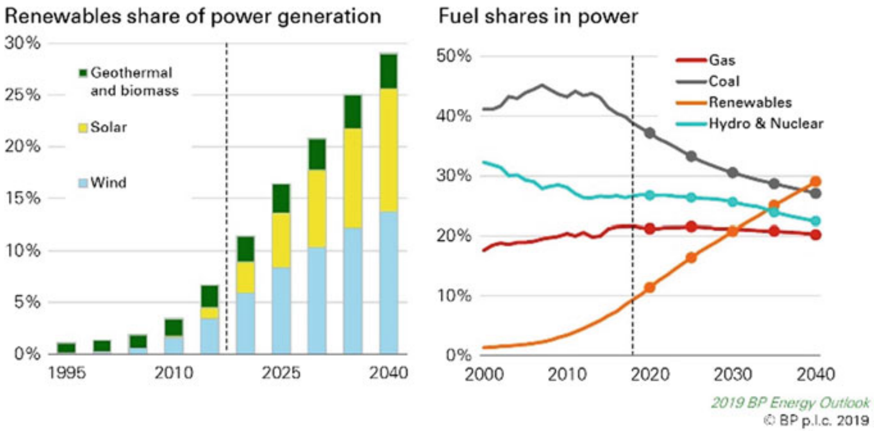

Fig. 22 BP Outlook 2019 energy mix forecast (Op. cit., Reference [3])

accounts for 94%, but this is only equivalent to the energy normally consumed in 3.3 s.[32] If the use of hydropower was disallowed or disavowed because of the carbon dioxide and other problems, less than one-fifth of a second of stored electricity would be available if solar and wind power were totally lost by a catastrophic natural disaster. While this scenario is highly improbable the example illustrates that even if solar and wind power dominate the energy mix they cannot meet all the energy needs What then will be the likely future energy mixes?

4 Tomorrow’s Energy Mix?

Each year the BP Company [153] publishes a number of publically accessible energy reports, in particular their ‘Energy Outlook’ series. In the latest edition,[33] BP has provided a forecast of the probable global energy mix up to 2040. Although this is somewhat of a shorter timespan than our ‘tomorrow’ scenario, as can be seen in Fig. 22, the forecast is for renewables to increase their share, from the less than 10% it is today, to almost 30% by 2040 and become the most dominant of the available ‘fuel’ sources. The bulk of the increase in renewables is slated to be from solar and wind power in roughly equally shares, but geothermal power, even with its seismic manifestations, and the carbon dioxide emitting biomass will also be part of the renewable mix.

The World Energy Council (WEC) [154], like BP, publishes a number of authoritative reports on global energy and environmental policies and proposes various ‘energy-use’ scenarios for general discussion. In a WEC study published two decades

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[32] Based on the annual US energy consumption of 4110 TWh.

[33] Op. cit., Reference [3].

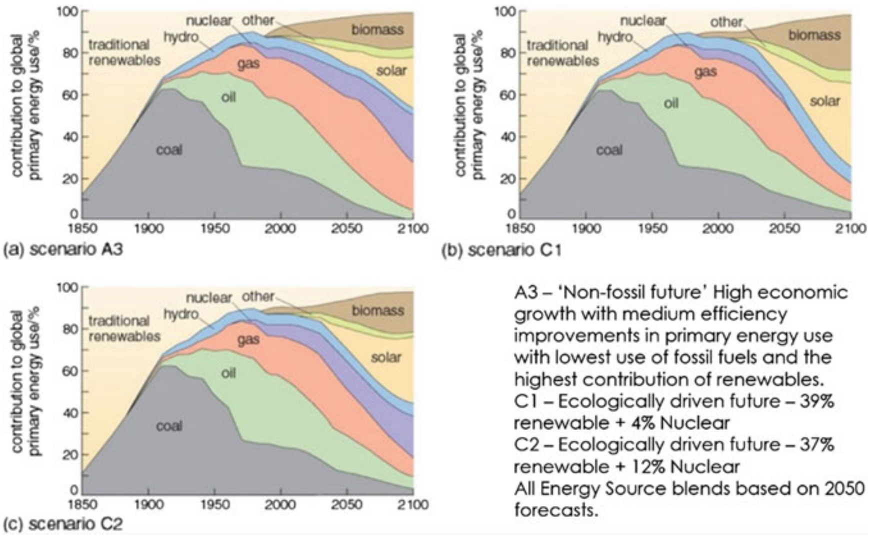
ago in partnership with the International Institute for Applied Systems Analyses (IIASA) [155] on 'Global Energy Perspectives [156, 157],' six future energy scenarios were investigated using three milieus, labeled Case A, B, and C, Table 5.

The primary emphasis of the study was for forecasts of possible energy mixes for the period up to 2050, but results were also presented out to 2100, the 'tomorrow' definition adopted for this paper. The results are presented in graphical form in Fig. 23 which was published by the OpenLearn Team in 2018 [158].

It can be seen, even by 2100, that fossil fuels are in the mix in all the scenarios, albeit in significantly diminishing proportions, while the use of renewables is increasing in all scenarios and becoming the dominant sources of energy. If hydro and nuclear power are included, then less than 30% of 'tomorrow's' energy will be provided by the traditional fossil fuel sources. It is interesting to note that in the WEC renewable scenarios, biomass plays a bigger role than wind power. Maybe this is an historical artifact, given the lineage of the scenarios, since the future potential

Table 5 Future energy scenarios WEC-IIASA [156, 157]

WEC-IIASA case	Milieu
A	'A future of impressive technological improvements and consequent high economic growth'
B	'A future with less ambitious, though perhaps more realistic, technological improvements, and consequently more intermediate economic growth'
C	'An ecologically driven future. It includes both substantial technological progress and unprecedented international cooperation centered explicitly on environmental protection and international equity'



A3 – 'Non-fossil future' High economic growth with medium efficiency improvements in primary energy use with lowest use of fossil fuels and the highest contribution of renewables.
C1 – Ecologically driven future – 39% renewable + 4% Nuclear
C2 – Ecologically driven future – 37% renewable + 12% Nuclear
All Energy Source blends based on 2050 forecasts.

Fig. 23 WEC energy transition scenarios [158]. Modified by Author of wind power was identified in the IIASA as far more significant than biomass in their encyclopedic report of 1884 pages, ‘Global Energy Assessment (GEA) [159].’ Although the data used to produce the graphs in Fig. 23 need to be updated, at least in terms of source proportions, the main point to be gleaned from them is that it seems highly unlikely that 100% renewable energy will be achieved by 2100, according to models used in such forecasts.

Nevertheless, there have been significant changes in the constituents of the global energy mix over the past two decades, especially during the last decade, and because of these rapid changes, forecasts of the future mix have tended to become less long term. In addition, more codicils have been attached to forecasts, such as if a specific mix is achieved in 2030, then it should be possible to attain a particular mix by 2050. Interestingly, a REN21[34] study reports that some energy experts are more optimistic about the timeframe of the eventual transition to renewables than the current energy mix models suggest. For the study, in 2016, REN21 interviewed ‘114 renowned energy experts from around the world, on the feasibility and challenges of achieving a 100% renewable energy future [160].’ The results are shown in Fig. 24 where it can be seen that although 71% agreed or strongly agreed that the use of 100% renewables was feasible and realistic, only 8% expected it to actually happen, albeit 72% expected renewables to account for at least 51% or more of the energy mix by 2050.

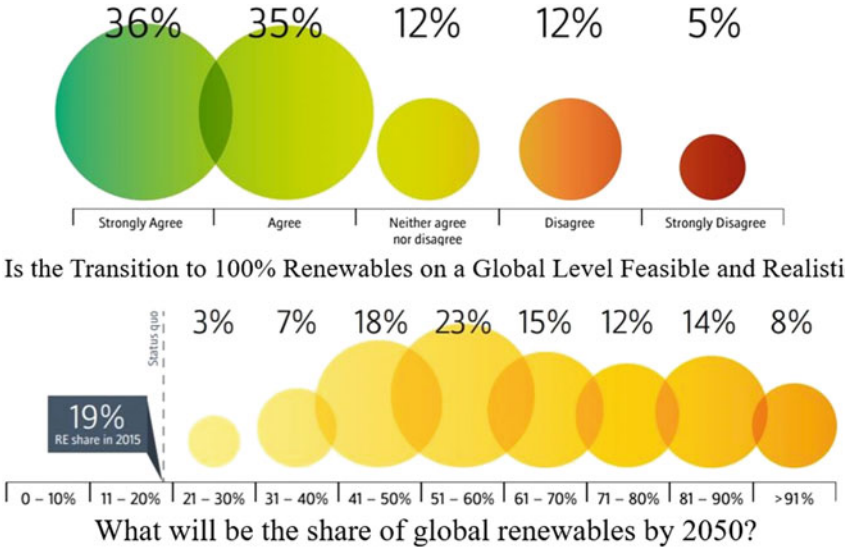


Fig. 24 Expert views on energy transitions [160]

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[34] REN21 is an international nonprofit association and is based at the United Nations Environment Programme (UNEP) in Paris.

5 Possible Energy Transitions

The transition to different energy mixes is already underway and appears to be gaining momentum as the growth in the use of renewable and sustainable energy sources continues to increase. However, if the two main challenges of ‘more energy-less carbon,’ Fig. 25,[35] are to be addressed on a global scale, how could this be achieved?

In 2013, WEC published a report [161] aimed at defining possible energy transition pathways to 2050 based on a three-year study by multinational experts. The two scenarios were labeled ‘Jazz’ and ‘Symphony.’ These scenarios were widely discussed through workshops, conferences, and other feedback mechanisms and in 2016 the two scenarios were expanded to three and renamed, ‘Modern Jazz,’ ‘Unfinished Symphony,’ and ‘Hard Rock,’ Table 6, with the pathway period extended to 2060 and elements of the 2015 United Nations Framework Convention on Climate Change (UNFCCC)’s ‘Paris Agreement’ [162] included. The ‘Unfinished Symphony’ particularly, but also the ‘Modern Jazz’ scenarios, would require, or at least imply, the need for international governance, raising concerns about a hidden agenda involving the time immemorial (and imperial) concept of a common political authority for all humanity, in essence ‘World Government.’ A number of other leading energy organizations [163] have also suggested scenarios which have some commonalities with all three WEC scenarios. For example, the five International SSP (Shared Socioeconomic Pathways)[36] are now being used as important contributions to the IPCC’s climate models which will be used in the upcoming 2020–21, IPCC’s sixth assessment report and will update the emission scenarios originally developed in 2000 [164]. The scenario SSP #3 [165], ‘Regional Rivalry—A Rocky Road (High challenges to mitigation and adaptation)’ is close to the WEC’s Hard Rock vision and

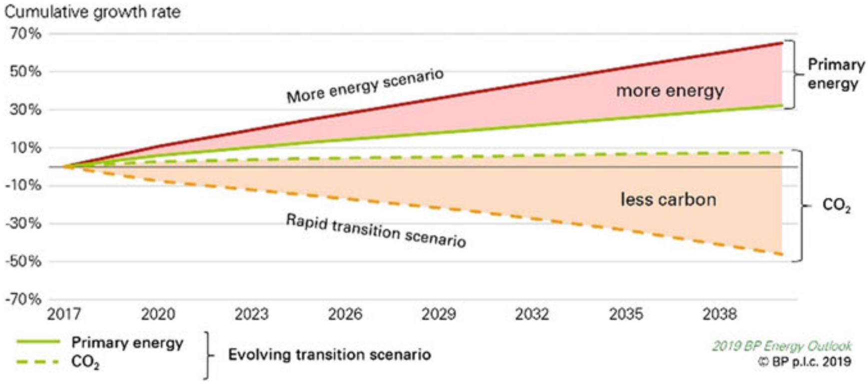

Fig. 25 BP Energy Outlook—the dual challenges (Op. cit., Reference [3], BP 2040 report Op. cit.)

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[35] BP 2040 report Op. cit [194].

[36] Teams of climate scientists, economists, and energy systems modelers have built a range of five new ‘pathways’ (SSP) that examine how global society, demographics and economics might change over the next century. These will be used to update the IPCC’s 6th Assessment Report.

Table 6 WEC transition pathways [166]

WEC transition pathways to 2060			
Pathway	Basic scenario	Key elements	2019 description
Unfinished Symphony (US)	Broad-based international governance, covering security, economic and environmental matters	• Strong policy • Long-term planning • Unified climate change • Voter driven	Strong global cooperation, united climate action and long-term integrated planning
Modern Jazz (MJ)	Economics focused international governance ensuring that capital markets, technology transfer and trade continue to function well	• Market mechanisms • Technology innovation • Energy access for all • Consumer driven	Market-driven, business and technologically innovative, energy accessible and economically prosperous world
Hard Rock (HR)	Fractured and weak international system that cannot address global challenges	• Fragmented policies • Local content • Best-Fit local solutions	Politically and economically fragmented world, where low economic growth and low innovation drive countries toward inward looking policies and national security issues, resulting in poor performance on emissions curtailment

envisages that global population will rise to over 12 billion by 2100, largely driven by developing countries, coupled with ‘a low international priority for addressing environmental concerns’ and with global average surface temperatures increasing by 3.85–4.07 °C at the start of the twenty-second century, way above the Paris Agreement targets of 1.5/2.0 °C.

It is worth recalling, however, that these energy transition scenarios are based on various models. Even so, for staunch environmentalists, the Hard Rock and SSP 3 scenarios must be depressing and disturbing, and although they appear to be unduly pessimistic, given the state of the present global socioeconomic and geopolitical situations, they may prove to be more accurate than anyone would wish, particularly if some of the frightening consequences of a warmer planet actually happen. The predictions for the SSP 3 scenario are that the temperature rise will increase to 2.25 °C by 2050. If this proves to be the case, then it is likely, but not certain, that international priorities will change rapidly along with precipitous rise in the global adoption of non-carbon and low-carbon renewable energy sources.

6 Concluding Remarks

Global investment in renewable energy developments between 2004 and 2017 has been estimated [167] to be 2.9 trillion $US (not including large hydropower) of which the vast bulk has been targeted by governments toward solar and wind energy via such mechanisms as environmentally related taxes or charges on energy products and personal transportation. These charges have usually led to significant increases in the cost/kWh of domestic residential electricity especially in countries like Germany. Indeed, as pointed out in a recent TED lecture [168] if Germany had used the $580 billion it spent on renewables to further develop its nuclear program then it would already be producing 100% of its energy needs from ‘clean zero-emission sources.’ While there is a great deal of legitimacy in such utterances, it seems likely that the public, outside of many US states and France, will not embrace nuclear power until the second half of the twenty-first century, if ever, and only then if the environmental forecasts of today become as cataclysmic as some insist. It remains to be seen whether timely nuclear power resurgence will ever occur, or is needed.

Despite the documented environmental issues and GHG problems associated with power generation by biomass combustion and water power, these forms of energy will remain in use with biomass probably retaining its status as a renewable and sustainable energy source. However, there could be a backlash against the use of some forms of biomass because of the large number of air pollution related deaths, 2.6 million in 2016, which are particularly prevalent among very low and low-income households which use wood, charcoal, crop waste, and dung for cooking and heating. At the moment, it is difficult to reconcile the continued used of biomass energies with the demands for reduced carbon dioxide emissions. Because of its higher energy density wind power developments—at least at the utility-scale level—will likely prove to be more attractive than equivalent solar systems, especially in offshore locations such the coasts of the UK and Denmark, but nevertheless by mid-century fossil fuels are likely to still play a dominant role which will gradually diminish over the second part of the century as they become less cost competitive and as societies begin to increasingly appreciate the scale of the harmful health effects of air pollution.

The potential for the global use of geothermal power is significant and its exploitation will likely increase as the Global Geothermal Alliance [169] has pledged a five-fold increase by 2030 [170], but exploration and start-up costs may dampen enthusiasm for its development in many global regions where clear alternatives exist. ‘Earthquake Fear’ will also need to be overcome. Although the average number of earthquakes does not appear to have increased, and the occurrence of large earthquakes (magnitude 7 and above) has been constant [171] since records began, methods of detection and location have improved, so the National Earthquake Information Center (NEIC) is said to locate between 12,000 and 14,000 earthquakes annually [172] (although NEIC [173] claim that they actually locate 30,000 per year and suggest that there are at least 1 million earthquakes globally each year!). So why the discrepancies in the annual data? Organizations like NEIC and the US Geological Survey are only interested in locating and reporting the most important earthquakes, i.e., those with a magnitude of 4 and above and not the magnitude 2 and 3 (and below) earthquakes associated with some geothermal activities. In the USA, it is estimated that there are only 12–50 such incidents annually and 1 (possibly) with a magnitude of 4 [174]. Although there is an absence of any convincing data to support the geothermal earthquake scenario, equally, data showing that the scenario is grossly overestimated is also limited, so it is likely that the fears will persist.

Many of the types of obstacles being encountered with the development of renewable energies and other low-carbon energy sources are of a similar nature to those which had to be overcome when transitioning from wood and whale oil to coal, natural gas, and oil. Why should the transition from fossil fuels be any different? Although energy transition over the past three centuries has given rise to Empires, it is unlikely that a unified global empire will be the result of the coming transition. Perhaps an indication that the transition is likely to follow to some extent the Hard Rock pathway is that recently it has been reported that global energy demand in 2018 increased by approximately twice the annual average rate since the start of the decade, and that, for the second year running, almost 70% of this new demand was met by fossil fuels.[37] Nevertheless, as Contescu [175] has stated,

> There should be an agreement that hasty conclusions about the inevitably of a catastrophic greenhouse warming effect just about to happen or already in progress is not a constructive approach especially when powerful interests like the media and the environmental movements try to sensationalize the alleged events.

Regardless, the thrust of Contescu's observations and comments are that the anthropogenic influences on climate change should be taken seriously and all stakeholders should work together objectively and without a 'sense of passionate crusaders' to address the many unanswered questions, but also collectively admit undeniable facts. A laudable sentiment and in many ways a restatement of what President Dwight D Eisenhower's said about scientific research in his 1961 farewell speech [176],

> Akin to, and largely responsible for the sweeping changes in our industrial-military posture, has been the technological revolution during recent decades. In this revolution, research has become central; it also becomes more formalized, complex, and costly. A steadily increasing share is conducted for, by, or at the direction of, the Federal government. Today, the solitary inventor, tinkering in his shop, has been overshadowed by task forces of scientists in laboratories and testing fields. In the same fashion, the free university, historically the fountainhead of free ideas and scientific discovery, has experienced a revolution in the conduct of research. Partly because of the huge costs involved, a government contract becomes virtually a substitute for intellectual curiosity. For every old blackboard there are now hundreds of new electronic computers. The prospect of domination of the nation's scholars by Federal employment, project allocations, and the power of money is ever present and is gravely to be regarded. Yet, in holding scientific research and discovery in respect, as we should, we must also be alert to the equal and opposite danger that public policy could itself become the captive of a scientific technological elite.

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[37] Kelly McParland, "Why will the carbon taxers stop now?" Article published by the National Post which appeared in the Windsor Star page NP 2, 9 April 2019.

As previously mentioned, the bulk of the investments in renewable energy to date have come from governments directly and indirectly, so if Eisenhower's fears are to be avoided, then perhaps an approach like Contescu's needs to be adopted to the forthcoming energy transitions, which may indeed culminate in 100% renewable energy use in the future, but not in the period stressed as necessary in the Paris Agreement.

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Exploring EKCs in Urban Water and Energy Use Patterns and Its Interconnections: A Case Study in Southern Spain

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Abstract This study aims to explore the existence of environmental Kuznets curves (EKCs) in urban water and energy use patterns at regional scale based on a wide data set of 336 municipalities in the Guadalquivir River Basin. A systematic analysis of the relationships between urban water-energy use patterns and indicators of economic development (i.e. income and employment) is carried out. Additionally, this study takes into account other determinants that might also have an impact on the urban use of these resources, such as population density, age and educational level. Results contribute to a better understanding of the socio-economic factors driving urban demands for energy and water, thus also offering policy guidelines to guarantee the sustainable management of both resources.

1 Introduction

Rapid urbanization and metropolitan expansion processes lead to an increasing use of all sorts of resources, including energy and water resources. At world level, urban areas are responsible for more than 20% of total water withdrawals and 70% of global energy consumption, thus threatening the sustainable use of limited resources and implying significant challenges for human welfare [7, 17]. This issue is especially significant in the case of water, since by 2050 the world's population may suffer from fresh-water scarcity [46, 47]. In fact, both resources might act as limiting factors for urban expansion and economic development, thus the analysis of the link between the urban use of these resources and economic development is attracting increasing interest among scholars, practitioners and policy-makers. Furthermore, these two resources are interconnected in urban production and use patterns, as illustrated by

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the concept of "water-energy nexus" which reflects these interdependence relations and its pivotal role in the sustainable development of the urban economy [17]. Therefore, understanding the factors behind urban water and energy use is critical from theoretical, technical and policy dimensions.

Both resources, energy and water, can be described as normal utilities with respect to urban uses, as income increases would lead to higher demand pressures. In this context, water and energy supply limitations only heighten the importance of analyzing the relationship between economic development and the urban demand of these interrelated resources, which is the main objective of this chapter. Most studies have shown the existence of an inverted U-shaped environmental Kuznets curve (EKC) to describe the relationship between economic development and energy and water use patterns, thus showing that resource use increases in a first stage of economic development, and decreases after achieving a certain threshold level of income (or development level) [34]. Nevertheless, there is a growing empirical literature showing that this is not always the case, leading to significant concerns about the sustainable use of these resources in urban agglomerations.

This study aims to shed some light on this issue, based on a wide data set of 336 municipalities in the Guadalquivir River Basin through a systematic analysis of the relationship between urban water-energy use patterns and indicators of economic development (i.e. income and employment). Additionally, the presented analysis includes other determinants that might also have an impact on the urban use of these resources, such as population density, age and educational level. It is worth noting that consumption and use concepts will be used indistinctively in the case of energy, while in the case of water, we will refer to the use of the withdrawal amount of water diverted to the urban sector which clearly differs from the final consumed amount.

The contribution of this study is that it analyzes water-energy use patterns at regional level (i.e. river basin level), thus going beyond the study of a single urban location or a specific production process as is the case in most studies in the existing literature. Furthermore, this study aims to offer a better understanding of socio-economic factors driving urban demands for energy and water, thus also offering policy guidelines to guarantee the sustainable management of both resources at regional level. After a brief literature review in the subsequent section about water and energy EKCs in the urban sector, Sect. 3 offers an analysis of the links between water and energy use patterns and economic development in our specific case study. Some policy implications of the shown analysis are discussed in Sect. 4. Finally, the last section summarizes some concluding remarks.

2 Water, Energy and Economic Development: Testing EKCs in the Urban Sector

Though the so-called Kuznets curve illustrated the paradoxical relationship between economic growth and income inequality [38], the instrument of the environmental Kuznets curve (EKC) (as firstly introduced by Grossman and Krueger [22]) has been extensively used to illustrate the relationship between specific environmental indicators and economic development represented by an inverted U-shaped curve [76]. Among these environmental indicators, water and energy use has attracted significant attention in the literature under the assumption that economic development constitutes a useful indicator to explain future trends of these resources' use [12, 36].

The potential validity of the EKC hypothesis has been extensively tested from several corners [10]. In most of them, total CO_2 emissions are used as the indicator of environmental degradation, but also the total energy consumption is used in numerous studies. The relationship between energy consumption and economic growth was firstly analyzed for the pioneering study by Kraft and Kraft [37] which examined this topic in the case of the USA. Since then, numerous studies have focused on the energy-growth nexus. In this regard, an extensive review of these previous studies has been done in the papers of Ozturk [48], Omri [49] and Tiba and Omri [68].

Some of these studies have also tested the energy-EKC hypothesis from a sector-level perspective. Among them, it is worth highlighting the studies by Richmond and Kaufmann [45], Nguyen-Van [61], Yoo and Lee [74], Zilio and Recalde [78] and Pablo-Romero et al. [54] referring to the industrial sector, those by Katircioğlu [33], Pablo-Romero et al. [50] referring to the tourism sector, and the studies by Lin and Du [40], Pablo-Romero et al. [51], and Rehermann and Pablo-Romero [60] referring to the transport sector.

Framed in the scope of sectorial studies testing the existence of the energy-EKC, it is worth highlighting those studies referring to energy consumption in the residential sector, as related to urban energy use patterns. Most previous papers analyzing the relationships between the residential energy consumption and income focus on the microeconomic behaviour of households, usually using household survey data, and finding that growth in residential energy consumption depends on the household's income level. In this respect, Alberinit et al. [1] explore the residential demand for energy in the USA and the household income influence on this demand, while Bohne et al. [5] carry out a global overview of residential building energy consumption in eight climate zones considering a total of 31 countries and 14 provinces/municipalities.

From a macroeconomic prospect, most of the studies that explore these nexus estimate the long-run and short-run elasticity of residential consumption for electricity. Among them, some of them have analyzed the nonlinear link between energy consumption and economic growth by considering the energy-EKC hypothesis. It may be highlighted, for instance, that the study by Yin et al. [73] calculate the short-run and long-run elasticities of residential electricity consumption in China in order to test the EKC, obtaining that the impact of income in residential electricity consumption is insignificant in rural areas, while it is significant but small in urban areas. Likewise, Liu et al. [41] use province-level panel data for China concluding that the per capita residential electricity consumption increased proportionally with the income growth of Chinese residents and not having been reached the income threshold at which residential electricity consumption automatically remains stable or decreases.

In the same line, Bouznit et al. [6] estimate a residential electricity consumption demand function for Algeria to explore its relation to income, finding that the link between electricity use and GDP presents an inverted N-shape, with the second turning point having been reached. Otherwise, Pablo-Romero and Sánchez-Braza [53] analyze the link between residential energy consumption and income for the EU-28, estimating the residential energy-EKC and calculating the elasticities with respect to income for each country, exploring the different behaviours between countries and concluding that the EKC hypothesis is confirmed for the residential sector in the EU-28 countries.

Moreover, Pablo-Romero et al. [55] study the residential energy-EKC referring to 14 transition countries, but highlighting that the estimate results do not support the EKC hypothesis. Similarly, Pablo-Romero et al. [52] analyze the evolution of total, household and public administration electricity consumption for municipalities in the South of Spain and showing that the obtained results do not support the energy-EKC hypothesis.

Conversely to the case of energy use, existing literature has not yet offered conclusive results regarding the link between use (or withdrawal) of water resources and economic development. Additionally, these few studies have usually offered very sensitive findings with respect to the applied analytical method and the data set used [34]. In this respect, heterogeneous data sets (e.g. developed and developing countries and/or regions) [70], limited samples with few time observations [12], as well as the specific conditions of the analyzed case study [77], may act as significant limitations for conclusive results.

The seminal work of Rock [62] constituted the first serious attempt to test the existence of an EKC with respect to global water use (all economic sectors included) upon a cross-sectional data set. This study showed the existence of an inverted U-shaped relationship between global water withdrawals and income (both in per capita terms) for a sample of USA states. Subsequently, Shiklomanov [8], Cole [12] and Duarte et al. [66] have arrived to similar findings using different samples of countries and estimation methodologies. On the contrary, other studies have not arrived to conclusive findings regarding the existence of an EKC to represent the evolution of water consumption and income based on cross-country analyses [19, 34].

The existence of an EKC in the relationship between water use and production indicators has also been tested for specific economic sectors. In the case of the agricultural sector, studies such as Glokany [20] and Bhattarai [4] have corroborated the existence of a U-inverted curve between agricultural water withdrawals and economic development indicators. With regard to the industrial sector, the relationship between per capita income and industrial water withdrawals generally follows a bell-shaped path, as argued by Jia et al. [32], Hemati et al. [27] and Gu et al. [23]. Finally, the urban sector (mainly composed by households, service firms and small industries) has been scarcely studied. Among this scant literature, Katz [34] analyzes the relationship between per capita income and water use for domestic uses, as well as for other economic sectors and the whole economy for different samples of countries and US states. In most cases, the EKC is confirmed for all sectors and samples analyzed when parametric methods are used. Conversely, non-conclusive results are obtained with nonparametric methods. In this regard, the study of Katz [34] represents one of the few studies to test EKC (both in its quadratic and cubic forms) in the urban sector at national level, thus showing the convenience to carry out specific sectoral studies at national or regional scales.

Otherwise, the relationships between water and energy use have recently received growing attention [26], regarding the fact that water use may induce the use of more energy, while the use of energy may also lead to higher water demand. This interdependence of energy and water resources can be translated into the concept of water-energy nexus [17]. In this sense, Wakeel et al. [71] consider energy and water as essential and inextricably linked resources recognized as indispensable inputs to the modern economy, making a literature review of previous studies. A majority of these studies have focused on the analysis of the link between energy and water use in the residential sector, finding that the energy intensity of residential end use is very high due to processes such as heating water, washing clothes and dishes and cooking activities [59].

Nevertheless, the analysis of the link between water and energy use patterns in urban environments, to the best of our knowledge, has generally focused on operational levels (e.g. certain generation process or technology) [7]. In this sense, studies at greater levels of analysis (e.g. regional) such as the one presented in this chapter are scarce, and thus needed in order to improve the existing knowledge about the implications of the water-energy nexus for the management and governance of these resources. Moreover, it would be recommended to analyze specific national or regional case studies in order to take into account the specific conditions of those locations.

Existing literature also fails to consider the potential moderating role played by other variables in the water-energy-income relationships. Within these other determinants, the following can be highlighted: population characteristics, such as density, age and educational level, as argued by Grafton et al. [21]; hydrological and climatic differences [63], and economic structural changes and processes, such as tertiarization and urbanization [23, 32, 76].

3 Methodology

According to the previous literature review, it is reasonable to consider that a causal relationship between energy consumption and water use may exist, which could be from energy to water use, from water use to energy consumption or reciprocal. In addition, this link between the variables is expected to be stronger in the residential sector [59]. Nevertheless, empirical studies that analyze these links are still scarce, which may be related to the impossibility to manage real data. In this study, the relationships between urban water and energy consumption are analyzed for 366 Guadalquivir Basin municipalities in the period from 2005 to 2014.

Additionally, the relationships between electricity and water use may be affected by other socio-economic variables, as these variables have been proven to have a positive or negative influence on energy or water consumption in previous studies. Among them, income level has been considered to significantly affect water and energy use. Therefore, it is expected to find a causal relationship between economic development indicators and water and energy use patterns. It is therefore necessary to study also these relationships.

According to the previous considerations, the first step of this study is to test how water and energy use are related, and if income has any effect on the variables. Initially, scatter plots may inform us about these relationships. But also, it is adequate to test the causality between these two variables and income. In order to do it, a series of pairwise panel Granger causality tests between the variables, by using the Dumitrescu and Hurlin [14] test, have been performed. As this test requires the variables to be stationary, the stochastic nature of the variables has been previously studied. In order to do so, cross-sectional dependence among the variables was studied initially by using the Pesaran CD (cross dependence) test [56] to consider which unit root test should be used. In the case that the null hypothesis of no cross-sectional dependence was rejected, then a second-generation panel unit root should be used. If the unit root test indicates that the series are I(0), then it is adequate to perform the Dumitrescu and Hurlin [14] test to analyze the Granger causality between variables.

Once the causality links are studied, the second step of the analysis is undertaken. Several water and electricity demand functions have been estimated based on panel-data regressions. These demand functions have been estimated by incorporating the explanatory variables in a sequential way. Thus, initially the water and energy demand functions have been estimated by including only the energy and water use variables, respectively, as shown in (1).

$$\begin{aligned} W_{it} &= A_{it} + \beta_1 E_{it} + u_{it} \\ E_{it} &= A_{it} + \beta_1 W_{it} + u_{it} \end{aligned} \tag{1}$$

where W and E refer to the per capita water and electricity use in logs, respectively. The term A indicates the sum of the time and individual effects and i and t subscripts indicate the municipality and year, respectively. Finally, u is the random error term.

Then, the income variable has been included in the demand functions to consider the effect of this variable in the relationships between energy and water use. As many of the previous studies undertaken (see the literature review) consider a positive linear effect running from income to water and energy use variables, the functions (2) incorporating the income variable have been also estimated.

$$\begin{aligned} W_{it} &= A_{it} + \beta_1 E_{it} + \beta_2 Y_{it} + u_{it} \\ E_{it} &= A_{it} + \beta_1 W_{it} + \beta_2 Y_{it} + u_{it} \end{aligned} \tag{2}$$

where Y indicates the per capita income in logs.

However, other previous studies have considered that there is a nonlinear impact between the income and the mentioned variables. Most of these studies analyze the nonlinearity by testing the water or energy-EKC hypotheses. In order to test the

EKC hypothesis, some studies include the income and the squared income variables in the demand function, while others include also the cubic income variable. These functions may be expressed as follows:

$$
\begin{aligned}
W_{it} &= A_{it} + \beta_1 E_{it} + \beta_2 Y_{it} + \beta_3 Y_{it}^2 + u_{it} \\
W_{it} &= A_{it} + \beta_1 E_{it} + \beta_2 Y_{it} + \beta_3 Y_{it}^2 + \beta_4 Y_{it}^3 + u_{it} \\
E_{it} &= A_{it} + \beta_1 W_{it} + \beta_2 Y_{it} + \beta_3 Y_{it}^2 + u_{it} \\
E_{it} &= A_{it} + \beta_1 W_{it} + \beta_2 Y_{it} + \beta_3 Y_{it}^2 + \beta_4 Y_{it}^3 + u_{it} \qquad (3)
\end{aligned}
$$

where according to Dinda [10],

If $\beta_2 = \beta_3 = \beta_4 = 0$, there is no relationship between E or W and Y.

If $\beta_2 > 0$ or $\beta_2 < 0$ and $\beta_3 = \beta_4 = 0$, a linear relationship between E or W and Y exits.

If $\beta_2 > 0$, $\beta_3 < 0$ and $\beta_4 = 0$, an inverted U-shaped relationship between E or W and Y exits. Then the EKC hypothesis is accepted.

If $\beta_2 < 0$, $\beta_3 > 0$ and $\beta_4 = 0$, an U-shaped relationship between E or W and Y exits.

If $\beta_2 > 0$, $\beta_3 < 0$ and $\beta_4 > 0$, an N-shaped figure describe the relationship between E or W and Y.

If $\beta_2 < 0$, $\beta_3 > 0$ and $\beta_4 < 0$, an opposite to the N-shaped curve describe relationship between E or W and Y.

To estimate these functions, instrumental variables techniques by the generalized method of moments (GMM) will be used, considering one and two delayed values for the water and energy variable (depending on the estimate function) as instruments. Finally, it is worth noting that when including the income variable and their squared and cubic values, multicollinearity problems may appear. Therefore, in order to avoid these problems, all variables have been transformed to deviations from the geometric mean of the sample as in Pablo-Romero and Sánchez-Braza [53].

4 Data

Data refer to 336 municipalities belonging to the Guadalquivir Basin. The Guadalquivir Basin is located in the south-west of Spain, in the region of Andalusia. It has an extension of 57,527 km^2 and a water reservoir capacity of 8,600 hm^3, with an average water use at about 3,800 hm^3 per year. Although the main water use (85%) is related to agriculture, residential and services water use (referred to in this study as urban water use) is relevant as it supplies a population of more than 4 million people, which are located in 466 municipalities of very different sizes.

The Guadalquivir River Basin Authority (GRBA) offers water use data related to agriculture, industry, services and residential sectors. Therefore, it is possible to consider urban water use as the sum of the two previously mentioned sectors. Figures, available from 2005 to 2014, are expressed in thousand m^3. Data from 2014 indicate that the per capita average water use in the basin was 0.087 thousand m^3.

Energy use in the cited municipalities may be obtained from the regional SIMA database [67]. This database uniquely offers data on electricity consumption, but available from 2000 to 2014 in most of the Andalusian municipalities, including much of those belonging to the Guadalquivir Basin. Data are divided into residential, industrial, agricultural and public administration sectors. Therefore, it is possible to approximate the urban electricity consumption by considering the total electricity consumption minus industrial and agricultural electricity uses. Figures are expressed in megawatt-hours/year and can be converted into per capita values by using the SIMA data related to population.

The crossing of the two databases allows us to obtain enough information on water and electricity consumption in 366 Guadalquivir Basin municipalities, in the period from 2005 to 2014. Table 1 shows the main descriptive statistics of the water and energy use variables in per capita terms.

Additionally, as income data may affect the relationships between water and electricity use, data related to the municipal income has also been considered. In this sense, SIMA database offers information related to personal income tax declarations. The variable value is expressed in 2010 constant euros, which can be converted into per capita terms. Table 2 shows the descriptive statistics of the variable.

Table 1 Descriptive statistics of per capita water and electricity use

Variable	Variability	Mean	St. deviation	Min	Max
Water use	Overall	0.00008	0.000039	$7.55e^{-11}$	0.00038
	Between		0.000035	$8.55e^{-6}$	0.00032
	Within		0.000017	−0.00008	0.00026
Electricity use	Overall	2.69627	1.9167	0.04113	38.938
	Between		1.5812	0.02121	18.664
	Within		1.0865	−14.060	22.971

Table 2 Descriptive statistics of per capita income

Variability	Mean	St. deviation	Min	Max
Overall	4675.72	2160.15	621.14	32875.90
Between		2100.64	735.24	28196.26
Within		515.12	−39.33	9355.37

5 Results and Discussion

5.1 Results

The first step of the analysis aims to explore the relationships between E, W and Y. Initially, the scatter plots are displayed to inform us about these relationships. Figure 1 shows the scatter plot of the electricity and water use in the Guadalquivir Basin municipalities. As can be observed, a quite linear relationship may be inferred between both variables. Likewise, the correlation observed between them, with a 0.9925 value, may also suggest that both variables may be linked among them.

Likewise, Fig. 2 shows the scatter plot between income and the water and electricity energy use. Once again, it seems to have quite linear relationships between variables, so it could be expected that income influences the mentioned variables.

Taking into account these results and in order to test how water and energy use are related, and if income has any effect on the variables, it is adequate to test the causality between these two variables and income.

Table 3 shows a series of pairwise panel Granger causality tests between the variables by using the Dumitrescu and Hurlin [14] test, when variables are expressed in per capita terms and converted into logs. As Pesaran CD test results do not allow to reject the null hypothesis of no cross-sectional dependence, the second-generation panel unit root CIPS (cross-sectional augmented Im Pesaran and Shin) tests by Pesaran [57] have been performed, with results showing that variables may be considered stationary. Therefore, it is adequate to perform the Dumitrescu and Hurlin [14] test to analyze the Granger causality between variables.

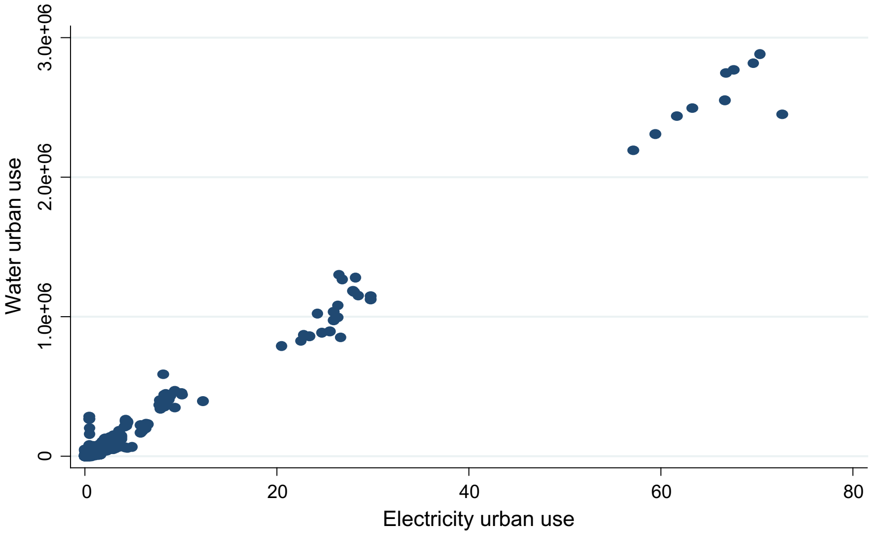

Fig. 1 Scatter plot between electricity and water use in the Guadalquivir Basin municipalities

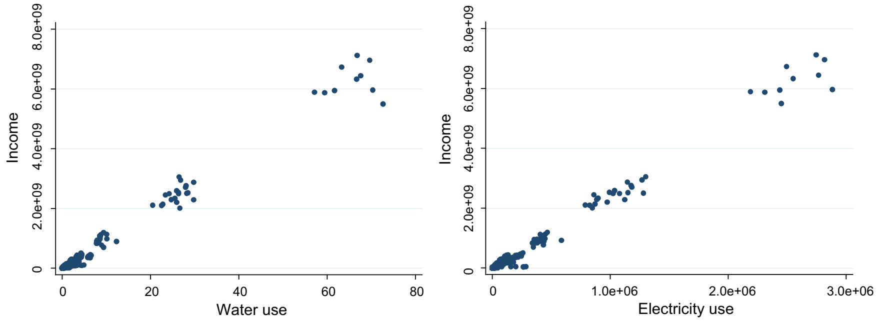

Fig. 2 Scatter plot between income and water and electricity use in the Guadalquivir Basin municipalities. *Source* Authors' own elaboration

Table 3 Granger causality in panel data: Dumitrescu and Hurlin test

Causality	Z-bar	Z-bar tilde
$W \rightarrow E$	25.7489***	5.1324***
$E \rightarrow W$	27.4985***	5.6573***
$Y \rightarrow E$	69.1671***	18.1578***
$Y \rightarrow W$	52.6804***	13.2118***
$E \rightarrow Y$	5.8438***	−0.8392
$W \rightarrow Y$	13.1980***	1.3671

Note *lags have been selected by using the AIC criteria

The results indicate that a bidirectional Granger causality relationship exists between the water and electricity use, while the causality between income and water use and income and electricity use is confirmed when running from income to the variables, but not when running from these variables to income.

Once the causality links between the variables have been studied, the demand functions [from (1) to (3)] are estimated. Table 4 shows the estimate results of the previous functions. Instrumental variables techniques by the generalized method of moments (GMM) have been used, considering one and two delayed values for the water and energy variable (depending on the estimate function) as instruments. Likewise, the functions have been estimated in presence or autocorrelation and heteroscedasticity according to the Wooldridge and Wald test for autocorrelation and homoscedasticity, respectively.

The first water function estimate results indicate that there is a positive and significant elasticity with respect to energy use. Nevertheless, when income is included in the function (in all estimates), the elasticity becomes negative, indicating that some kind of substitution relationship exists between both variables. In the case of the electricity use functions, the results are quite similar. A positive (but non-significant) elasticity is observed with respect to water use when income is not included in the

Table 4 GMM estimates for water and energy regression functions

Variable	Water use				Electricity use			
Y		0.429*** (0.047)	0.446*** (0.048)	0.275*** (0.056)		0.508*** (0.025)	0.518*** (0.026)	0.400*** (0.031)
Y^2			−0.072 (0.049)	−0.078* (0.048)			−0.047* (0.028)	−0.051* (0.028)
Y^3				0.198*** (0.035)				0.131*** (0.020)
E	0.080*** (0.029)	−0.108*** (0.037)	−0.110*** (0.037)	−0.135*** (0.037)				
W					0.006 (0.015)	−0.046*** (0.014)	−0.047*** (0.014)	−0.056*** (0.014)
Kleibergen-Paap rk under identification test	2502***	2154***	2154***	2151***	1515***	1491***	1491***	1483***
Kleibergen-Paap rk weak identification test	12,000***	13,000***	13,000***	13,000***	2123.1***	2030.4***	2027.3***	1997.6***
Sargan over identification test	2.052	0.094	0.080	0.146	0.019	2.141	2.218	2.700

Note ***, **, * represent 1%, 5% and 10% significance levels, respectively analysis, but a negative elasticity is observed when income is included in the function (in all estimates).

On the other hand, the relationships between income and electricity or water seem to be very similar. In both cases, a positive and significant elasticity are observed when income is included in a linear function. Likewise, when including the squared term an EKC shape is confirmed. Nevertheless, if the cubic term is also included an N-shape is observed. Therefore, the results in both cases, i.e. for water and electricity use, determine that when income grows, the use of these variables tends to grow initially and decrease if income is still growing, but once again tends to grow when the income becomes higher. Therefore, if income tends to grow in future, we can expect an increase in water and electricity use, although some kind of substitution may be obtained between both variables.

5.2 Discussion

The obtained results indicate that relationships between income and electricity and water use patters register a positive and significant elasticity. These findings support the EKC hypotheses, confirming the existence of an inverted U-shaped EKC to describe these relationships when the squared term of income is considered. However, when the cubic term is also included, an N-shaped EKC is not found. These results are in line with the conclusions obtained in previous literature, as the studies by Pablo-Romero and Sánchez-Braza [53] and Bouznit et al. [6] in the case of energy use, or the ones by Rock [62], Shiklomanov [8], Cole [12] and Duarte et al. [66] related to water use.

In addition, previous studies have considered other variables when analyzing the water or energy EKCs. In this sense, Costantini and Martini [9] consider that the inclusion of these factors should be convenient, since it could condition the some obtained conclusions. In this sense, some population and territory characteristics may influence the energy-water use relationships. Among these variables, population density and urbanization have been included in studies investigating the relationship between economic growth and energy consumption, as for example, the studies by Holden and Norland [13] and Dujardin et al. [28], respectively. These studies indicate that urban characteristics of the analyzed municipalities may determinate the significance of the water-energy-economic development nexus. In this sense, urban density may play an important role in order to improve efficiency favouring energy and water use savings [13].

Regarding population characteristics, age and educational attainment may have also some kind of impact on the relationship. The first one has been considered to positively influence the urban water consumption [35, 63], while the second is considered to have an impact on both water and energy consumption. Related to water use, several studies such as House-Peters et al. [29] and Shandas and Parandvash [65] suggest that education has a negative effect on water consumption, considering then that this variable improves environmental conservation. In the same vein, several studies related to energy consumption in urban areas suggest that education may influence the purchase of energy efficiency appliances [72].

6 Policy Implications

Water and energy resources are indispensable inputs for economic development and human welfare, and increasing consumption pressures are expected from households by 2050 [46]. Consequently, as exposed in Lee et al. [39], the water-energy nexus is increasingly highlighted as a fundamental issue for strategic policy considerations and future sustainability planning, also considering that both resources, energy and water, are highly vulnerable to the effects of global climate change [58]. In recent decades, policy interest has increased due to the increasing challenges regarding three fundamental aspects: supply security, sustainable use and efficient generation of water and energy, leading to growing international concerns (as shown by the various United Nations Sustainable Development Goals related to energy and water use) and actions in terms of legislation and policy reforms. Furthermore, in the case of urban environments, the constraining nature of water and energy resources is maximized, limiting the expansion of urban areas and their capacity to harbour the growing population (world population will reach 9 billion by 2050, 70% of which will be urban). Additionally, as shown in previous sections, urban use of these resources is interlinked, since most water infrastructures (e.g. conveyance, pumping, potable treatment, reclamation) rely on a high energy consumption [64]. Therefore, it is foreseeable that development of energy-intensive technologies will become inevitable leading to higher water-related energy intensity and environmental impacts in future [69].

In this regard, some studies have analyzed the trade-offs between energy and water by modelling water demand for energy generation and the energy requirements for water services [43, 44]. Nevertheless, the systematic study of the global water-energy-economic development relationship for urban environments is still scarce, since existing literature generally focus on a specific resource and production process [46].

According to Fang and Chen [17], the rapid urbanization and expansion of metropolitan areas have severely increased the demands on energy and water resources, threatening the sustainability of the urban economy and environment. This issue is especially relevant in the case of water in closed river basins, such as the analyzed case study, where all available resources are used among the alternative uses (including the environment) and no supply increases are foreseen [15, 16, 42]. Several studies suggest that a joint management of water and energy resources in urban areas should be desirable, since the water-energy nexus in the urban context is fundamentally determined by decision-making at local and regional (e.g. watershed) scales. Apart from the development of technical solutions that might help to couple energy and water generation at local levels (e.g. desalination with wind power energy), Scott et al. [64] argue that coupling water-energy policies implies the consideration of the linkages between the use of both resources in urban environments in the decision-making process framed within a multi-tiered institutional scheme (e.g. local, watershed, regional, national), as well as between the resource stocks and the changing human demand of these resources. Thus, decision and policy-making regarding water-energy use patterns in urban environments may consider resource governance aspects (above mere resource management characteristic of operational levels), thus raising opportunities for development of global-change adaptation policies in response to current and future challenges, such as urban population growth, migration pressures and climate change. In this respect, studies such as those of the Intergovernmental Panel on Climate Change (IPCC) [31] and Scott et al. [64] argue that adapting strategies to reduce vulnerability of urban areas to global climate change may lead to water and energy use increases and acceleration of environmental degradation (e.g. carbon emissions and water scarcity), since per capita water and energy consumption for irrigation of urban green areas, air-conditioning and other uses may increase. In this regard, some studies have considered the correlation between the water-energy nexus and greenhouse gas emissions (see, for instance, Feng et al. [18] and Zhang et al. [75]).

In this context of increasing global challenges due to population growth, accelerating urbanization and climate change, among others, multi-tiered institutional cooperation has emerged as a useful framework to develop the much needed reforms at all policy scales. Following Pittock [58], to deal with all these questions, coordinated policy-making is required, taking into account that the conflicts and synergies between climate, energy, water and environmental policies can create additional challenges for governments to deploy integrated policies in order to deliver multiple benefits. The challenges for policy-makers are to develop effective policies and tools that integrate the water-energy nexus into policy and investment decisions [30].

Regarding water resources, the Global Water Partnership defines integrated water resource management (IWRM) as a "process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" [25]. Thus, IWRM is a comprehensive, multidisciplinary and cross-sectoral planning and implementation tool for managing and developing water resources [2]. In our opinion, IWRM framework should be extended to other resources that, like energy, present a clear interconnection with water consumption, especially in urban contexts. In this respect, the forthcoming reform of the EU Water Framework Directive, which is the masterpiece of the European water legislation, should take into account the water-energy nexus, thus avoiding fragmentation and inconsistencies between water and energy legislations and governance institutions to strategically integrate both sectors [3].

7 Concluding Remarks

The analysis of the link between water and energy use patterns in urban environments has generally focused on operational levels, thus studies at greater levels of analysis (e.g. regional) such as the one presented in this chapter are needed in order to improve the existing knowledge about the implications of the water-energy nexus for the management and governance of these resources. The main contribution of this study is that it analyzes water-energy use patterns at the regional level (i.e. river basin level), thus going beyond the study of a single urban location or a specific production process as is the case in most studies in the existing literature.

In the case of the Guadalquivir Basin analyzed in this study, the relationships between income and electricity and water use patterns are characterized by the existence of a positive and significant elasticity. Likewise, an EKC shape is confirmed when including the squared term of the income variable and the N-shaped EKC is observed when the cubic term is included. Therefore, if income tends to grow in future, we can expect an increase in water and electricity use, although some kind of substitution may be obtained between both variables.

In the policy arena, since urban demands of both resources are increasingly interrelated, the need for joint water and energy resource management is nowadays more evident than ever through what has been called energy-water policy coupling. In this regard, the study of these relationships offers relevant information for sustainable resources management and planning, especially in those locations where water and energy supplies face significant constraints (as is the case of the Mediterranean region). Moreover, though resources can be managed at multiple scales, in the case of energy and water resources their management is usually carried out at regional (or national) level, requiring studies that go beyond local boundaries. Furthermore, we believe that regional (or national) decision-making for water and energy resources raise new opportunities for adaptation to global change processes and guarantee the sustainable management of both resources.

Finally, and regarding territory characteristics, two indicators can be considered to influence the water-energy nexus: territory population density and urban/rural characteristics of the municipality. These indicators have been previously considered in local studies; for example, in Domene and Saurí [11] and Güneralp et al. [24]. Taking into account that other variables may influence the relationships, it may be appropriate to include these variables in future studies to determine whether or not they have significant effects on the energy-water relationships.

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Mining Phosphate from Wastewater: Treatment and Reuse

D. Mukherjee, R. Ray and N. Biswas

Abstract Phosphorus is essential for all living beings and it also serves as an important macro-nutrient for biological tissues. It is a vital element, needed to sustain food production and is widely used in the agricultural sector. However, phosphorus as a resource is limited, with estimates suggesting that the world supply could be depleted in a few decades. As a result, it will elevate the issues related to food production, and therefore, consideration of its recovery has become a focus of interest to researchers. Wastewaters from municipalities and some industries can contain high concentration of phosphorus which, if not treated, can cause eutrophication to receiving waters. In recent years, treatment and reuse of phosphate mining wastewater have been gaining considerable attention. The mining of phosphorus from raw phosphate rock (PR) can lead to air pollution, eutrophication in receiving waters, land degradation through phosphogypsum (emitted by stacks near the mining sites), and soil contamination. Recently, various treatment methods have been suggested to treat phosphorus-rich wastewaters. These include chemical precipitation, biological, combined chemical and biological treatment, and several wastewater and sludge-based methods. A brief description of these has been presented in this chapter.

1 Introduction

In recent years, environmental impact by human activities has become a serious concern. Our present lifestyle is supported through large-scale exploitation of natural resources like minerals, agricultural land, forestry, and water. Phosphorus is essential to all living life and is a crucial component in fertilizers to sustain high crop yield. It has been reported that there is no substitute for phosphorus in food production and with a projected nine billion population of the world by 2050, having sufficient phosphorus will be critical for the future food security [14]. Currently, phosphate rock is the main source of phosphorus. However, it is non-renewable, expensive,

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and getting depleted [12, 14]. Studies have reported that, globally, the commercial phosphate reserves will be depleted in 50–100 years based on the current rate of extraction, and the remaining reserve will be of low quality and very expensive to extract [12]. It has been reported that by the middle of this century, the food production will increase by 30%. Currently, 82% of the mined phosphorus is used in agriculture, 7% is used to produce animal feed, and the remaining 11% of the mined phosphorus is used in industry and medicine for the production of pharmaceuticals, oils, detergents, or even textiles [11, 52].

If untreated wastewater with high levels of phosphorus, which could be as high as 100 mg/L, is released into the water body, it can cause an imbalance of aquatic organisms and affect the water quality by causing eutrophication, which decreases dissolved oxygen levels and increases excessive algae growth [23, 29]. The suggested allowable level of phosphorus concentration in treated wastewater, in general, should not exceed 50 μg L^{-1} [57] to limit eutrophication. Therefore, it is imperative that the phosphorus-laden wastewater must be treated, and every effort should be made to recover and reuse phosphorus [35].

There are several methods that have been proposed to reduce phosphorus during the wastewater treatment [7]. One of the passive systems, that is sustainable, uses enhanced biological phosphorus removal (EBPR). The process depends on a specialized community of microbial flora that facilitates recycling and complete removal of phosphorus from municipal wastewaters [31].

2 Global Phosphate Rock Reserve

Recovery of phosphorus from mining wastewater could reduce the dependency on the global phosphate rock market [3]. Phosphate is an inorganic salt of phosphoric acid and found naturally as a phosphate rock [34, 52]. Phosphate can be found both as phosphate rock and potash ore. Phosphate rock is an igneous rock containing phosphate ions named as rock phosphate or phosphorite [1]. Potash is also mined as a salt of phosphate, which contains potassium in water-soluble form.

China, Russia, USA, Morocco, and South Africa are some of the major phosphate producing countries in the world, as shown in Fig. 1 [52]. The small Polynesian island, Nauru and Banana Island, has a massive deposit of phosphate of highest quality (Ali et al. [2]. Besides this, Egypt, Israel, Jordan, Navassa Island, Tunisia, Togo, and Jordan also have large phosphate mining industries. USA has the largest reserves of phosphorus, while South Africa exports the largest quantity. Consequently, the geopolitical situation can play an important role on the price and availability of phosphorus [11]. Approximately, 95% of the US phosphate rock mined is used to manufacture wet-process phosphoric acid and superphosphoric acid, used as feedstocks for the production of liquid ammonium phosphate fertilizers and animal feed supplements [24]. Mosaic is the largest phosphate mining company in the world, which produces 5% of world phosphate production [8, 56]. In Canada, a substantial deposit of phosphate has been found in Saskatchewan. Currently, eleven phosphate

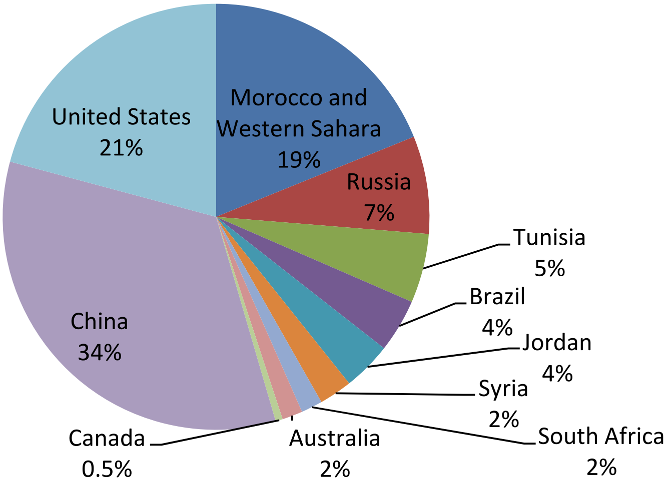

Fig. 1 World rock phosphate production 2008: 148.4 million tones [56]

mining companies are in operation in Canada. A large amount of phosphate rock is found on the continental shelf and on seamounts in the Atlantic and Pacific Oceans [56]. Recovering these deposits from oceans is still too expensive [51]; however, researchers are investigating cost-effective techniques to extract phosphates from underwater [13, 51]. In terms of its production, the State of Florida alone produces 75% of phosphate required for USA and 25% for the world [55].

3 Peak Phosphorus

In 1949, Hubbert showed that the production of all-natural resources has a peak time, after which the production will decrease, and price will increase. This effect is called Hubbert peak [12]. Due to the availability of natural phosphates being limited, the world could face dwindling supplies of phosphate unless proper steps are taken to its efficient use and further recovery from wastes. Though alternatives are available through organic manure and mineral fertilizers, phosphate is the prime source of fertilizer for our modern agricultural industry. Unfortunately, there is no substitute for the critical role of phosphate in plant development and production. In 2008, the total reserve of phosphorus was estimated to be approximately 3,200 MT, with a peak production of 28 MT/year in 2034, shown in Fig. 2. Some researchers believe that Hubbert-peak phosphorus will arrive within 30 years, and at the current rate, it could be depleted within 50–100 years [59]. According to Hubbert, the crucial time, for any limited resource, is not when the production starts declining but when the production is at its peak. Between 2007 and 2008, the world experienced its first

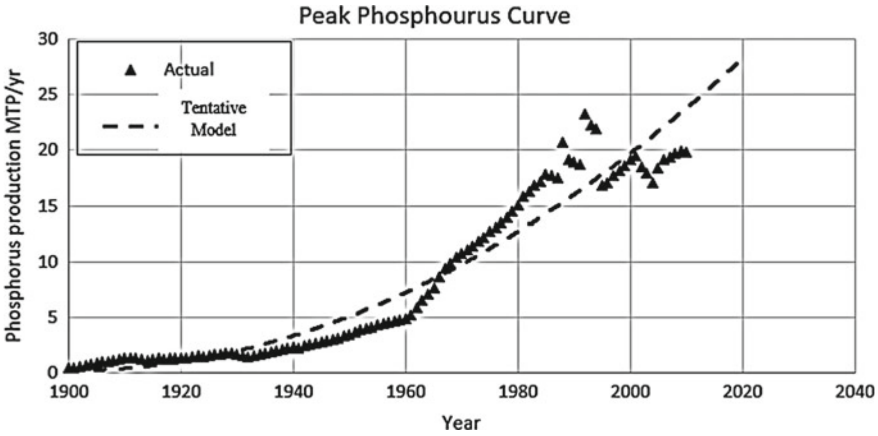

Fig. 2 Peak phosphorus 'Hubbert' curve, indicating that production will eventually reach a maximum, after which it will decline [12]

significant price shock of phosphate rock when it increased by US$300/ton in just 14 months [33].

Because the peak time is approaching, now is the appropriate time to recover and reuse phosphate in a significant way.

4 Phosphate Mining Wastewater

A large quantity of water is used by the phosphate mining industries. Water is required both during mining and processing of the phosphate ore. The water demand is high during the washing and flotation cycle. The Mosaic company in Florida, the largest phosphate mining company of the world, has a permit to use 76 million gallon of water per day from the central Florida groundwater aquifer [40]. They require around 2000 gallons of water for each ton of phosphate production, which is an indication of the large amount of water required for this industry [40]. Runoff from phosphate mining sites is another environmental issue and this, if untreated, can lead to severe water contamination. Approximately, 40% of the marine lifecycle has already been affected due to this pollution [58]. Some of the mines also have to deal with the radioactive materials in their process wastewater. In one report, it has been suggested that phosphate mine tailings lead to radon release because of the presence of the radioactive element, uranium [42, 58].

Wastewater produced from phosphate mining has been characterized by several researchers worldwide [21, 29, 63, 18]. Jiries et al. [26] investigated the effluent wastewater from phosphate mining to establish its constituents. El-Hasan [18] reported high levels of heavy metals in the slime produced from phosphate mining in Jordan. In phosphate mining wastewater, phosphate is mostly present as organic phosphate, inorganic phosphate, oligophosphate, and polyphosphate [1, 29]. Phosphate ore processing wastewater can result in radioactive phosphogypsum wastes [21, 45]. The phosphogypsum is stored in massive piles known as gyp stacks, which produces reservoirs of acidic wastewater [15]. This acidic wastewater can cause serious environmental problem if released without treatment. Some phosphate rock deposits are also a source of significant quantities of radioactive uranium isotopes [21].

Phosphate mine slime (PMS) is a byproduct from phosphate mining industry, which is stored in settling ponds and may occupy thirty to forty percent of a mine site. For each ton of manufactured phosphate discharge, approximately one ton of PMS is generated, which causes a serious waste disposal problem for many countries [15]. PMS is discharged into the environment through the wastewater generated during the processing of ores. Heavy metals such as cadmium, zinc, copper, and chromium are also found in phosphate mining wastewaters [21, 47].

Since phosphate mining wastewater normally contains high concentration of phosphorus, it is a good source to reclaim the phosphate from the wastewater. Following primary or secondary treatment, it can also be used by the agricultural sector [63]. Rimawaie et al. [47] investigated the water quality produced from phosphate mining and found that it can be used as irrigation water for salt-tolerant plants after removing contaminants such as heavy metals. The treated water was used to cultivate various types of animal fodder like *Zea mays* spp. and *Medicago Lipulina* spp. These can also be a potential source of fertilizer for seasonal crops. Jellali et al. [25] studied the reuse of PMS as a cost-effective adsorbent in removing phosphate anions from synthetic wastewater that has received secondary treatment. The cost-effective and high adsorptive capability of PMS makes it an attractive material for phosphate anions removal with the possibility of agronomic reuse as fertilizer [25].

In phosphate mining, water is used in two steps, during extraction of the ores followed by water usage during processing. In conventional mechanized extracting process where ores are extracted both from underwater and underground, the major use of water is as a coolant. The water used in this process is same as in other ore mining processes. Solution mining is also a recent technique used in phosphate mining used by industries [21, 46]. In this process, heated brine is used to dissolve sylvite (KCl) from the ore and later phosphate is precipitated out when brine is cooled. The solution mining method, where the overall mining cost is much lower, requires a higher quantity of water than the conventional method. This has driven most of the phosphate mining industries, including those in North America, to choose the solution method. In the second step of the solution method where ores are processed to extract phosphate, a larger quantity of water is required. Ores are crushed and then flotation technique is used to separate clay, dolomite, and sand from the phosphate ores. Flotation is a widely used method where desired material can be segregated from the mineral ore [46].

When phosphate is processed into fertilizer using sulfuric acid, gypsum is formed as a byproduct, termed phosphogypsum. This Phosphogypsum is radioactive due to the natural presence of radioactive metals [21] PMS can be a cause of change in groundwater flow depending on the permeability of the soil on site.

The average ionic composition of phosphate mining wastewater found by researchers is listed in Table 1 [26, [47]. The difference in the Na concentration could be due to the use of brine [47]. The average concentration of phosphorus is normally high (20 mg/L) in municipal wastewater [36]. Therefore, it is an excellent source for reclamation of phosphorus.

5 Treatment of Phosphate Mining Wastewater for Phosphorous Reuse

Concurrently treating and scavenging of phosphate from mining wastewater can be a complicated process and may require the removal of other impurities, first. For example, phosphorus mining wastewater may require heavy as well as radioactive metal removal [25]. Phosphorus can be removed by both chemical precipitation and biological treatment [39]. For heavy metal removal, precipitation technique is normally used as a combined process with phosphorus removal. A brief description of both chemical precipitation and biological treatment is given below.

5.1 Chemical Precipitation Treatment

Chemical precipitation is the most widely used method in treating phosphate mining wastewater due to its high phosphorus removal efficiency, up to 90%, [54]. The principle of wastewater phosphorus removal relies on the concept that dissolved orthophosphate can be converted to its insoluble form. This method uses di and tri valent metal salts. Normally, iron salts (Fe^{2+} and Fe^{3+}) or aluminum salts (Al^{3+}) are used to precipitate phosphorus from wastewater. Calcium (Ca^{2+}) is also used in the form of lime ($CaCO_3$) to precipitate phosphorus. Metal salts can be added in the primary or upstream of the secondary clarifier. Insoluble phosphates are then removed by solid separation process such as sedimentation, filtration, or flotation [61]. A typical chemical precipitation plant for phosphorus removal is given in Fig. 3.

Lime, alum, and iron salts can be used for chemical precipitation of phosphates. The reaction proceeds as given below [36].

Lime

$$10Ca^{2+} + 6PO_4^{3-} + 2OH^- \leftrightarrow Ca_{10}(PO_4)_6(OH)_2 \downarrow \quad (1)$$

$$Mg^{2+} + 2OH^- \leftrightarrow Mg(OH)_2 \quad (2)$$

$$Ca^{2+} + CO_3^2 \leftrightarrow CaCO_3 \quad (3)$$

Table 1 Ionic composition of phosphate mining wastewater

References	pH	P (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	HCO_3 (mg/L)	NO_3^{-1} (mg/L)	SO_4^{-2} (mg/L)
Jiries [26]	7.55	210	203.1	142.7	63.6	3.8	234.9	19.7	614.4
[47]	7.4	234	130.6	58.4	233.5	7.1	373.3	12.8	496

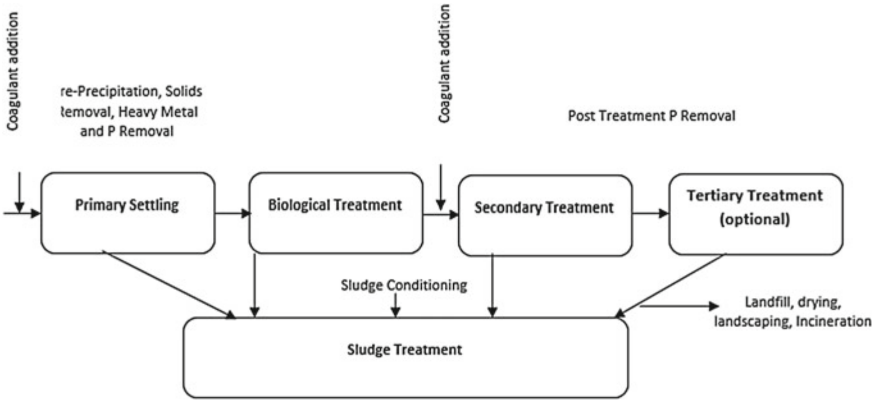

Fig. 3 Combined chemical and biological treatment for phosphate mining wastewater

Alum

$$Al^{3-} + PO_4^{3-} \leftrightarrow AlPO_4 \downarrow \tag{4}$$

$$2Al^{3-} + 3OH \leftrightarrow Al(OH)_3 \downarrow \tag{5}$$

Iron

$$Fe^{3+} + PO_4^{3-} \leftrightarrow FePO_4 \downarrow \tag{6}$$

$$Fe^{3+} + 3OH \leftrightarrow Fe(OH)_3 \downarrow \tag{7}$$

In previous studies, phosphorus recovery was carried out from acidic wastewater by hydroxyapatites [4, 32]. This was done by using lime at various molar ratios (Ca/P = 1.4 and above), which showed 80% recovery efficiency of phosphorus from the wastewater [10]. A feasibility study was carried out for implementing an ammonia and phosphate recovery system, by calcium-activated synthetic zeolite in a wastewater treatment plant in metropolitan areas of Barcelona; the study concluded that implementation of this method would be beneficial, however, more research is required in the synthesis and activation of zeolites [60].

5.2 *Biological Treatment*

The assimilation process and enhanced biological phosphorus removal (EBPR) are two major biological treatment processes used for phosphorus removal from mining wastewater [30, 64]. A short description of both processes is given below.

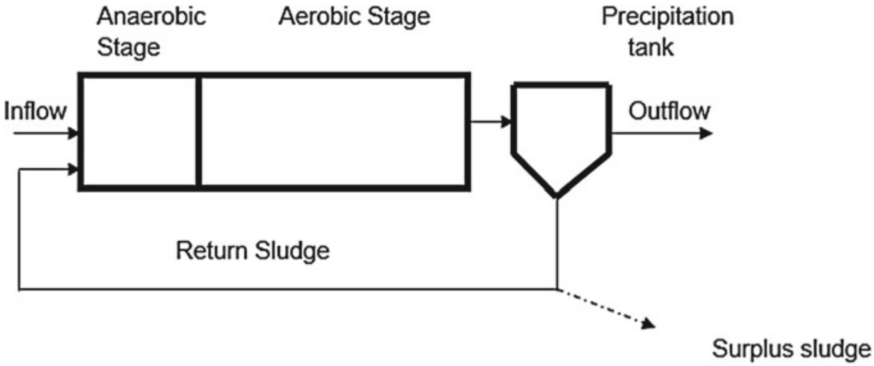

Fig. 4 Typical EBPR used in phosphate mining wastewater treatment

Phosphorus removal from wastewater has long been achieved through biological assimilation. The process involves the incorporation of phosphorus, an essential element, into the biomass of photosynthetic organisms [2]. Normally, a treatment pond with planktonic or attached algae rooted or floated is used to remove the phosphorus from the wastewater. Biological assimilation requires a large area of wetland and regular removal of net biomass. This could be a cheaper technique to remove phosphorus from mining wastes. However, the required land may not be always available, and the system requires constant supervision.

The EBPR process uses phosphate-accumulating organisms (PAOs) which store polyphosphate as an energy reserve in their intercellular granules [37, 41]. A schematic diagram of a typical EBPR is shown in Fig. 4.

6 Reuse of Phosphate Mining Wastewater

Due to the increasing price of phosphate, several researchers are investigating efficient ways to reuse the phosphate mining wastewater, which can be a potential source of the element [19, 25]. Recently, couple of techniques have been proposed to reuse phosphate mining wastewater sludge in the agricultural sector [63]. It can be done by applying the primary sludge directly to the land where the phosphates from wastewater are consumed as fertilizer. Primary sludge can also be used after initial treatment. Another technique includes combining sludge with fertilizers in different ratios [63]. Besides it’s usage as fertilizer, the phosphate mining industries are now reusing their wastewater, after complete or partial treatment, in the mining operation [14]. This can reduce the high demand of water—often the groundwater in the area.

A pilot study was carried out by Rimwai et al. (2007) in Jordan to reuse the phosphate mining wastewater directly in its raw form and after primary treatment. They planted two species of crop (*Zea mays* spp. *and Medicago lupulina* spp.) in six separate plots, 50 m^2 each. Different types of water—fresh, mine wastewater, and

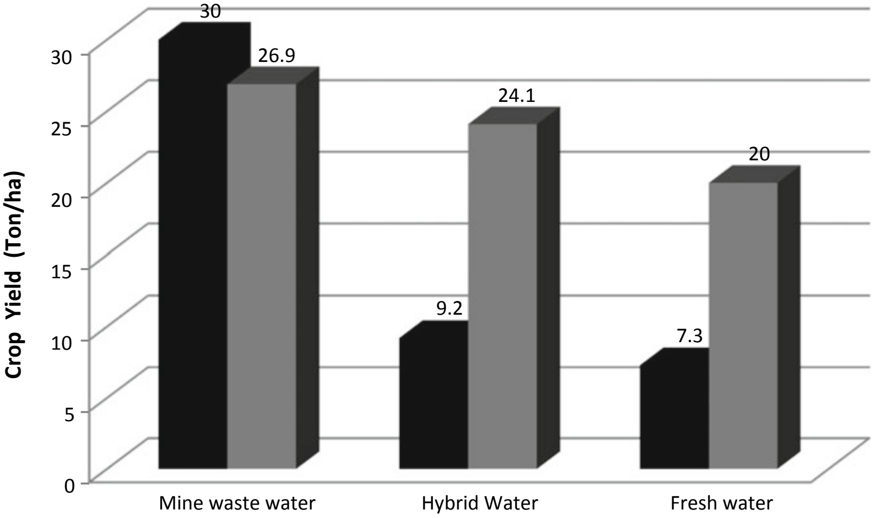

Fig. 5 Crop yield of *Zea mays* (*black*) and *Medicago lupulina* (*gray*) in different types of agricultural water (Rimwai et al. 2007)

hybrid (50% fresh with 50% mine wastewater)—were used as an agricultural water for both the crops. Water, soil, and plant samples were analyzed at different times during the plant growth. Crop yield was used to calculate the efficiency of the addition of phosphate mining wastewater. Crop yield production with hybrid wastewater was found to be 31% more when compared to the yield using only mine wastewater for *Medicago lupulina* spp. (Fig. 5). However, this production was heavily affected when high salinity was introduced in the mining wastewater. Recently, several high salinity-tolerant crops have been introduced in different parts of the world by genetic manipulation so that these can grow when irrigated with mining wastewater [48, 20]. Literature search shows that none of these or similar studies included the effects of any types of radioactive materials on the crops. However, this should be an important consideration in terms of the future use of mining wastewater as irrigation water [20].

An extensive series of studies on phosphorous recovery has been carried out by various researchers [6, 43, 44]. One of the studies investigated two-stage intermittent aeration process to understand the factors affecting phosphorus removal in domestic sewage treatment. They concluded that longer aeration cycle can negatively impact the phosphorus removal [62]. Another study considered recovery of phosphorous as struvite ($MgNH_4PO_4{\cdot}6H_2O$) by using a magnesium ammonium phosphate (MAP) fluidized bed crystallizer. They used a pilot-scale crystallization of struvite collected from the centrate from an anaerobic digester. Operating pH (8.0–8.2) and recycle ratio (5–9) were maintained to control the supersaturation conditions inside the reactor. It was possible to remove 75–85% of phosphorous by providing a narrow window of up-flow velocity of 400–410 cm/min [6].

The phosphorus recovery from wastewater is possible through struvite crystallization technologies [22]. Struvite (aluminum–magnesium phosphate) is a byproduct of phosphate removal during the biological wastewater removal process [22]. This struvite can be used as a fertilizer directly in the field [28]. It not only can reduce the phosphorus pollution of the environment but also can mitigate the agricultural need for artificial phosphorus as fertilizers [28].

7 Summary and Conclusions

Though the reuse of phosphate mining wastewater is still not practiced widely, the high demand of natural phosphate and high demand of natural groundwater by the phosphate mining industries would soon cause them to realize that the possible reuse of their wastewater is eventual and necessary. An efficient recycling technique is in high demand where less water is available for phosphate mining. A combined treatment of phosphate mining wastewater with possible reuse of phosphate would allow the industries to be efficient in their water consumption, as well as increased fertilizer production in the secondary treatment facilities.

Treatment of phosphate mining wastewater is still focused on possible removal of heavy metals. Unfortunately, limited studies have been done in improving the water quality by removing the radioactive metal nuclides. The current trend of phosphate depletion worldwide can lead our agricultural sectors to suffer in the future. Hence, reclamation from wastewaters can be a potential source of additional phosphates. A combined chemical and biological treatment method can be used to treat both the heavy metals and the phosphorus, but, at present, most of these methods are not focused on the reuse of phosphate or its byproduct in agricultural or in other sectors. This reuse gives us an opportunity to reduce the usage of fresh groundwater while reducing the problem of sludge management through reduced sludge production hence, less demand on landfills.

The reuse of phosphate mining wastewater has several benefits, which are related to sustainable production and consumption. These benefits are:

1. Reduction of direct pressure on natural phosphate which is already at peak.
2. Reduction in quantity of water used by phosphate mining industries.
3. Reduction of the volume of sludge produced and increased diversion to agricultural land.
4. Development of sustainable consumption of mined phosphate which would reduce the dependence of agricultural production on a single source of fertilizer.

Reuse of wastewater is still considered to be an expensive method by many industries in the world. Simultaneous reuse of phosphate mining wastewater as a fertilizer and its usage in the mine itself, as process water, can be a desirable model for cost-efficient water balance technology where water is recycled and reused while reducing the environmental impact. However, more research and development of techniques to achieve the reuse of mining wastewater are needed.

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Toward Sustainable Agriculture: Net-Houses Instead of Greenhouses for Saving Energy and Water in Arid Regions

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The limitation of protected cultivations in arid regions is mainly due to the overheating of the air inside the conventional agricultural structures (greenhouses) during hot and long summer seasons. In summer, the ambient air temperature exceeds 45 °C and the transmitted solar energy into the greenhouse is much higher than the plant requirements. Therefore, the greenhouse accumulates around 10 MJ m^{-2} of heat energy per day. This requires an expensive, energy-consuming cooling system to remove such amount of heat and to achieve favorable conditions for plant growth. Greenhouse cooling methods that are commonly used worldwide are ventilation, heat prevention (shading) and evaporative cooling. Cooling greenhouses are facing several challenges in arid regions due to the excessive solar irradiance, extremely high ambient air temperature, as well as water scarcity and salinity. These challenges and possible solutions will be discussed in this chapter. In addition, a new concept (net-house) as a naturally ventilated alternative agricultural structure, covered with a low-cost, translucent material (i.e., plastic net) will be introduced. Plastic nets covering the net-house should prevent heat from accumulating inside the structure. Such covering materials are a suitable alternative instead of the conventional covering materials (i.e., glass and plastic films) that are unfavorable under arid climatic conditions. The proposed net-house does not require cooling and ventilation equipment, while it provides a uniform distribution of the internal solar radiation and a suitable environment for plant growth. Providing such an alternative agricultural structure should contribute to increasing the area of protected cultivation in arid regions and enhancing the quality and productivity of crops. Production costs will be significantly decreased because cooling and ventilation systems were eliminated, (zero consumption of electric energy and cooling water).

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1 Protected Cultivation Challenges in Arid Regions

In summer of arid regions such as in the Arabian Peninsula, the western and eastern desert of Egypt, and the south parts of Libya and Algeria, etc., protected cultivation has become essential for protecting crops from the harsh environment and enhancing and managing crop production throughout the year. The main technical problem of using greenhouses is to maintain the inside air temperatures and relative humidity which are favorable for plant growth in summer. Greenhouses work well in regions with a cold or mild climate; however, in hot and sunny regions overheating of the inside greenhouse air is an essential obstacle that makes it very difficult to grow plants in a greenhouse in summer without efficient cooling systems [1–3]. Therefore, several efforts have been made worldwide to adopt greenhouses to hot and sunny climate conditions [4, 5]. Climate in arid regions is characterized by: hot and long summer seasons (the ambient temperature exceeds 45 °C at around noon); intensive solar radiation flux (the daily integral of solar radiation reaches to 30 MJ m^{-2}); dusty and dry weather (relative humidity levels of the ambient air drop below 10% most of the daytime); and water resources are limited and brackish (salty). Such harsh weather conditions degrade the optical and mechanical properties of greenhouses covering materials such as plastic films. Moreover, such conditions drastically reduce the performance of the cooling systems in the greenhouses. Methods commercially used for cooling the inside greenhouse air in hot summer can be divided into three main categories: ventilation, evaporative cooling, and heat prevention (i.e., shading).

1.1 Ventilation

Ventilation either natural or mechanical is replacing the hot air in the greenhouse with the relatively cooler outside air. In areas where summer is not severe and the maximum ambient temperature remains less than 33 °C, ventilation alone is sufficient for cooling greenhouse air [4]. The effectiveness of natural ventilation depends on the temperature difference between inside and outside the greenhouse (bouncy effect) and on the wind speed outside the greenhouse (wind effect). At low wind speed, exhaust fans are needed to induce air circulation through the greenhouse vents (forced ventilation). Exhaustive discussions of natural and forced ventilation for greenhouses worldwide are available in [6–11]. In the arid environment, ventilation methods alone are not efficient because they replace the overheated greenhouse air with a very hot ambient air. Thus, ventilation methods cannot provide adequate cooling capacity and suitable environment for plant growth in greenhouses unless combined with another source of cooling (e.g., evaporative coolers and/or shading nets).

1.2 Evaporative Cooling

Evaporative cooling is a constant enthalpy process; it lowers the greenhouse air temperature significantly below the ambient air temperature and enhances the relative humidity in the greenhouses. Commercial evaporative cooling systems commonly used for cooling greenhouses are the wet pad-fan system [12, 13] and fogging systems [14, 15]. These cooling systems can reduce greenhouse air temperature by 8–12 °C and increase the relative humidity by about 20–30% on average [12–15]. These systems operate properly in hot and dry climate if a pure and freshwater resource is available for wetting the pad or to be sprayed into fine droplets through the nozzles of a fogging system. The lack of freshwater resources in the deserts and the high salinity of the underground water cause a fast deterioration of the evaporative cooling performance of these systems. For example, salt buildup on the pad surfaces (of the wet pad-fan systems) blocks the airflow. Also, brackish water cannot be used for operating a fogging system because it blocks the fogging nozzle orifices; thus, costly water treatment is necessary or a periodical installation of new pads and/or fogging nozzles is required. This would increase the operational costs of the greenhouse. Accordingly, deflecting the radiation heat load on the greenhouse cover (heat prevention) may provide a solution for cooling the greenhouses.

1.3 Heat Prevention

Through heat prevention methods, the radiation heat load can be reduced before entering the greenhouse by either absorbing and/or reflecting a portion of the incident solar radiation on the greenhouse cover. This is accomplished by using commercial shading technique (curtains, clothes or plastic nets) or using a radiation-filtering roof (blocking the near infrared radiation, NIR, via reflection or absorption and transmitting the photosynthetically active radiation, PAR). Presently, NIR-reflecting plastic film covers have been developed. These films are able to reduce greenhouse air temperature by about 5 °C; however, their lifetime is very short (a few months) [16]. This reduction is not enough in regions where the ambient temperature may exceed 45 °C in summer. There is a need to develop and improve these film covers. Shading the roof of a greenhouse is usually performed by various conventional methods such as (i) whitening the roof with an aqueous solution of hydrated calcium oxide [$Ca(OH)_2$], and (ii) deploying plastic nets of various colors, or movable refractive screens or curtains. The whitening is washed away if rains fall over the greenhouse and its shading density cannot be changed once applied. An external or internal shade can also be obtained by using movable plastic nets, curtains, or refractive screens applied above or below the roof of the greenhouse. All shading methods are used to control the amount of solar energy entering the greenhouse and reduce the heating load in summer. Besides protecting plants against excessive heat load, shading significantly reduces the water requirement in arid regions [17, 18]. The disadvantage of shading, when they are used below the roof of the greenhouse, is that when the net is fully deployed, it will decrease the effectiveness of the natural roof ventilation and negatively affect the greenhouse microclimate. Moreover, the presence of shading materials in the greenhouse absorbs a portion of solar radiation and reemits it again in the greenhouse, and reflects back a portion also inside the greenhouse. Therefore, the effect of internal shading on reducing the greenhouse air temperature is expected to be low. Even though shading is applied to a greenhouse, an efficient cooling system along with forced ventilation that consumes additional power is required to reduce the inside greenhouse air temperature in summer of arid regions.

2 Plastic Nets Can Replace Plastic Films for Sustainable Agriculture

During the last decade, low-cost plastic nets have begun to replace plastic films in agricultural structures designed to protect crops. In particular, plastic nets have been widely used in recent years for covering agricultural structures (net-houses) to protect crops in arid climatic regions. Different varieties of plastic nets, made from high-density polyethylene (HDPE), are widely used for shading animal houses, car parking, and protecting crops and nurseries from, hail, strong wind, snow, strong rainfall, insects, animals, and birds. The most important application of the plastic nets in hot and sunny regions is to shade plants from high solar radiation levels in order to improve the microclimate in the net-houses.

2.1 Advantages of the Plastic Net Covering

The wide use of plastic nets instead of plastic films as covering materials is attributed to the fact that plastic nets offer many advantages and environmental benefits when they are used as net-houses [19, 20]. The main advantages of using plastic nets covering for crops protection are:

(i) Reducing the solar radiation heating load, and the increase of the inside net-house air temperature is much lower than the uncooled greenhouse that works as a solar thermal collector.
(ii) Eliminating the use of electric-powered evaporative cooling and ventilation systems which means zero consumption of electric energy as well as cooling water.
(iii) Reducing crop transpiration as well as water consumption for irrigation in arid regions.

(iv) Preventing insect pests from entering the net-house, which should improve environmental and human-health conditions by reducing the need for pesticides.

(v) Scattering of solar radiation diffusively allowing plants to receive light from all sides. A recent study found that the diffuse radiation transmitted through nets was enhanced by 17–170% depending upon the color and structure of the net textures [21].

(vi) Reducing air velocities in a net-covered structure eliminates wind damage to leaves and fruits.

(vii) Perforated plastic nets act as a thermal barrier between the plants and the outside cooled environment at night; this eliminates heating systems used for greenhouses. The net porosity and its color can regulate the transmitted solar radiation intensity into the net-house as well as the spectrum quality of light. Thus, in sunny regions, the light under nets can be adjusted to fulfill the crop growth requirements in summer and in winter, and farmers can protect plants from frost in winter and sunspots in summer.

(viii) Colored nets can filter out (by reflection) different colors in the visible light (PAR: 400–700 nm) spectrum, and they can produce changes in flowering and branching patterns; therefore, plant morphology can be controlled under colored nets according to specific requirements [22, 23].

In particular, cultivation of crops under plastic shading net-covered structure (net-house) may contribute to enhancing productivity, quality, and homogeneity of plants and fruits throughout most of the year in hot and sunny regions. This is mainly due to its low-cost structure and the advantages of saving energy and water to operate greenhouses that can be achieved.

2.2 Physical Properties of Shading Nets

Commercial plastic shading nets are characterized by (i) the net porosity (ϕ), defined as the empty area divided by the total surface area of the net, and (ii) the shading factor (SF), defined as the percentage of global solar radiation that the net is able to block. Net manufacturers usually designate a net by the net color followed by the nominal shading percentage (%). For example, white-50 means the net is white and it blocks 50% of the incident solar radiation. The net material (colored HDPE) is usually opaque to transmit radiation. Net textures consist of either interlaced threads or interlaced strips. Scanned photographs for eight commercial nets having different colors and texture structures are illustrated in Fig. 1.

Manufacturers usually estimate the SF by measuring the net transmittance at an incident angle of 45° using artificial lighting. However, the resulting value of SF does not represent the actual daily shading power of the net. Net solidity ($1 - \phi$) is a constant that describes the texture structure and differs from the shading factor (SF) of the net. In fact, the SF changes with the daytime, the incidence angle of

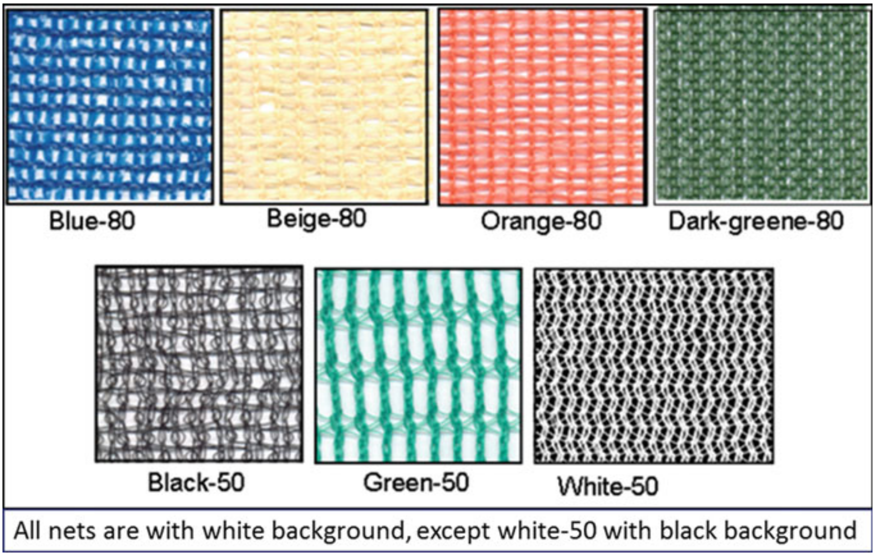


Fig. 1 Scanned photographs for different types of commercial nets used for shading purposes

solar beam radiation, the net orientation, and its location. The time-dependence of SF is equal to $(1 - \tau_g)$, and τ_g is the transmittance of the net to global solar radiation (i.e., instantaneous value). The daily integral of shading factor that a net can produce (integrated shading factor, ISF) is defined by the following equation:

$$\mathrm{ISF} = 1.0 - \int_{\mathrm{t}_1}^{t_2} S_t \mathrm{d}t \Big/ \int_{t_1}^{t_2} S_i \mathrm{d}t, \tag{1}$$

where t_1 and t_2 are the sunrise and sunset times, respectively; S_i and S_t are the incident and transmitted global solar radiation. The radiative properties (i.e., transmittance,τ_g reflectance, ρ_g, and absorptance, $\propto_g$) of a net to global solar radiation (as instantaneous values) can also be integrated as the second term on the right side in Eq. (1) to obtain daily integral values for these properties. Table 1 shows the physical properties of nets in Fig. 1; based on the data in Table 1, the nominal SF (measured by manufacturers) differs from the daily integral of SF (ISF) which is appropriate to describe the shading power of a net. Moreover, nets with bright colors (white, orange, and beige) have higher transmittance to global solar radiation than their porosities. This attributed to the high forward scattering of the net to solar radiation as affected by its bright color.

Table 1 Nominal and integrated shading factor (SF, ISF), net porosity, and the daily integral of the radiative properties for different types of the net

Net type	Nominal SF (%)	Net porosity ϕ (%)	Estimated ISF (%)	The daily integral of global	
				Transmittance	Reflectance
White-50	50	28	38	0.62	0.37
Green-50	50	51	48	0.52	0.17
Black-50	50	50	54	0.46	0.08
Blue-80	80	21	70	0.3	0.19
Beige-80	80	12	58	0.42	0.39
Orange-80	80	23	70	0.3	0.28
Dark green-80	80	20	75	0.25	0.12

3 The Conventional Net-Houses

Three styles of net-houses are commonly used: gable style, curved-arch style, and parallelogram style. These are the conventional structures, usually covered with one type of net (having a certain color, shading factor, and porosity). In the conventional net-houses (covered with one type of net), the transmittance patterns of these structures to solar radiation are nearly constant during the day similar to that in the greenhouses. In clear sunny days, the transmittance patterns to global solar radiation for three net-house models representing the commonly used net-house structures (i.e., the gable, parallelogram, and curved-arch styles) are measured and illustrated in Fig. 2a–c comparing with a gable-type greenhouse transmittance (Fig. 2d).

The three net-house models were simultaneously covered with three types of the net (white-50, green-50, and black-50) as shown in Table 1. On the other hand, in sunny regions with intensive solar irradiance, nets with low porosities (high shading factors) are usually used to cover the net-houses to strongly reduce the transmitted solar radiation at around noon. Consequently, the transmitted radiation inside these houses is very low in the early morning and late afternoon which may not fulfill crop growth requirements. In addition, net with low porosity would significantly reduce the ventilation rate of the net-house, which negatively affects crop growth and crop production. Nets in Table 1 can be classified into three categories based on their transmittance to the PAR if they were used to cover conventional net-house structures and the types of crops that can grow successfully in the net-houses. Table 2 summarizes this classification based on the optimum PAR required for each crop to grow (PAR_{opt}).

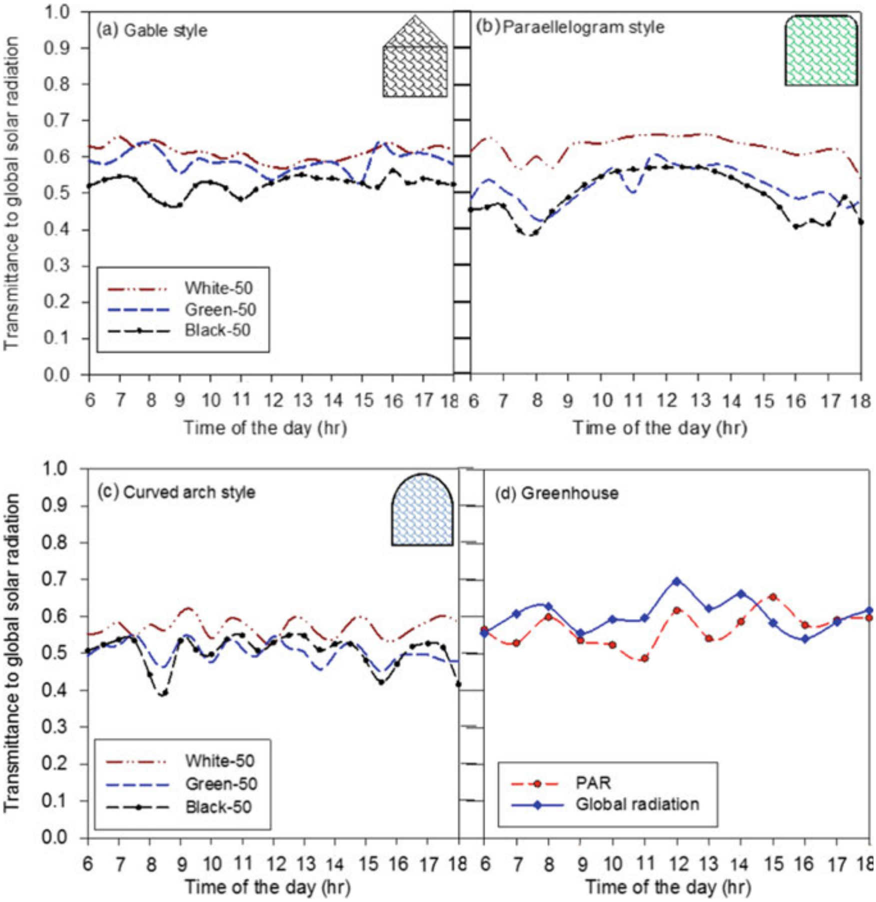


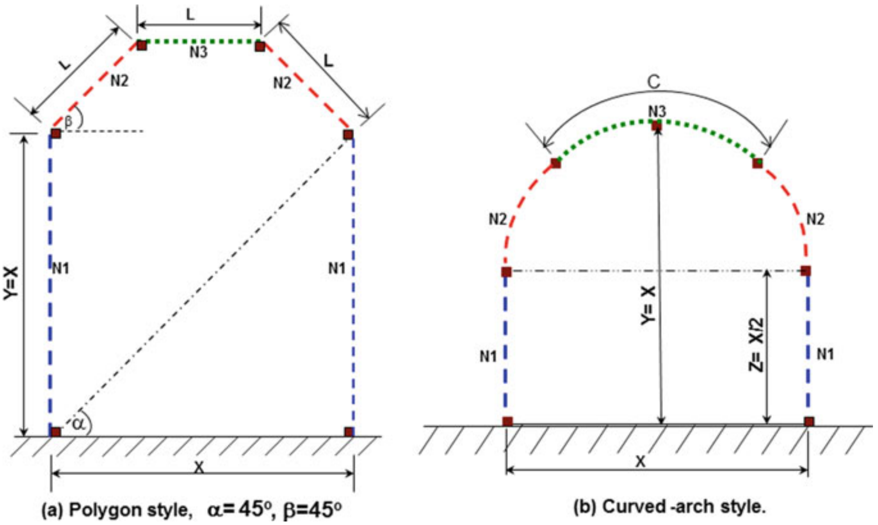
Fig. 2 Transmittance of conventional net-houses and a greenhouse to global solar radiation: **a** The gable style, **b** parallelogram style, **c** curved-arch style, and **d** gable-type greenhouse; each type of net used to cover the three net-house models for one day, after [24]

4 New Concept

To overcome the above-mentioned problem (low transmitted radiation into the net-houses in the early morning and late afternoon and the reduction of air flow to the net-house), two new designs for net-house structures have been recently proposed and tested [24]. One is polygon style, as in Fig. 3a, and the other is curved-arch style as in Fig. 3b. The new designs are able to enhance the transmission of solar radiation in the early morning and in the late afternoon and strongly reduce the transmission of solar radiation at around noon. In the proposed structure, nets with high porosities are used vertically to cover the sides of the structure (N1) to enhance the radiation and ventilation rate in the crop level. Nets with medium porosity are used to cover

Table 2 Crops and plants that can be grown in net-houses covered with the three categories of nets in relation to the PAR values required for optimum growth (PAR_{opt}), after [22]

PARopt (W m^{-2})	Crops and plants
Dark green-80, Blue-80 and Orange-80	
< 30	Indoor and ornamental plants
15–36	Lettuce, spinach
36–60	Cucumber
50–75	Different types of transplants
Green-50 and Beige-80	
30–60	Sweet peppers, eggplants
76	Strawberry
60–90	Tomato
$\geq$60	Carnations
Black-50 and White-50	
100–135	Rice, wheat



(a) Polygon style, α=45°, β=45°

(b) Curved-arch style.

Fig. 3 Diagram for the proposed net-house structures, **a** is for the polygon-style, and **b** is for the curved-arc style; the curved part in (**b**) is divided into three equal parts, each having a length of C, after [24]

the tilted surfaces of the structure (N2). Nets with low porosities are used to cover the upper horizontal or curved surfaces of the structure (N3) to serve at around noon.

The three types of nets, with high (N1), medium (N2), and low (N3) porosities are selected based on the following desired characteristics:

(i) High diffusive ability to enhance the transmitted diffuse radiation by converting a portion of direct solar beam radiation into diffuse radiation during transmission. This is important to have a uniform radiation distribution over plant canopy and let crops in the net-house receive solar radiation from all sides. Nets with light colors (e.g., white, yellow, beige, etc.) have higher diffusive abilities than nets with dark colors (e.g., black, blue, dark green, etc.) [22].

(ii) Cutting out solar radiation by optimizing the shading factor. Nets with high shading factor (low porosity) are used for covering the horizontal surfaces (N3 in Fig. 3a, b); nets with medium shading factor are used for covering the tilted surfaces (N2 in Fig. 3a, b); and nets with low shading factors (high porosity) are used for covering the vertical surfaces (N1 in Fig. 3a, b).

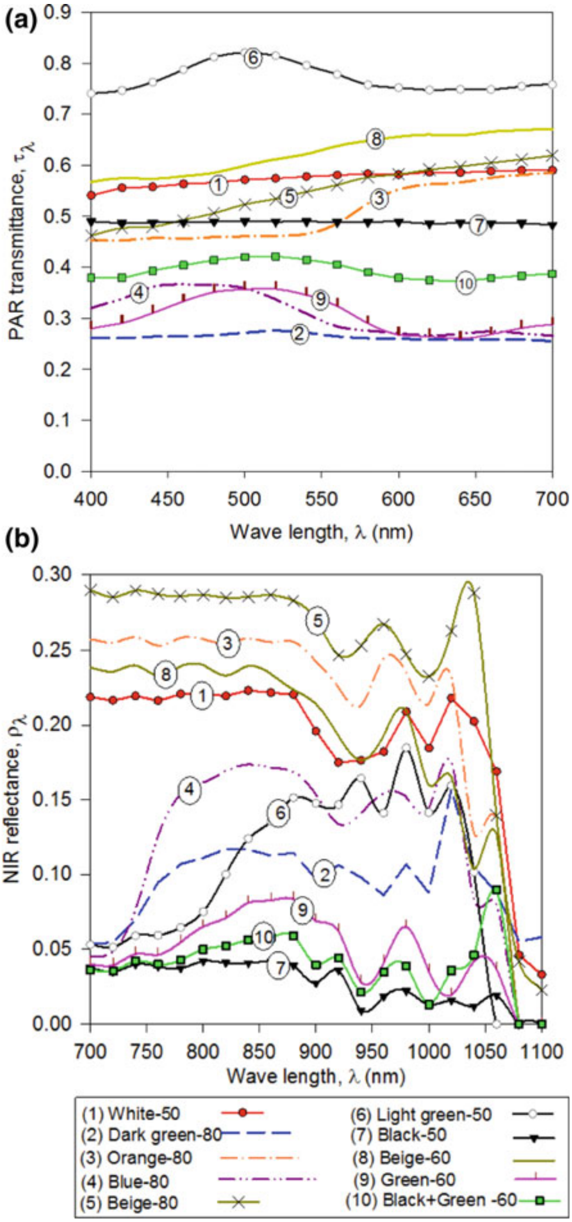
(iii) High reflectance to NIR radiation (700–2500 nm) to improve the environment in the net-house in hot climates, and high transmittance to PAR (400–700 nm) to significantly enhance crop growth. For more clarification, the spectral transmittance of 10 net samples to the PAR is illustrated in Fig. 4a, and the spectral reflectance of the 10 net samples to the NIR is illustrated in Fig. 4b.

The main objective of the new design concept is to modify the transmittance pattern of solar radiation inside the net-house. Two models (1 m × 2 m floor area of each) of the proposed structures in Fig. 3a, b were covered with three types of net, and the transmittance pattern of each net-house structure to solar radiation was measured and illustrated in Fig. 5. The two designs significantly enhance the transmittance in the early morning and late afternoon (Fig. 5). This improvement may be attributed to: (i) in the early morning and late afternoon (when sun elevation is low), solar radiation passes through the high-porosity net (N1) having high transmittance value, (ii) the internal reflection of solar radiation on the inner surfaces of N1 and N2, which enhances the net solar radiation over the net-house floor, and (iii) at around noon (when sun elevation is high) solar radiation passes through the low porosity net (N3) having low transmittance value, which significantly reduces the transmitted radiation.

The design of the new structures is based on dividing the daytime (from sunrise to sunset) into five equal periods: two before noon, one around noon, and two in the afternoon. The nets were arranged to meet the transmittance requirements for the different periods. Most of the solar irradiance that reaches the net-house floor passes through nets with (i) high porosity during the first and last periods, (ii) medium porosity during the second and fourth periods, and (iii) low porosity during the third (noon) period. This arrangement resulted in the transmittance patterns shown in Fig. 5. On the other hand, if the same net is used to cover all surfaces, the transmittance pattern would be similar to those in Fig. 2(a-c).

A recent study [24] compared a polygon-style net-house, like the one shown in Fig. 3a, (having a floor of 4-m × 8-m, and covered with three types of nets) with an evaporatively cooled greenhouse having a floor area of 32-m^2; both were oriented in the N–S direction and operate simultaneously under the same climatic conditions. The comparison includes the microclimatic parameters (i.e., air temperatures, relative humidity, global solar radiation, and PAR), electric energy, and water consumption

Fig. 4 Spectral transmittance to the PAR (**a**) and spectral reflectance to the NIR (**b**) measured for 10 types of plastic shading net are commonly used in arid regions for crop protection



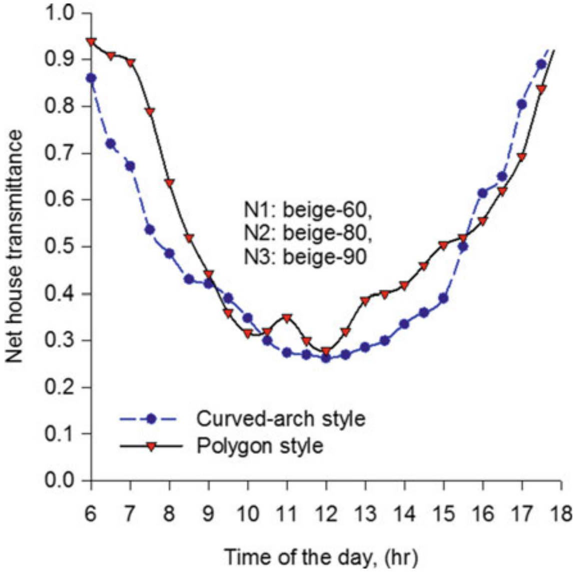


Fig. 5 Transmittance patterns of the polygon and curved-arch structures (in Fig. 3a, b), covered with three types of plastic net and measured in March 2014, Riyadh, Saudi Arabia, after [24]

in both structures. The net-house is able to provide a suitable environment for crop growth in mild conditions (winter, spring, and autumn). Diurnal variation of the air temperatures inside the net-house and the evaporatively cooled greenhouse are very similar (Fig. 6), which means that the inside air temperature is reduced as much as it is in the cooled greenhouse. Thus, the expenses of cooling and ventilation of

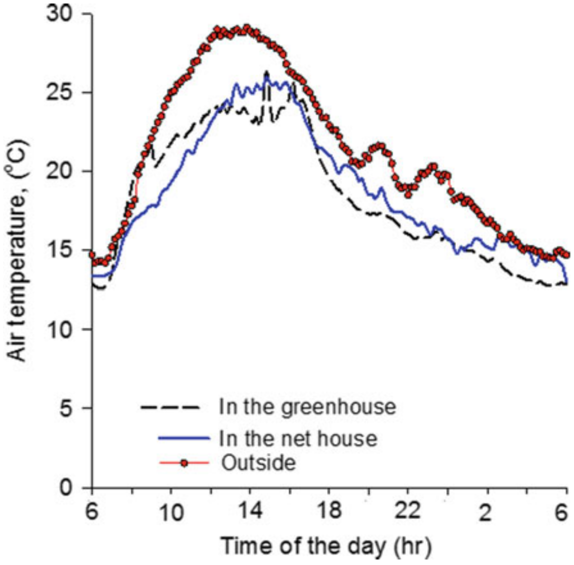


Fig. 6 Diurnal variation of the air temperature measured inside and outside the net-house and the greenhouse, after [24]

the greenhouse can be eliminated in the net-house. However, in the summer of arid regions, the outside ambient temperature often exceeds 45 °C and solar irradiance of about 1000–1200 W m^{-2} at around noon. Therefore, the air temperature in the net-house is usually higher than that in the cooled greenhouse. This can be controlled based on the porosity, shading factor, and color of nets covering the polygon structure. Nets with low porosity may be able to provide an appropriate microclimate for crop growth under extensive solar irradiance in hot summer.

In summer, the relative humidity in the greenhouse is usually higher than that in the net-house because of the use of evaporative cooling to cool the greenhouse air. On the other hand, the relative humidity levels are sometimes higher in the net-house than outside, probably because of the higher rate of evapotranspiration from crops and soil in the net-house. In summer seasons of arid regions, the relative humidity of the ambient air is usually below 15% at around noon. The evapotranspiration of mature crops in the net-house is expected to be higher than in the cooled greenhouse; this may enhance the relative humidity to the desired levels for crop growth in the net-house. Although the transmittance of the developed net-house is low at around noon (Fig. 5), the integral global radiation and PAR transmitted into the net-house were estimated to be 8.1 MJ m^{-2} day^{-1} and 3.0 MJ m^{-2} day^{-1}, respectively, and those in the greenhouse were 9.0 MJ m^{-2} day^{-1} and 3.5 MJ m^{-2} day^{-1}, respectively (Fig. 7). This means that the daily integral of the PAR transmitted into the net-house was almost similar to that in the greenhouse. In addition, these amounts of PAR in the net-house can fulfill any crop growth requirements during the day in regions characterized by intensive solar irradiance (Fig. 7). Accordingly, the newly developed naturally ventilated, uncooled, net-house may provide inside environment similar to that of the mechanically ventilated, evaporatively cooled greenhouse. However, based on several previous experiments to estimate water consumption in the net - house in comparison with a fan-pad cooled greenhouse, the net-house reduced water consumption by 13 kg m^{-2} day^{-1} in summer and by 0.94 kg m^{-2} day^{-1} in winter and reduced electric energy consumption by 0.26 kW-h m^{-2} day^{-1} in summer and by 0.18 kW-h m^{-2} day^{-1} in winter as shown in Table 3.

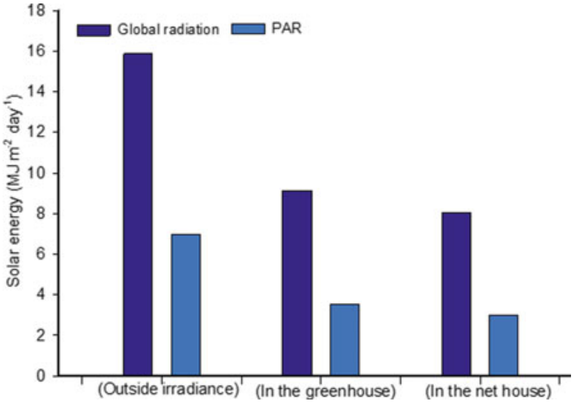


Fig. 7 Daily integral of the global solar radiation and PAR were estimated outside and inside the net-house and greenhouse based on several days of measurements conducted in Riyadh, Saudi Arabia, after [24]

Table 3 Water and electric energy consumption in the newly developed net-house and in the evaporatively cooled greenhouse during the 24-h period, per unit area of the floor, after [24]

	Plant	Evapotranspiration (kg m^{-2} day^{-1})	Evaporative cooling (kg m^{-2} day^{-1})	Electric energy for ventilation (kw-h m^{-2} day^{-1})
In summer				
The net-house	(Cucumber)	6.7	0.0	0.0 (natural ventilation)
The greenhouse	(Cucumber)	3.16	13.26	0.26
In winter				
The net-house	(Chrysanthemum)	0.49	0.0	0.0
The greenhouse	(Chrysanthemum)	0.23	1.2	0.18

5 Financial Impact

In some countries, the costs of electricity and water are subsidized by the government. For example, the costs of electricity and water in Saudi Arabia are as follows: SAR 0.2/kWh and SAR 7.5/m^3, respectively, where SAR is the currency abbreviation for the Saudi riyal and \$1 = SAR3.75. Based on 2017 market prices, the costs to construct a PE-covered greenhouse and a similar net-house were 715-SAR and 357-SAR per m^2, respectively. Based on these criteria, the total (fixed and running) costs can be reduced from 26.25 million SAR (\$7 million) to 3.6 million SAR (\$0.96 million) for continuously planting one hectare of crops under net-houses instead of greenhouses for one year. In terms of water and electricity consumption, growing one hectare of crops continuously for one year under net-houses, instead of greenhouses, would save at least \$-100,000 per year in water and electricity costs. If similar cost estimation was analyzed in countries where electricity and water are more expensive, the results may lead to much more valuable economic profits.

6 Conclusion

New concept has been developed, and two agriculture structures (net-houses) have been designed and evaluated to be used in hot and sunny regions. The new structures are polygon and curved-arch; each consists of seven surfaces covered with three types of plastic nets. The new designs significantly enhanced the transmission of solar radiation in the morning and afternoon and depressed it at around noon. The resulted pattern of radiation transmission is more suitable for regions having intensive solar irradiance than that observed in the conventional net-houses. The PAR transmitted into the newly developed net-houses can fulfill the crop growth requirements as in the greenhouses. In addition, they provided a microclimate similar to that in the evaporatively cooled greenhouses, without the use of cooling or ventilation systems. The modified net-houses can effectively replace the greenhouses in hot and sunny regions as they reduce energy and water consumption.

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Sustainable Food for Thought

Tachelle Z.-T. Ting and Jacqueline A. Stagner

Abstract There is not a single solution for sustainable food for the future. Multiple sources, with differing views on the effect of diets on our health, the global population, society, and the future of the environment, are able to compromise on an 'imperfect' solution. Unsurprisingly, the better, more environmental-friendly, less energy- and water-intensive foods are generally plant-based. Because strict plant-based diets cut out all animal products, the happy medium is the Mediterranean diet. The Mediterranean diet is mainly plant-based, with some fish, eggs, and even less meat and dairy recommended. This bodes well for different cultures, health, and people universally and projects well for the planet's future. The authors hope that this chapter will provide factual insight from multiple sources for readers to make informed decisions of what to consume on a daily basis.

1 Introduction

In recent years, the fear of our planet's future has caused much ruckus. Many modern-day systems and products are unsustainable. Much time and effort are being placed into finding sustainable alternatives. One area of focus is on humans' diets and how to reduce the environmental and health impacts associated with the food that we eat. However, this challenge can seem daunting to many people. Bonneau [1], a zero-waste chef, once noted, 'We don't need a handful of people doing zero waste perfectly. We need millions of people doing it imperfectly.' This is a good model for how we should be eating. Eat plant-based not restrictively but to the best of your ability.

Something that many are doing multiple times a day that affects our planet and our future is eating. Many fads and diets recycle themselves in the media in the west while in the east, there is the struggle of inadequate nutrition. Koerber et al. [2] coin this issue as the 'double burden of disease'. There is a problem of quantity of food

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reaching everyone worldwide and a problem of quality of food everyone deserves [2]. This is becoming a global issue as well as an environmental issue.

It is predicted by Godfray et al. [3] that the world population will plateau in 2050 at approximately nine billion people and that sixty-six percent of the world's population will be living in cities [2]. While the number of people who are hungry has decreased, the problem of micronutrient malnourishment remains an issue [3]. With the steady increase of urbanization, animal products are being favoured. It is also observed that there is an adoption of the Western diet in countries such as China, Mexico, and Brazil [2]. The Western diet is rich in meat and cheese as opposed to the Eastern diet, which staples include rice and soup [3]. Animal products not only contribute to unnecessary greenhouse gases but also contribute to increasing rates of obesity and some diseases [2]. The mass production of agriculture has faults as well [3]. Kesavan and Swaminathan [4] concluded that the latest bacteria- and herbicide-tolerant crops not only present genotoxic effects, they are also unsustainable. The solution is not fixing all of our crops to perfection, but having enough good, fresh produce for everyone.

Castane and Anton [5] indicate that our diets and food sources are responsible for about one-third of our impact on climate change and land use. An increase in overall food consumption and, more directly, an increase in meat consumption affect the environment and the world's health [5]. The Mediterranean diet and Vegan diet are highlighted as having a low environmental impact, as they both are plant-based [5]. Approximately, one-third of the world's cereal is fed to animals [3]. A reduction in animal product consumption rather than a termination of animal product consumption is promoted for a number of reasons [3]. For the portion of livestock that feeds on grass, not grain, it would be worse for the environment if that grassland was converted to arable land. Pigs and poultry consume human food waste. Livestock plows land, and their manure is valuable. It is suggested that specific foods are not eliminated from our diets, but rather that we shift our mindset on what is good food [3].

Plant-based foods require much less land in comparison to animal-based products [2]. This occurs because the transformation of energy from plants to animal products is extremely low [2]. The energy gained from animal-based products is extremely low, especially compared to how much land it takes to produce animal-based products [2]. Water statistics are shared; it takes 15,415 l to produce 1 kg of beef, 5988 l/kg of pork, 5060 l/kg of cheese, 3265 l/kg of eggs, 1827 l/kg of wheat, 822 l/kg of apples, 287 l/kg of potatoes, and 214 l/kg of tomatoes [2]. Plant-based foods offer cleaner energy to our bodies and our planet [2].

Governments should be creating policies and putting tax dollars toward the food their citizens consume. It is extremely difficult to tell people what to eat and what not to eat. Eating is so much more than the food on our plates or something to keep us going throughout the day. Food is a part of culture and tradition, bringing families together, and creating experiences. People should be given the facts and decide what to do with them. The issue of sustainability of our food is looked at as a large-scale, multi-faceted idea that needs to be tackled from many perspectives, from the beginning (food production) to the end (selling food).

2 The Link Between Nutrition and Health

In recent years, we have improved in our moral duty of making sure the entire world is fed; however, a staggering number remains malnourished [3]. This does not necessarily mean hungry. Malnourished may mean that some individuals simply do not have enough food and some, despite having enough food, are without the proper nutrients [3]. Focusing on the quantity as well as the quality of food, new, sustainable technologies are being implemented.

The main macromolecules include fats, carbohydrates, and protein. Western society has often put much focus on protein, not only that it is a vital component of our diets, but also that it may be the most important macromolecule to live a healthy life. However, Dallas et al. [6] discuss how too much protein is difficult for our digestive system to process. Interestingly enough, the Western society that places much focus on protein has the highest rate of weight-loss surgeries, which in turn leads to less hydrogen chloride and decreases the amount of pepsin available to denature and digest protein [6]. Too much protein makes it harder for our digestive systems to do their jobs. The body's preferred energy source is carbohydrates [6].

Lopez-Jaramillo et al. [7] claim that health comes from diversity in a diet. A variety of foods should be consumed. The majority of one's diet should be fibrous carbohydrates (about fifty percent), fats (about twenty-five percent), and both plant and animal proteins (about twenty percent) [7]. It was found that a fruit-, vegetable-, and legume-rich diet reduced mortality [7].

Friedman [8] observes the trend in America; the obese population continues to grow. An effort to stop the epidemic is seen with a trend of more high-protein, low-carbohydrate diets being implemented. While the results do show that a high-protein diet could be used for weight loss, there are many possible dangerous side effects to this diet as well. The diet is often called the Atkins diet because it was popularized by Dr. Atkins [8]. Individuals who are considering this diet are warned to be cautious if one is susceptible to kidney disease. Although Dr. Atkins disagrees, there has been correlation seen between high-protein diets and kidney damage, in turn possibly leading to heart disease as well [8]. There has been no concrete evidence for high-protein diets leading to weight loss. An American study that has shown participants lost weight by following a high-protein diet is not conclusive, as there are too many outside factors that were not controlled [8]. An Australian high-protein diet study shows no difference between the standard diet and Atkins diet (Note: article does not define what a 'standard diet would be') [8]. There is also no concrete evidence that a high-protein diet causes kidney issues, but it can accelerate kidney complications in individuals who have chronic kidney disease [8]. Antonio et al. [9] performed a study with high-protein diets in unison with high-resistance training; the results show no benefits or drawbacks [9]. The study used young males who regularly resistance train. The control cohort continued training with their regular diets while the study cohort increased the amount of protein consumption in their diets. The average amount of protein consumed was 2.6 ± 0.8 and 3.3 ± 0.8 g/kg/day for the control and study groups, respectively. The results anticipated negative health results, such as an imbalance of lipids and damage to the kidneys; however, the results showed no increase in health issues and no change in body composition between the control and study groups [9].

Pinheiro and Wilson [10] compare the three macromolecules; one gram of fat gives nine kcal while one gram of protein and carbohydrate both give four kcal. There is no concrete evidence showing a correlation between the amount of fat consumption and weight lost or gained. However, all fats are not created equal [10]. The two fats that have opposite effects on the body are saturated fatty acids and unsaturated fatty acids. A reduced consumption of saturated fatty acids (mostly found in animal products) can reduce the risks of chronic heart disease [10]. Replacing saturated fatty acids with unsaturated fatty acids also has been shown to reduce the risk of chronic heart disease [10]. Unsaturated fatty acids typically come from plant foods [10].

Dernini et al.'s [11] analysis shows both health and nutrition benefits from a Mediterranean diet. Studies have shown a reduced risk for illness, particularly cancers of organs involved in the digestive system (i.e., stomach, colorectal, pancreatic, liver, etc.), when individuals consume a Mediterranean diet [11]. In a study of men and women of different ethnic backgrounds, Park et al. [12] found that there is little variation in risk of colorectal cancer. The study found that implementing a Mediterranean diet lowered the risk of colorectal cancer in people of many different ethnicities. As well, a Mediterranean diet achieves most nutritional requirements, and an overall healthier body weight is seen [12]. Perez-Jimenez et al. [13] state olive oil is a key part of the Mediterranean diet and a major source of monounsaturated fatty acids (MUFAs). When ingested, olive oil has been shown to improve the lipid profile (i.e., patterns of lipids in blood) and to have anti-inflammatory effects on the body [13]. Drewnowski [14] shows high-fat diets have been shown to increase obesity as well as coronary heart disease.

A diet rich in grains, fruits, and vegetables has been suggested as the most healthful; however, it has been seen worldwide that people of all cultures and backgrounds enjoy high-fat foods [14]. Fats greatly stimulate the human senses. The smell, taste, and texture of fat are very appealing [14]. A taste for sugar and fat has been seen in very young children [11, 14]. Studies have shown that, although everyone, overweight and slim, tends to prefer sweet foods, the overweight population chooses sweet foods that are high in fat [14]. The overweight population has also shown more tendencies to binge eat, and these binges mainly consist of sweet, fatty foods [14]. Finkelstein et al. [15] note that trends are seen within families and passed through generations; overweight children tend to have overweight parents. Although studies have shown obese men enjoy eating saturated fats, obese women enjoy eating unsaturated fats [15]. For example, obese men tend to eat more red meats, and obese women tend to eat more dairy [15]. Richer countries and people are able to afford a high-fat diet, decreasing the amount of complex carbohydrates and fiber consumed. A trend of developing countries eating a higher-fat diet, i.e., a larger amount of meat, dairy, and eggs, is seen in correlation with increasing obesity trends worldwide [15]. Much evidence supports that inappropriate nutrition is directly linked to disease development [15]. Therefore, it is crucial to have an understanding of what foods are needed to sustain a healthy nutritional state of the population.

Table 1 Cardiac issues and garlic consumption, based on the results of [16]

Cardiac issue	Effect of garlic
Hypertension	Reduced blood pressure
Hypercholesterolemia	Varied results. Inferred that cholesterol can be lowered by garlic consumption, with the use of statins
Coronary artery calcium and epicardial adipose tissue	Increased brown-to-white epicardial adipose tissue ratio, which is an indicator for a lower risk of ischemic heart disease
Biomarkers of inflammation	Decreased inflammation

Varshney and Budoff [16] state heart disease is one of the leading causes of death in developed countries. Houston [17] adds in America, cardiovascular disease is the number one killer. A healthy lifestyle is shown to dramatically decrease the risks of cardiovascular diseases. Varshney and Budoff [16] studied different types of cardiac issues in conjunction with the consumption of garlic. A summary of the findings is shown in Table 1. This study suggests the cardiovascular benefits of garlic, a component of the Mediterranean diet.

The Mediterranean diet, a diet rich in omega-3 fatty acids (fats from fish, nuts, and especially olive oil), decreased cardiovascular mortality. Monounsaturated fatty acids (MUFAs) and polyunsaturated fatty acids (PUFAs) decreased the risk of coronary heart disease, while saturated fatty acids and trans-fatty acids were correlated with an increased risk of coronary heart disease [16]. Coconut oil consumption had little effect on heart disease risk [16]. Dairy has been shown to decrease coronary heart disease [16]. Sugar and refined carbohydrates increased risk of coronary heart disease. Fermented foods, fruits, and vegetables decreased risk of coronary heart disease [16]. Coronary artery calcification, coronary heart disease, and cardiovascular disease are all dramatically decreased on a vegetarian diet [16, 17].

Morris [18] finds saturated fats have been shown to lead to dementia, while the Mediterranean diet has been shown to protect the brain from degenerative neurological diseases. The key ingredients for good neurological health are as follows: focus on plant-based foods and reduce animal/high-saturated fat foods [18]. It has been found that green leafy vegetables and berries have the greatest effects against cognitive decline [18].

Stevens et al. [19] find that there is not much information on the effects of diet on the human epigenome. It is thought that there must be an effect of diet on the human epigenome, as human disease can come for either genetics or the environment [19]. A lack of proper macro- and micro-nutrients correlates to negative behavior. Through studying paternal and maternal diets, it was shown that a poor diet is correlated to health problems in the offspring [19]. These health problems may occur by a means of interrupting healthy methylation of DNA. DNA methylation is directly related to neurodevelopment. Thus, mutations in DNA methylation, possibly caused by diet, can cause neurological disorders such as autism as well as behavioral disorders such as depression [19].

3 Models for a Healthful and Sustainable Diet

Seed [20] uses the Mediterranean diet as a standard for a healthy and sustainable diet. Qatar has tried to enforce a dietary guideline, and Seed has outlined it and reviewed the results. The title of the diet is 'Eat Healthy while Protecting the Environment.' An emphasis is placed on plant-based foods, as they are more sustainable and lower greenhouse gas emissions and water use [20]. Plant-based foods are also good for you, reducing the risk of non-communicable disease and chronic disease [20]. Reducing food waste is also part of the plan, as more than thirty percent of food is wasted in high-income and middle-income countries [20].

Koerber et al. [2] use the term 'Wholesome Nutrition' to describe a diet that is sustainable and nutritious. The majority of the diet is plant-based, focusing on fruits and vegetables, whole grains, legumes, and dairy. It is noted that meat, fish, and eggs are to be consumed only if wanted [2]. The four components that create 'Wholesome Nutrition' are health, environment, economics, and society. Health was newly added in the 1980s, as it is important globally [2]. Sustainable nutrition looks at all parts of food from start to finish: input production, agricultural production, food processing, distribution, preparation of meals, and disposal. Problems range from energy prices to livestock breeding [2].

Nutrition is one of the top three contributors to greenhouse gas emissions [2]. In Germany, 85% of agricultural emissions are from animal products while the remaining 15% is from plant-based food. Interestingly enough, animal products contribute to one-third of humans' energy when consumed while the other two-thirds of energy are supplied by plant-based foods [2]. Koerber et al. [2] note that leaning toward a plant-based diet will effectively decrease greenhouse gases. Dernini et al. [11] echo the effect of a low-impact, plant-based diet. The Mediterranean diet is mostly plant-based; less water is used, and less greenhouse gases are emitted [11]. The Mediterranean diet encourages diversity in agriculture as well [3].

Plant foods will decrease the cost for food production, in turn helping poorer countries [2]. A predominantly plant-based diet increases consumption of complex carbohydrates and decreases consumption of fat and cholesterol [2]. Fiber can be obtained only from plants and is essential for a healthy diet. As well, it increases satiety. Thus, in malnourished populations, increasing fiber and complex carbohydrates can have health benefits while also satisfying appetites [2]. The Mediterranean diet, high in fiber and low in saturated fats, is also recommended for populations facing obesity struggles [11].

It is important to note that while it is not the most sustainable or the most healthful, the Mediterranean diet is recommended due to its diversity [5]. Food is more than just its production and nutrition facts. Dernini et al. [11] found that the Mediterranean diet makes a happy compromise, as it is culturally appropriate globally, can be modified from region to region, and its base is mostly plants. The plant-based foods give it sustainability, and the animal-based foods (dairy, fish, eggs, and white meat—in small servings [4]) add culture. Mediterranean cultures emphasize food as important in day-to-day living [11]. It is a means of communication and socializing. This is also seen in different traditions and religions [11].

It is important to keep in mind that no matter what type of food is produced; globally, more than thirty percent of food is wasted [3]. In poorer areas, food waste is due to a lack of healthy storage for food, such as refrigeration; thus, food is spoiled. In richer areas, ‘use by’ dates on food products encourage consumers to throw away good food [3].

Clean water should never be taken for granted, especially as we march into the future. Ultimately, all foods link back to the water that nurtured them. It is not surprising that Mabhaudhi et al. [21] note in places where water is scarce, nutrition and health challenges increase. Collaborative efforts targeted at tackling water, food, nutrition, and health challenges should go hand-in-hand.

Food produced organically decreases the amount of greenhouse gases being produced [2]. Organic farming has been shown to build more humus that is able to absorb CO_2 from the atmosphere [2]. Koerber also advocates for regional and seasonal farming. Regional farming is to cut down on the amount of transportation needed for transporting food. Seasonal farming is to reduce greenhouse gases, because out-of-season production of produce requires extra heating and plastic. Out of season, produce requires more packaging to maintain its freshness [2]. Processed foods need more energy than unprocessed foods. As well, the process of processing foods uses more water [2].

In the agriculture industry, technology is being used to grow and maintain crops [4]. Our use of pesticides, fungicides, and herbicides is doing more damage than good. Combining Mendelian genetics with biotechnology can breed hybrid crops [4]. This can be a method of bettering agriculture as it increases biodiversity. Kesavan and Swaminathan [4] show that more research needs to be done, as there are disadvantages to biotechnology as well. Thus, this is not a final solution to sustainable food. Jones [22] notes that the stability of ecosystems, that is making ecosystems sustainable long term, comes from biodiversity. To preserve our agricultural resources, there must be a variety of crops. Diversity aids in adaptation to environmental changes in the future [22].

4 Education

One program, which is trying to tackle the issue of proper nutrition, is eNutrition. The goal of eNutrition, as stated by Geissler et al. [23], is to educate the public about their health, from a nutrition standpoint, using online sources. They echo the fact that many chronic diseases are related to nutrition. They have plans to make their program international, but for now, they are educating Africa. eNutrition highlights that this goal of education is only made possible through a group effort. The eNutrition Academy’s goal is to have nutrition training in Africa, to improve the health and well-being of the public.

Effectively educating the next generation is essential for worldwide solutions. Newson et al. [24] state that part of the education deals with changing the population's behavior, for better health and nutrition, especially among underprivileged groups. Pelletier et al. [25] defined a group of barriers at the population level. They linked this group to urgent health, social, and environmental problems, and there is an urgent need for effective and sustainable solutions at the population level [25]. Mabhaudhi et al. [21] claim not much is being done with the research available, due to a lack of systematic research connecting not only nutrition to health but also to water and agriculture. There is a lot of room for improvement. Policies must also consider the quality of water used for agriculture to have success in benefiting the malnourished, rural households [21]. Producers should have more sustainable foods available [2]. Economic tax incentives and honest pricing can encourage consumers' wants. In addition, clear labeling (e.g., letting the consumers know which food choices would be more sustainable compared to others), can help consumers make better-informed decisions about the food that they purchase. Ultimately, ensuring healthful, sustainable food for the world's population is a multi-faceted problem that will require multi-faceted solutions.

5 Conclusion

As the world's population increases and urbanization continues, sustainable food is going to be a challenge. This chapter has reviewed the environmental and health impacts of various diets. The main conclusions are summarized in Table 2 as follows.

Supply and demand of animal products are increasing; however, animal product consumption is closely linked to diseases and obesity. Plant-based food has the lowest environmental impact and, in turn, the lowest production cost. The Mediterranean diet proposes a happy medium, mainly plant-based with choice animal products to respect different cultures.

Table 2 Diet type and key attributes

Diet	Attributes
Plant-based	Lowest environmental impact. Lowest production cost. Healthiest
Mediterranean	Mid-environmental impact. Mainly plant-based. Fatty acids from fish found to be neurologically beneficial
Animal products	Highest environmental impact. Correlated to cardiovascular diet. Culturally favoured

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Tomorrow's Green Buildings: Optimum Natural Insulation Material Modeling

Lutfu S. Sua, Figen Balo and Ukbe Ucar

Abstract The structures renovation's economical impact generally relies on the devices and energy-saving methods' application. By wall insulation, great economical impact is accomplished. In this regard, it is even greater than changing the windows. The wall insulation option resolutions of structures vary in the materials utilized, labor force spending, and other ways. The renovation's cost based on the resolutions applied. The criteria describing the existing wall isolation options may have diverse values. Additionally, they may differ in diverse instructions, i.e., a greater value of some criteria represents a preferable situation, while for others they signify a worse state. By means of multicriteria assessment methodologies, a reconciliation variable is needed, which can be obtained in this environment. To decrease the impact of diverse methodologies on computational conclusions, it can be proposed to evaluate the phenomenon (or object) thought by a few diverse methodologies, with the detection of the average forecast value. Thus, the several special multicriteria assessment methodologies' disadvantages could be replaced by the others' benefits. In recent years, thermal insulation materials' many styles are present in the market. The calculations made in this study by AHP multicriteria assessment methodology allowed us to determine the most effective insulation material option out of ten used alternatives commercial insulation materials. In the second stage, the most assessable natural alternative insulation material among ten different uncommercial-natural insulation materials is analyzed with the same methodology.

Keywords Natural insulation material · Green building · Green insulation · Mathematical modeling

1 Introduction

The building exterior walls' insulation efficiency can be the most significant field through which energy-saving can be obtained. By an appropriate exterior envelope, the buildings' energy performances can be improved. Better insulation levels mean

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energy profits affiliated with lower ecological effect because of lower energy consumption for cooling and heating with the energy system designed, but concurrently it is an important financial topic. The building quality and energy performances can be obtained through highly efficient envelopes. The thermal insulation materials are mainly utilized in the structure sector. The structures are responsible for one-third of the total energy consumption, of which about 50% is used for cooling and heating the structures. These materials are applied in the structure sector mainly to protect ambiance temperature, from 1 to 100 °C. Generally, the people living in the cold areas desire warmer internal atmosphere. Similarly, the people living in the hot areas desire making their internal atmosphere so cool. The thermal loss occurs from hotter regions to colder regions. To accomplish this loss, structures thermal insulation is insured to protect needed temperature in the structure [1]. In Figs. 1 and 2, world

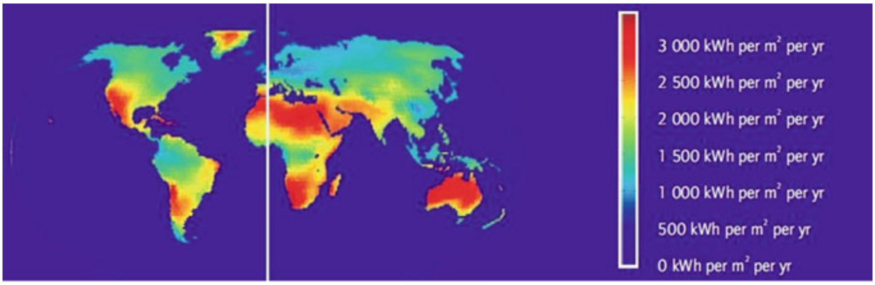

Fig. 1 World insolation map [2]

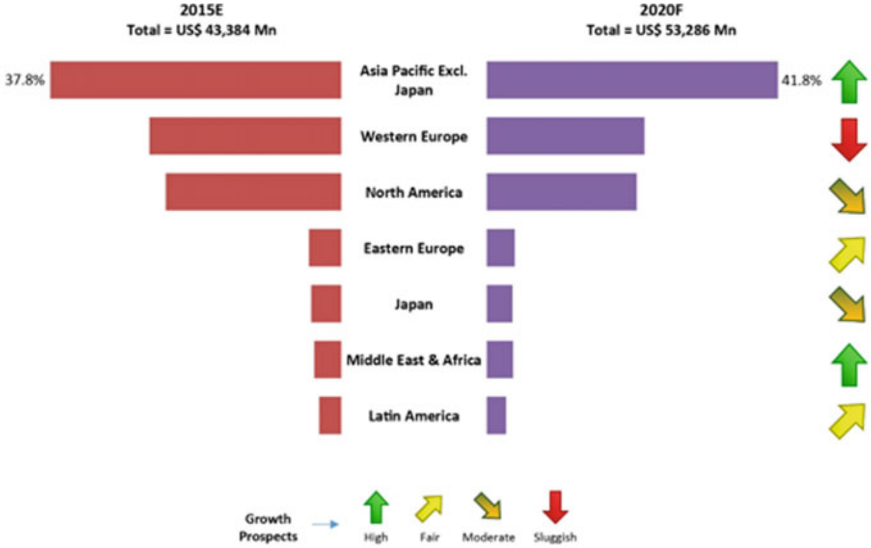

Fig. 2 Global thermal insulation material market value split, by region, 2015 and 2020 [3]

insulation map and global thermal insulation material market values split, by region, 2015 and 2020 are shown, respectively.

The external walls' insulation efficacy relies upon numerous options [4, 5]: the thermal renovation's cost, adhesive bond withstand (thermal/concrete isolating board), thermal isolating board's thermal transmittance, fabric, tensile strength of strengthening, the mix's compressive strength utilized in strengthening, textured finish's compressive strength, adhesion's strength between thermal isolating board and the concrete mix utilized in strengthening, adhesion's strength between concrete and textured finish, textured finish's water absorption, service life, the force's value required to extract, work execution's time, the pin warranty period [6].

In the structures, the thermal insulation's purpose is to decrease the thermal transfer between inside ambiance and outside ambiance [7]. The building wall insulation's aims are to rise buildings' market value and service life (which can be increased up to about 45 years), improve building structures' performance, decrease energy depletion, restore buildings' operating parameters, improve buildings' facades architectural solutions, increase the building's comfort level. The insulation material choice is important to build engineering designs as it can obtain many effects. Insulation material market's key segments are shown in Fig. 3. Commonly utilized insulating materials' classification is given in Fig. 4.

The building walls' isolation for warm-keeping occurs of successive operations, i.e., immobilization of the thermal isolation board to the wall of structure, finishing, immobilization of the strengthened network to the thermal isolation board, etc. Each of the operations needs some special materials (mortar, adhesive, pins, reinforcing mesh, insulating boards, etc.) and labor. Different materials, changing in weight, durability, thermal parameters, etc. can be utilized. The structure materials' selection determines the walls' thermal isolation's cost. For most of the housing structures, the heavy load of the cost for renewal is placed upon the owner organizations. Thus, they are interested in building wall insulation's lower expenses [1].

Within this framework, a rational selection becomes a practical problem and important search. The criteria explaining the existing thermal isolation options for building walls may be evaluated differently; for some, they can be preferable while for others, worse than others. Additionally, they may vary in diverse instructions, i.e., sometimes, the rising criterion value can show a preferable status, while in others it means the opposite [6, 10].

There are many difficulties against the thermal isolation sector such as thermal isolation material's small cognizance in developing economies and thermal isolation's great capital expense in constructions.

The thermal insulation is developed to reduce the heat transfer through a system. It is created with combination of materials or one material, which works against the heat's flow. The insulation materials can be applied to any shape, surface, or size. There are many advantages of such insulations in buildings. The insulation materials decrease or prevent heat transfer in several different modes (convection, radiation, and conduction) from inside to the outside or vice versa if the surrounding temperature is low or high [11]. The building insulation will insure the comfort to the structure,

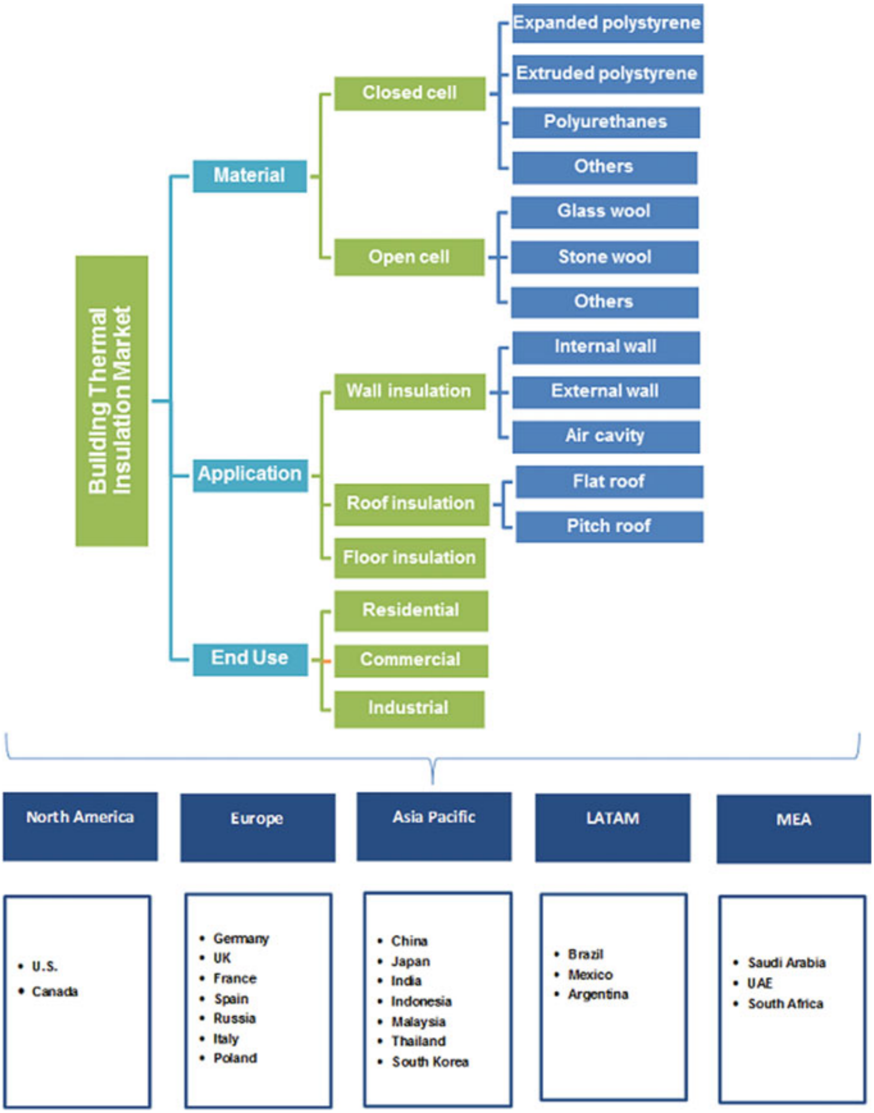

Fig. 3 Insulation materials market key segments [8]

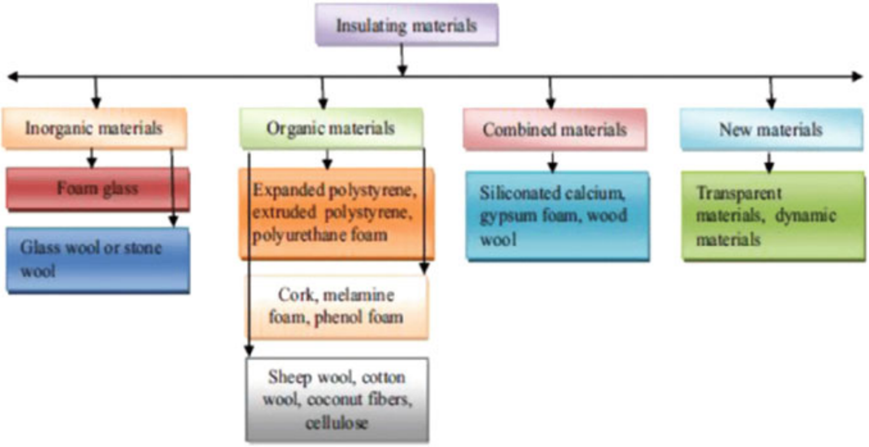

Fig. 4 Commonly utilized insulation material classification [9]

compose a healthier building environment, decrease the energy bills, and have a positive ecological effect. The building insulation material in addition to the structure will adjust the temperature, making the habitat more comfortable, particularly in extreme weather conditions. Adding thermal insulation material to the building will result in less energy consumption. The insulation material will keep the building warmer in the winter and cooler in the summer. This will diminish the amount of cooling and heating devices that are needed to obtain the residence comfort. On account of this, building insulation will decrease the costs of heating–cooling and energy bills. The building insulation's benefit is not only concerned with the residents inside the residence but also keeping the environment out of pollutants. For air conditioning, the isolated structure will contribute to less energy consumption. This will diminish the harmful carbon compounds emitted because of the energy consumption and also decrease the chemicals' amount emitted in the air from heating–cooling equipment. Thus, insulation material is an important component in the so-called green building policy [1, 12].

To maintain the living quality of occupants, a comfortable indoor temperature condition is important for supplying healthy ecological conditions and comfort. For human, the body temperature's optimal value depending on physiological requirements is about 37 °C, without considering ecological conditions. Therefore, it is critical to sustain the indoor thermal conditions in residences that maintain the thermal indoor temperature conditions for better human performance and productivity [13]. The thermal heat gains and losses in a building without insulation are given in Fig. 5.

Insulation is a relevant technical solution for cutting energy consumption in buildings. On the existing and new buildings' external walls, the commercial insulation is generally known as exterior insulation. A lot of elements support the analysis of this insulated wall system and its energy effectiveness, such as its exterior place, the

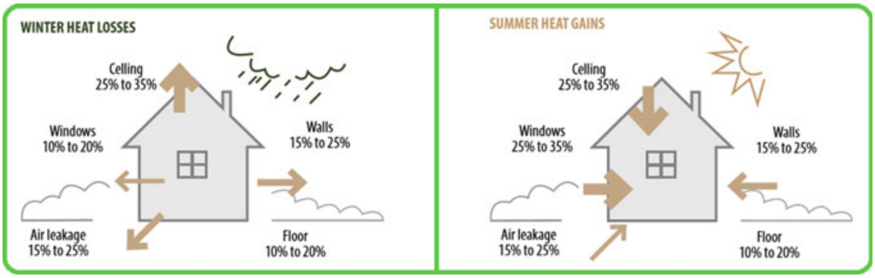

Fig. 5 Thermal heat gains and losses in a building without insulation [2]

insulation's continual unbroken layer's performance, its total high thermal resistance value, lack of thermal bridges through the insulation thickness, and less air infiltration ratios. In the market, a wide selection of insulating materials exists and it is the duty of the planner to select the appropriate product depending on the application [14]. Considering the insulation's life expectation and system requirements, product might be satisfactory and final choice can be based on cost, availability, and other effects.

A number of studies have focused on simulation-based techniques to determine the external wall's energy performance. For the evaluation of the construction depending on U-values and CIBSE (The Chartered Institution of Building Services Engineers) Guide A from RdSAP software, insulated external walls were analyzed by using the simplified steady state heat loss model by Strube et al. The obtained results were assessed to the Passiv Hause Enerphit standards [15]. In Italian climate conditions, three different conventional wall structures' effectiveness was investigated by Stazi et al. These performances were analyzed by modeling CFD Fluent and software EnergyPlus [16]. For 20-year old external wall insulation system, the hygrothermal and thermal effectivenesses were analyzed by using laboratory tests and monitoring, parametric analysis, and simulations by Stazi et al. [17]. Holm and Künzel assessed the determined examples' and wall models' fundamentals (including obtainable results and required data) of guidelines which were obtained by utilizing analyzes with simulations assist [18]. In Germany, Künzel et al. studied a multistory's substantial number of external wall insulation installations with relatively wind-driven rain and severe temperature fluctuations [19]. In North America, the external insulation systems on lightweight structures were evaluated by using WUFI programme at moderate and cold climates by Künzel and Zirkelbach [20]. For the evaluation of building envelopes' hygrothermal performances, Černý and Pavlík presented the laboratory model to simulate on-site terms that can be utilized [21]. The lightweight thermal protection system's 3D model was developed by Gongan et al. A sandwiched panel was produced by ANSYS software and subjected to thermal and mechanical loads by ANSYS software. The parametric design language along with moving asymptotes' globally convergent method algorithm was utilized for the minimum weight thermal protection system's optimization. After optimization, the obtained thermal protection system was 0.37 lighter [22]. In large Dewar tanks, Nast et al. investigated multilayer insulation. To measure the cryogenic fluid boil off and multilayer insulation's thermal conductivity, a simulation model was designed. For planning large propellant tanks for NASA, the test results were utilized [23]. By Sutheesh and Chollackal, the simulation software and numerical models were utilized to analyze the multilayer insulation's thermal performance [24]. By inverse problem method, Alifanov et al. determined the radiative and thermal properties such as emissivity and thermal conductance by measuring the heat flux and temperature [25]. By Bapat et al., a numerical model was developed with combined radiation and conduction, to determine the multilayer insulation's thermal performance with glass fabric spacer and double-aluminized Mylar reflective foil. The conduction raised with raise in layer density because of the enhanced insulation's efficient thermal conductivity [26]. Tingwu et al. numerically examined the effect of options such as thickness, emissivity, density location layout, and foils' number, the materials' density and the foils' emissivity. It was determined that the best effectiveness is obtained at layers' particular number. If the layer's number raises, the insulation's overall conductivity raises because of the greatly conductive metallic foils' domination [27]. Loveday and Bojic examined the insulation distribution's effect. They modeled three-layered structures using UK climate data [28]. De Wilde et al. used terraced houses' transient model utilizing the EnergyPlus simulation to compare indefiniteness in climate change estimate with variations' a number in construction materials' thickness, building occupancy patterns, and HVAC control settings [29]. Gregg and Gupta reported on a GPS-based Model's (DECoRuM-Adapt: carbon counting, carbon reduction model, and domestic energy) use for six building archetypes utilizing Stockport, Bristol, and Oxford data. By means of dynamic thermal simulation, they evaluated the change in overheating with reference to adaptation packages [30]. Orme et al. presented outcomes obtained from APACHE regression analysis and thermal analysis. For alternative climate scenarios, they demonstrated the different insulation measures' sensitivity [31]. Porritt et al. utilized dynamic thermal simulation to examine the expertise of late centuries terraced buildings in the UK to deal with next thermal waves by accepting various mitigations containing insulation, ventilation, and solar shading strategies [32]. By EnergyPlus simulation, Oikonomou et al. evaluated the diversities in buildings' inside temperatures during high external media temperature by identifying the buildings' thermal characteristics in London [33]. In London characteristics, Mavrogianni et al. used EnergyPlus to obtain dynamic thermal simulations for dwelling types' 3456 combinations [34]. Carmeliet and Blocken discussed the wind-driven rain quantification search by numerical, experimental, and semiempirical methods. The authors compared the wind-driven rain search summary according to building science [35]. By Kumaran and Karagiozis, a transient 3-D and 2-D model was performed comparatively early modeling predictions through the LATENITE method designed at IRCINRCC. This method was used to numerically obtain air, moisture, and heat transport by different expanded wall insulation systems [36]. Hopfe and McLeod particularly investigated the dynamic modeling's limitations in point of input and data resources. For example, inhomogeneity in structure materials makes it hard to refrain ambiguity in modeling characteristics [37]. Karamanos et al. examined the stone wool insulation's performance under altering humidity and temperature conditions by modeling besides the long-term laboratory experiments [38]. Sanders summarized present models for analysis on the risk of transition condensation. For modeling purposes, he discussed the data's availability on material characteristics and proper boundary conditions [39].

The multicriteria decision-making methodology is planned to guide project squads step by step in a way that does sustainable structure plan inexpensive and easy. A reconciliation variable can be obtained by implementing multicriteria assessment methodologies [10, 40–46]. Whichever method utilized, the criteria weights and values should be recognized. The materials' different characteristics utilized can be obtained in specifications, manuals, etc. By experts, the criteria weights should be obtained. There are numerous aspects of determination [47–52]. Some are not correct enough because they are very basic; the others are very complex for a functional implementation. However, the professional assessment's correctness substantially relies upon the criteria number. When this number increases, a boundary can be achieved while a professional can no longer compare the options and make mental mathematic to obtain their weights.

Early identification of the structure energy use targets and the efficient energy precautions are important for sustainable structure plan. The realistic efficiency goals are set depending upon these first conclusions. These efficiency goals provide that all suggested plans will obtain a desired level of energy efficiency.

2 Solution Methodology

Analytic hierarchy process (AHP) is a solution methodology that helps to choose the best alternative among multiple alternatives considering a set of criteria. It is an analytic solution methodology based on expert opinions. The method involves a three-phase hierarchic structure composed of goal–criterion–alternative and enables the selection of the best alternative through the evaluation of criteria based on the overall goal and evaluation of alternatives based on the criteria (Fig. 6).

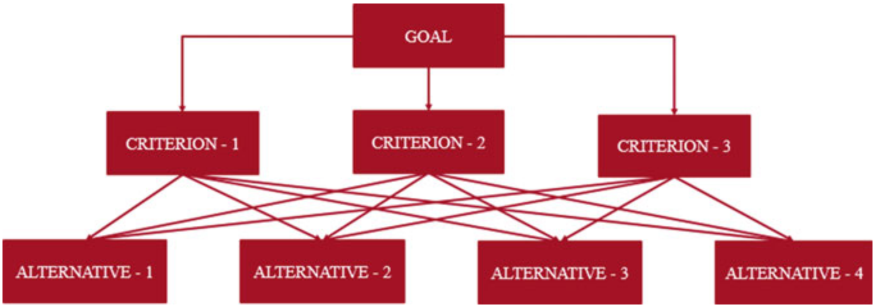

Fig. 6 Hierarchic structure of AHP methodology

This solution methodology is quite useful from various aspects for the decision-making problems. Many criteria and alternatives can be evaluated in an analytic way and the best alternative can be determined through the use of this method. Without using any methodology and among many possible combinations, choosing the most appropriate alternative manually is a very difficult task. In this aspect, the method provides a great advantage to the decision maker. Within the method, the decision maker can reflect his/her opinions to the solution in a flexible way. The alternatives and the criteria can be evaluated both pairwise and totally in more detailed and objective way. Moreover, the method can be used effectively in eliminating the ambiguity where it exists along with risk factor.

The method is composed of a flow with six steps. Initially, the problem is defined, the goals are determined, and alternatives along with the criteria are listed. The next step involves pairwise comparison of the criteria which results in pairwise comparison matrix. Degrees of priority for the criteria are determined based on this matrix and consistency of it is measured. Priority distributions for the alternatives based on each criterion along with consistency ratios are calculated, and finally, the most appropriate alternative is determined. The consistency ratios are expected to be less than 0.1; otherwise, the alternatives and the criteria are expected to be reevaluated. Steps of AHP method are summarized below [53]:

Step 1: Defining the decision-making problem
Step 2: Developing the comparison matrix for the criteria
Step 3: Determining percentage weight distribution of the criteria
Step 4: Measuring the reliability value of criteria comparisons
Step 5: Determining the percentage weight distribution at m decision point for each criterion
Step 6: Determining resulting distributions at decision points

Advantages of AHP methodology can be listed as follows;

It enables the evaluation of all alternatives based on many criteria. Conducting all these calculations manually is difficult and takes considerable amount of time.
Users of the methodology can express their opinions in a flexible way and make detailed evaluations by adding different criteria and goals.
It provides a process for evaluation and use of information to reevaluate the conflicts and obtain solutions for them.
Where ambiguity and risk are involved, the method helps eliminating the ambiguity.

3 Results and Findings

This study involves the process of determining the most appropriate insulation material for the externally insulated walls based on thermal properties.

In this study, both commercial and uncommercial-natural insulation materials are evaluated to AHP methodology. The commercial insulation materials are used commonly in the markets. But the uncommercial-natural insulation materials can be offered to more natural alternatives.

The first phase of the study involves determining the best insulation material among uncommercial-natural insulation for externally insulated walls. Five different criteria and ten different insulation materials are considered for this purpose. Properties of the selected alternatives are provided in Table 1.

AHP methodology is used as the solution method and the related hierarchic structure for uncommercial-natural insulation materials is provided in Fig. 7. Expert Choice software is used to solve the problem.

Based on the solution mechanism mentioned above, prioritization of the criteria is done as the first step. Prioritization involves pairwise comparison of the criteria. Each criterion is compared against the other criteria on a scale from 1 to 9 based on its relative importance against the other. The developed matrix showing these relative importance values is used to calculate the "relative weight" of each factor shown in Fig. 8.

Furthermore, a consistency ratio is calculated to obtain information about consistency among pairwise comparisons. Lower ratios indicate lower inconsistency among the comparisons done in the previous stage. Consistency ratio is calculated

Table 1 Properties of the alternatives for uncommercial-natural insulation materials [6]

Thermal insulation material	Density (kg/m^3)	Specific heat (kJ/kg K)	Thermal conductivity (W/m K)	Thermal transmittance (W/m^2 K)	Thermal wave shift (h)
Cellulose(1)	70	2	0.039	0.296	11.1
Coir	105	1.5	0.043	0.318	11.0
Cork	130	2.1	0.040	0.302	12.6
Flax	30	1.6	0.040	0.302	9.8
Hemp	90	1.7	0.040	0.302	11.2
Jute	35	2.4	0.038	0.290	10.3
Kenaf	100	1.7	0.030	0.241	12.0
Mineralized wood fiber	533	1.8	0.065	0.425	15.7
Sheep wool	20	1.8	0.038	0.290	9.6
Cotton (recycled)	25	1.6	0.039	0.296	9.7

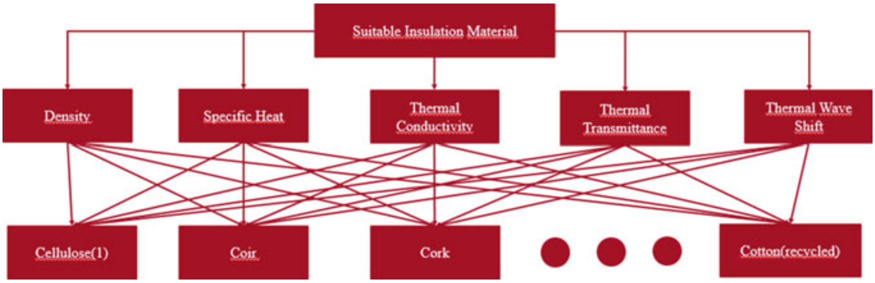

Fig. 7 Hierarchic structure

Fig. 8 Prioritization of the criteria

to be 0.08 which is lower than 0.1, thus it can be concluded that the analysis is consistent. Figure 8 indicates that "thermal conductivity" is the most important criterion of all while "density" is the less important one. Considering these criteria and their priority values, the alternatives are ranked and the analysis results are presented in Fig. 9.

According to the results given in Fig. 9, "Kenaf" is found to be the most appropriate insulating material among 10 insulating materials based on the stated criteria. It is also clear from the figure that the material ranked last is "mineral wood fiber." Additionally, it is found that consistency ratio of all matrixes of the analysis is lower than 0.1.

The second phase of the study involves the process of determining the most appropriate commercial insulation material for the externally insulated walls based on thermal properties. Five different criteria and ten different insulation materials are considered within the study. The properties of the selected alternatives for external insulation are provided below in Table 2.

AHP methodology is used as the solution method and the related hierarchic structure is provided in Fig. 10.

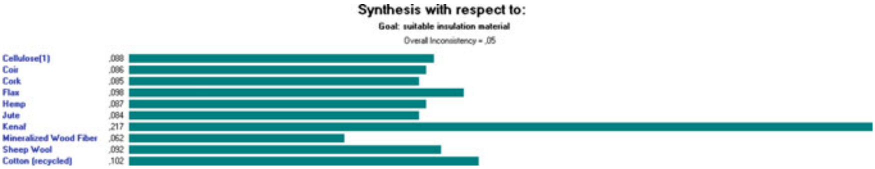

Fig. 9 Results for uncommercial-natural insulation materials

Table 2 Properties of the alternatives for commercial insulation [6]

Thermal insulation material	Density (kg/m^3)	Specific heat (kJ/kg K)	Thermal conductivity (W/m K)	Thermal transmittance (W/m^2 K)	Thermal wave shift (h)
EPS	22	1.3	0.035	0.272	9.6
Glass wool	21	1	0.035	0.272	9.5
Perlite	100	0.8	0.052	0.364	10.0
Polyisocyanurate	30	1.4	0.022	0.187	10.2
Polyurethane	44	1.5	0.025	0.208	10.5
Vermiculite	80	0.9	0.062	0.412	9.7
XPS	40	1.7	0.034	0.266	10.2
Recycled glass fiber	450	0.8	0.031	0.248	14.6
Recycled PET	60	1.2	0.034	0.266	10.3
Recycled textile	50	1.2	0.040	0.302	10.0

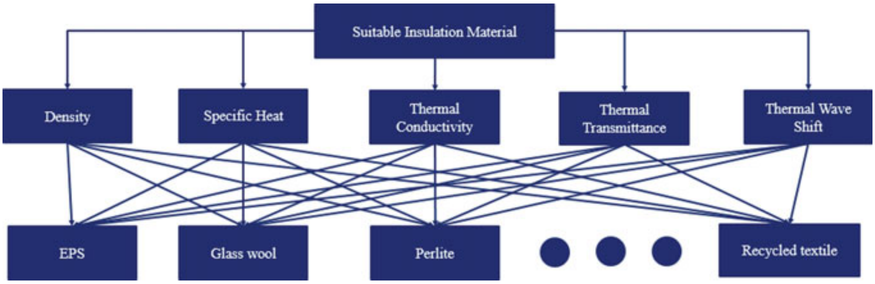

Fig. 10 Hierarchic structure

Based on the solution mechanism mentioned above, prioritization of the criteria is done as the first step and the results are provided in Fig. 11.

Consistency ratio is calculated to be 0.08 which is lower than 0.1, thus it can be concluded that the analysis is consistent. Figure 11 indicates that "thermal conductivity" is the most important criterion of all while "density" is the less important

Fig. 11 Prioritization of the criteria

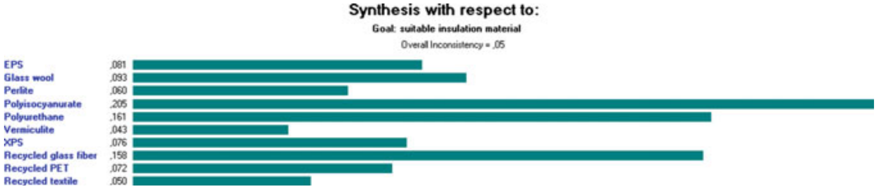

Fig. 12 Results for commercial insulation materials

one. Considering these criteria and their priority values, the alternatives are ranked and the analysis results are presented in Fig. 12. Moreover, consistency ratio in all matrices is calculated to be less than 0.1.

The most appropriate commercial insulation material among 10 different alternatives is turned out to be "Polyisocyanurate" based on the mentioned criteria while "recycled textile" is ranked the last among all alternatives that are used as thermal insulation materials in the market commercially. "Kenaf" is determined to be the best alternative when uncommercial-natural insulation materials are evaluated in terms of thermal properties. When evaluated from both material properties, it is observed that "kenaf" is a candidate to be used in the market commercially among other uncommercial-natural insulation materials.

4 Conclusions

As a complicated system, the constructions play an important role in our society and lives. Thus, the constructions account for a big share of energy and raw material consumption, world C emission, and so on. Constructions throughout the world consume about half of the total energy use. The well-known power performance measures' widespread implementation and interest on other parameters that impact structure sustainability will need to revamp these opinions during the plan. The power consumption, the only most significant option impacting sustainability, can characteristically be decreased importantly, compared to the traditional contemporary buildings. This can be generally achieved by means of appropriate selection and installation of building insulation materials.

In this study, the thermal insulation materials' thermal properties are assessed. All of the findings were analyzed using multicriteria decision making to determine clear view of material solutions by the relative significance of each criterion.

It is also aimed to determine the best "uncommercial-natural insulation material" choice that can be commercialized, for the firms producing insulation materials in the market. Recently, government incentives toward increasing the use of environment-friendly materials have significantly increased. This study can be used as a reference for the producers in terms of determining the most appropriate alternative while selecting a natural and ecologic material to be used in the production of commercial insulation material.

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Improving the Uncertainties of Building's Lifetime in the Evaluation of Environmental Impacts

Endrit Hoxha

Abstract Despite the large amount of existing research that has focused on the analysis of the uncertainties of environmental impacts of buildings, the improvement of its reliability still remains a problem. Current studies highlighted the influence of uncertainties in the minimization of effectiveness of life cycle assessment (LCA) method for decision making. With an aim of improving the reliability for strengthening the comparison of building projects, in this study, we propose a novel way of interpretation of environmental impacts. Coupling uncertainty and sensitivity analysis to the model for the evaluation of environmental impacts of buildings was possible to improve the robustness of project comparisons. Moreover, it is found that the contribution of uncertainties of inputs is not the same for different values of a building's lifetime.

Keywords Embodied carbon · Uncertainty analysis · Sensitivity analysis · Projects comparison

1 Introduction

National Centers for Environmental Information [1] highlighted the increment of average yearly surface temperature by almost 1 °C in the last 30 years. According to the worst scenario as defined by the United Nations Environment Program (UNEP), the temperature will continue to rise. Due to this, several animals and plants will not be able to adapt and may face extinction [2]. This is because of the problem of climate change for which the construction industry is identified as the biggest culprits, responsible for 40% of primary energy demand and 33% of greenhouse gas emissions [3]. To tackle the problem of climate change, the building sector needs to be carbon neutral by the year 2050 [4].

Minimization of impacts of buildings has been the core objective of several researchers during the past 20 years. Low-carbon materials [5–7], active systems [8], and passive strategies [9, 10] have been developed for the purpose of reducing

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the environmental burden of buildings. Their performance is commonly calculated with the help of life cycle assessment (LCA) method [11].

However, the largest challenge faced today is the reliability of results that reduces the effectiveness of LCA for decision making [12–14]. The consequence of large uncertainties regarding LCA's results is the impossibility of a robust comparison of different scenarios. To solve this gap, the researchers were first focused on the identification of the sources of uncertainties, and based on that, they classified them into groups [15–17]. In the case of a building's LCA, the sources of uncertainties are due to the input data, model, and the user's level of practice. Furthermore, researchers have developed numerous methods for the calculation of the uncertainties of the environmental impacts of materials or components and of buildings. Earlier, Monte Carlo method was proposed as being the most precise, but due to this method's time consumption, other analytical methods were developed and published in literature [18, 19].

In the meantime, the improvement of the reliability of a building's LCA results has been the aim of a few research studies. Their aims have been mostly to calculate the degree of reliability of environmental impacts or contribution of uncertainties of inputs to those of buildings. Propagating the uncertainties of mass, transport distance, and energy of operational phase, Blengini and di Carlo [20] found a coefficient of variation of 25% for environmental impacts of buildings. Bilec and Aktas [21] calculated an error of 25% around the mean by analyzing the uncertainties of a building's lifetime and its materials. The influence of the parameter of building's lifetime in the comparison of projects is analyzed in Hoxha et al. [22]. In conclusion, they found that the project with lower impacts for certain values of building lifetime will not always be lower for the other values. Focusing the aim of the study in the assessment of the materials or the contribution of a component's uncertainty, Hoxha et al. [23] analyzed the environmental impacts of 30 single- and multi-family houses. They found insulation materials and non-structural wood as the main sources that controlled the uncertainties of environmental impacts of buildings. In conclusion, due to uncertainties, it is possible to distinguish the best project only when their results have a difference of more than 20%.

Based on the literature review, despite the large amount of research that has focused on the analysis of the uncertainties of a building's LCA results, the improvement of its reliability still remains a problem. Moreover, the problem is more crucial when we compare different scenarios during the pre-design phase of the project. To overcome this gap, the aim of this exploratory study is to propose a solution that would strengthen the comparison of different projects.

2 Method

The methodology that has been applied in this study lies in the application of uncertainty and sensitivity analysis to the model of assessment of environmental impacts of buildings. For this purpose, we first define the approach required to evaluate the environmental impact of buildings. Then, with the help of Monte Carlo method, the uncertainties of input parameters can be propagated at two levels. Uncertainties of amount of used materials, their coefficient of impacts, and service life are propagated to the environmental impacts of building's components. Further, the uncertainties of environmental impacts of components are propagated to the environmental impacts of buildings. Even the parameter of building's service life is considered uncertain, but it is treated differently in the calculation. In this study, the uncertainties of mass, coefficient of impacts, and service life of materials are calculated for every year between 1 and 150 years of a building's service life. So, the uncertainties of input parameters are propagated based on their probability mass function (see Robert and Casella [24]) despite the uncertainties of building's service life that are discretized in single values. Subsequently, the sensitivity analysis as a last step is applied for any values of building's service life. It is used to identify the input parameters with the largest contribution to the uncertainties of environmental impacts of buildings.

2.1 Environmental Impact Assessment

The method that has been used for the evaluation of the environmental impacts of building is inspired from European norm EN-15804 [25] and EN-15978 [26]. According to these norms, the environmental impacts of components and consequently of buildings are broken down to its life cycle stages: production ($A1$–$A3$), construction ($A4$–$A5$), use ($B1$–$B5$), operational ($B6$–$B7$), and end of life ($C1$–$C4$). Impacts of these stages can then be classified into the embodied ($A1$–$A5 + B1$–$B5 + C1$–$C4$) and operational ($B6$–$B7$). The boundary of the study is limited by considering into assessment only the embodied impacts. Information for embodied impacts of buildings' components is extracted from INIES database [27] that provides environmental information under the form of Environmental Product Declaration (EPD). They cover the impacts for the production ($A1$–$A3$), construction ($A4$–$A5$), as well as end-of-life stages ($C1$–$C4$). By also covering the impacts of replacement stage ($B4$), the simplified equation used in benchmarking for evaluating the embodied impacts has the form:

$$I_{\mathrm{b}} = \sum_i I_{f,i} = \sum_i m_i \cdot k_{f,i} \cdot \left(\left\lfloor \frac{\mathrm{ReqSL}}{\mathrm{DVE}(i)} \right\rfloor + 1 \right) \tag{1}$$

where I_{b} presents the embodied impacts of building; $I_{f,i}$ presents the embodied impacts of material i for the impact category f; m_i presents the mass of material i; $k_{f,i}$ presents the coefficient of impact for the impact category f associated with the life cycle of one unit mass of the building material i; $\lfloor\ \rfloor$ presents the greatest integer function; ReqSL presents the lifetime of building and DVE(i) presents the lifetime of materials.

The values of coefficient of impacts are evaluated according to the CML method as developed by the Center of Environmental Science of Leiden University [28]. The calculations are limited to the global warming potential (GWP) indicator which is expressed in terms of kg of CO_2 equivalent normalized by m^2 of floor area of the building.

2.2 Uncertainty Analysis

Uncertainties regarding the embodied impacts of buildings are also analyzed in step two. Uncertainties of inputs' parameters (mass, coefficient of impacts, and service life) are propagated to the environmental impacts of materials. Further, the uncertainties of environmental impacts of materials are propagated to those of building. Monte Carlo method [29], being the most reliable, is used for the propagation of the uncertainties. The principle of this method relies on repeated random sampling in order to obtain numerical results.

Firstly, a database is created through a literature review with around 1500 data for the coefficient impacts and 1500 data for the lifetime of building's components. For the coefficient of impacts, the data have been extracted from INIES [27] and ecoivent database [30]; on the other hand, the data of service have been collected from different publications and documents [31–34]. Based on these, data are identified that best fit the distribution laws and, consequently, the probability mass functions for each input parameter. Through an iterative procedure, values from the probability mass functions of inputs are chosen at random to compute a probability mass function of embodied impacts of materials. Then, the values from embodied impacts of materials are chosen randomly for the calculation of probability mass function of embodied impacts of a single-family house. The process of uncertainty analysis of the environmental impact of a single-family house is summarized in Fig. 1.

2.3 Sensitivity Analysis

The influence of the uncertainty of environmental impacts of materials to those of a single-family house is calculated with the help of sensitivity analysis as proposed by Saltelli et al. [35]. The sensitivity index for the calculation of these contributions takes the form:

$$R_i = \frac{\mathrm{var}\left(I_{f,i}\right)}{\mathrm{var}(I_\mathrm{b})} \times 100 \tag{2}$$

where $\mathrm{var}\left(I_{f,i}\right)$ presents the variance of the environmental impacts of material i for the impact category f; $\mathrm{var}(I_\mathrm{b})$ presents the variance of the environmental impact of building.

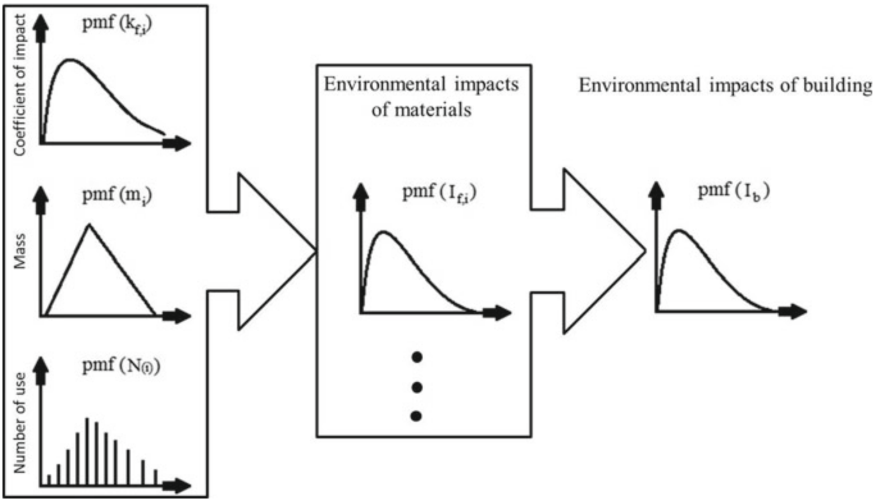

Fig. 1 Diagram of uncertainty propagation with Monte Carlo method (PMF–probability mass function)

3 Case Study

The method presented in the previous sections has been applied for a single-family house of 100 m^2 of energy reference area as developed by the Scientific and Technical Centre for Building [36]. It does not correspond to a real building but was developed as a representation of single-family houses in France. In order to compare the environmental impacts of projects, two possible scenarios have been considered. One corresponds to a wood structure and the other one to a reinforced concrete structure. Necessary data for the purpose of evaluation of the environmental impacts of the projects considering the uncertainties of input parameters are presented in Table 1.

4 Results

Results of the uncertainty analysis for the global warming potential (GWP) indicator have been presented in Fig. 2. For both projects, the 95% confidence interval has been computed once by considering a uniform distribution U (0; 150) of a building's lifespan, and once by considering a Weibull distribution W (2.8; 73.5). Based on the amplitudes of mean values, project 2 presents lower impacts. However, considering the fact that the confidence intervals intersect, it is not possible to conclude with robustness on the project with lower environmental impacts. Taking into consideration the intersection of intervals, for the uniform distribution of building's lifespan, we can state with a confidence level of 75% that project 2 has lower impacts. On the other hand, for the case of Weibull distribution, we can state with a confidence

Table 1 List of materials used for the construction of the two studied houses

Building materials or elements		Unit	Quantity		Lifetime (years)	Coefficient of impact
			R/concrete house	Wood house		
Non-structural clay	Tiles	kg	6422	IDEM	W(1.6; 16)	LN(0.2; 0.04)
Structural clay	Wall	kg	25,727	–	BL	LN(0.17; 0.04)
Non-structural concrete	Sill	kg	0.15	–	LN(25.4; 11)	LN(298; 29)
	Mortar	kg	1530	504.9	LN(34.6; 19.8)	LN(0.39; 0.054)
	Poor concrete	m^3	1.44	IDEM	BL	LN(160; 27)
Reinforced concrete	Concrete CEM I	m^3	28	15	BL	LN(360; 47)
	Concrete CEM III	m^3	11.3	IDEM	BL	LN(238; 34)
Non-structural steel	Uprights and rails	kg	54.5	IDEM	LN(20.5; 14.4)	LN(2.7; 0.43)
	Garage door	m^2	4.8	IDEM	LN(15.4; 8.1)	LN(127; 96)
	Valves	kg	27.5	IDEM	LN(10.6; 4.5)	LN(2.65; 0.43)
Non-structural wood	Cabinet for sink	kg	39	IDEM	T(15,15,47)	N(−0.78; 0.2)
	Ext. and int. doors	m^2	13.5	13.45	Wl(3.6, 36)	LN(80; 44)
	Shutter	kg	–	203.19	W(2.8; 23.2)	N(−0.78; 0.2)
	Paneling	kg	–	709.02	W(3, 31)	N(−1; 0.057)
Structural wood		kg	2292	11,002	BL	N(−0.8; 0.15)
Insulation	Glass wool	kg	–	809	Ex(17.5)	LN(1.4; 0.37)
	Rock wool	kg	1211	–	Ex(18.6)	LN(2.1; 0.3)
	Polyurethane	kg	243.5	IDEM	U(20,60)	LN(4.4; 0.61)
PVC	Shutter	kg	86	IDEM	Ex(10)	LN(4.2; 0.45)
	Paneling	kg	256	IDEM	LN(14.7; 4.5)	LN(2.6; 0.77)
	Pipelines	kg	–	519.5	N(22.9; 6)	LN(2.1; 0.51)
Bitumen	Waterproofing	m^2	160	IDEM	Ex(15.5)	LN(5; 0.46)
Plaster		kg	4643	IDEM	LN(20.5; 14.4)	LN(0.24; 0.054)
Solar panel		m^2	4	IDEM	LN(7, 17)	LN(346; 94)
Windows	PVC frame	m^2	15.6	–	LN(25.4; 11)	LN(66; 3.5)
	Wood frame	m^2	–	15.6	T(25,25,68)	LN(45; 32)

(continued)

Table 1 (continued)

Building materials or elements		Unit	Quantity		Lifetime (years)	Coefficient of impact
			R/concrete house	Wood house		
Paint	Paint	kg	167	–	W(2.3; 11.5)	LN(2.4; 1.2)
	Varnish	kg	–	315	W(2.3; 11.5)	LN(4.1; 3.1)
Electrical equipment		u	1	IDEM	LN(15.6; 6)	LN(1270,127)
Sanitary installation	Porcelain WC	u	2	IDEM	Ex(10)	LN(128; 9.6)
	Porcelain sink	u	2	IDEM	T(15,20,47)	LN(50; 3.76)
	Acrylic bathtub	u	1	IDEM	LN(14, 14)	LN(138; 20)
	Kitchen sink	u	1	IDEM	T(15; 20; 47)	LN(72; 15)
	Shower plate	u	1	IDEM	LN(14, 14)	LN(63; 13.1)
	Porcelain paving	kg	2020	672	LN(34.6; 19.8)	LN(1; 0.16)
Zinc	Gutter system	kg	170	IDEM	W(4.9; 25.4)	LN(3.6; 0.145)

Note Ex-Exponential

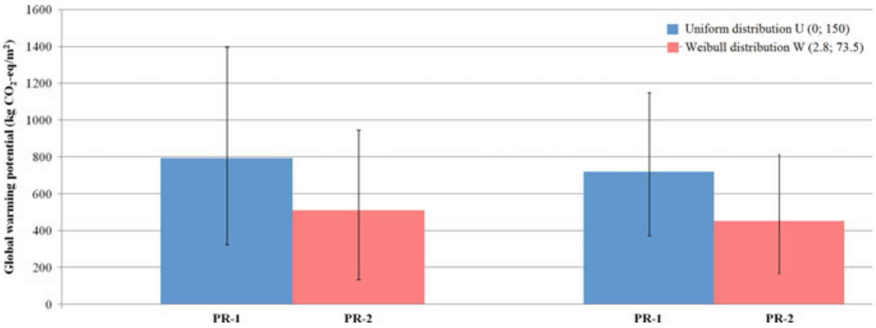

Fig. 2 Comparison of environmental impacts of projects

level of 85% that project 2 has lower impacts. For this reason, by considering the building's lifetime as an uncertain input, we cannot conclude with robustness on the project with lower impacts.

In order to understand the influence of a building's lifetime on its environmental impacts better, and to be able to strengthen the comparison between projects, in Fig. 3, the results assessed for 25, 50, 70, and 150 years of building's lifespan have been presented. The first general conclusion that has been drawn from the results is regarding the influence of building's lifetime on the robustness of the comparison of the impacts of projects. For 25 and 50 years of a building's lifetime, the confidence intervals of environmental impacts of projects do not intersect. Thus, we can

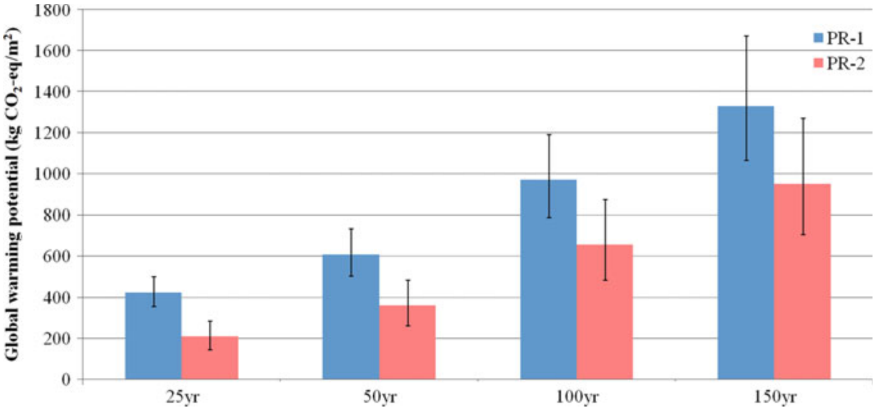

Fig. 3 Environmental impacts of projects for 25, 50, 100, and 150 years of building's lifetime

conclude with robustness that project 2 presents lower impacts. Whereas, for a building's lifetime of 100 and 150 years, the confidence intervals of the environmental impacts of both projects intersect. Logically, this conclusion highlights the necessity of evaluating the environmental impacts for anytime during the first 150 years of a building's lifetime.

Results presented in Fig. 4 identify project 2 with lower impacts in case of a building's lifetime lower than 60 years. Furthermore, for a building's lifetime between 60 years and 150 years, the confidence intervals of environmental impacts for the two projects intersect, and we cannot robustly choose the best project. This is due to rising uncertainties regarding environmental impacts of a building with a longer lifespan.

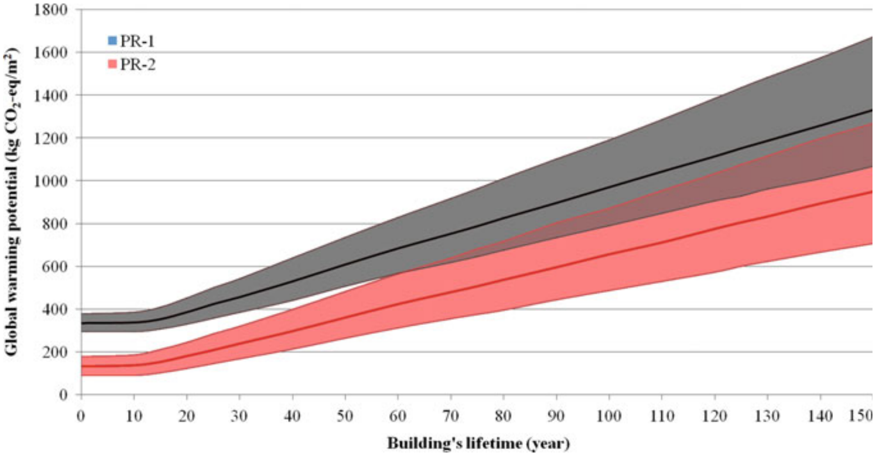

Fig. 4 Comparison of environmental impacts of two projects (error represent 95% of probable values)

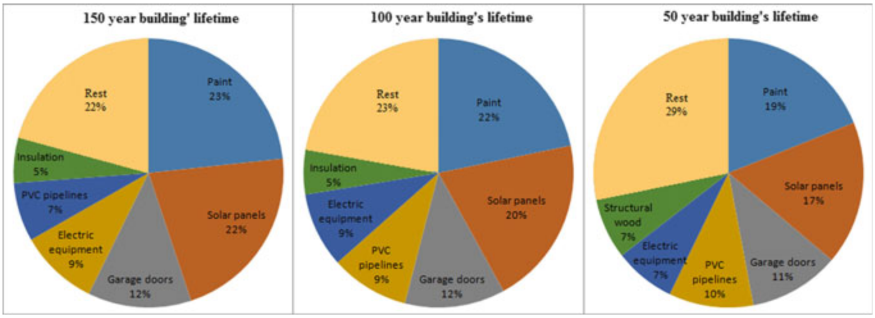

Fig. 5 Relative contribution of uncertainties of environmental impacts of materials to those of building

Since the building's lifetime is an uncertain and an unidentifiable parameter, thus to increase the robustness of comparison between projects, it becomes paramount to identify the inputs' contribution (materials' lifetime, coefficient of impact, and quantity) to the uncertainty of environmental impacts of the building. Between the two projects, it is reasonable that the sensitivity analysis should be applied to the second one. Minimization of uncertainties of the environmental impacts in the second project improves the reliability of the results evaluated, and thereby increases the robustness of comparison.

With the help of the sensitivity analysis as proposed by Hoxha et al. [36], the results of uncertainty contributions of environmental impacts of materials to those of the building have been presented in Fig. 5. For the first 50 years of a building's lifetime, the main contributor to the uncertainty of a building's environmental impacts is painted with 19% influence. The contributions of other components are solar panels (17%), garage doors (11%), PVC pipelines (10%), electrical equipment (7%), structural wood (7%), and the rest of materials (29%).

For a building's lifetime of 100 years, the uncertainty contribution of paint, solar panels, and garage doors increases to 22%, 20%, and 12%, respectively. Furthermore, for a building's lifetime of 150 years, the uncertainty contribution of these materials is even higher. However, most remarkable is the change in hierarchy of these uncertainty contributions. PVC pipelines are ranked as the fourth biggest contributor for a building's lifetime equal to 50 and 100 years, but fifth for 150 years. The hierarchy also changes for structural wood which is identified within the largest contributors to uncertainties for a building's lifetime of 50 years. It is replaced by insulation in the case of a building's lifetime equaling 100 and 150 years.

On the basis of these results, we can draw the conclusion that the sensitivity analysis should be applied for every value of a building's lifetime in order to reliably evaluate the contribution of uncertainties of environmental impact of each material to that of the building.

Sensitivity analysis at material scale for paint, solar panels, garage doors, PVC pipelines, and electric equipment identified their lifetime as the parameter with the highest contribution [37]. In order to strengthen the comparison of environmental

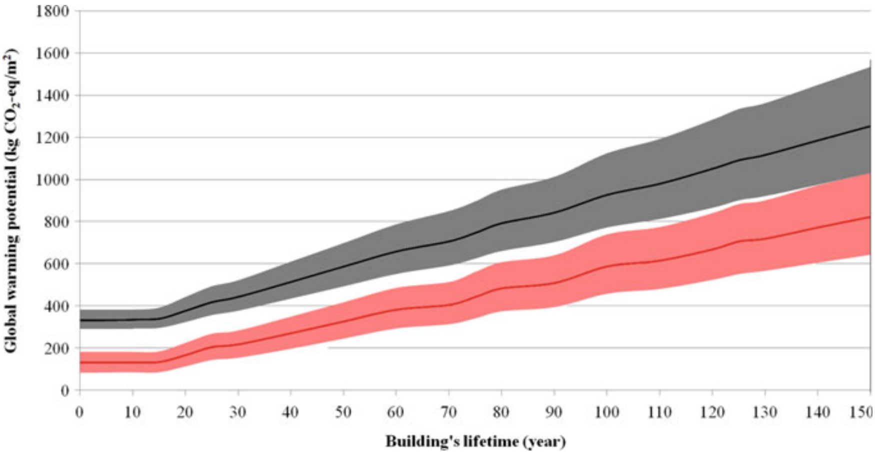

Fig. 6 Comparison of environmental impacts of two projects (error represent 95% of probable values)

impacts between two projects, the lifetime of paint, solar panels, garage doors, PVC pipelines, and electric equipment is accordingly adjusted.

In Fig. 6, the environmental impacts of a building for fixed components' lifetime are presented.

5 Conclusion

In this study, we analyzed the problem of uncertainties of environmental impacts, especially of a building's lifetime, in the comparison of projects at the early design phase of the building. Because of the uncertainties of inputs (lifetime of materials and building, impact coefficient and quantity), it was not possible to compare the projects in a robust manner since the confidence intervals of impacts intersected. In conclusion, we found the parameter of a building's lifetime as the main contributor. To strengthen the comparison of the projects, it is thus proposed to assess impacts for all building life spans. This way of presenting impacts shows the values of building's lifetime wherein the confidence intervals intersect. To overcome this problem, a sensitivity analysis identified the contribution of uncertainties of inputs to those of the environmental impacts of building. As an unexpected result, we found that the contribution of uncertainties of inputs was not the same for different values of a building's lifetime. For this reason, it was concluded that the identification of the contribution of the uncertainties of inputs to those of environmental impacts of the building should be computed for all values of its lifetime. Improving the reliability of the main responsible inputs enabled the robust comparison of projects by identifying the one with lower environmental impact. However, further work is required to extend the results of this exploratory study, in particular toward identifying the parameter of uncertainties of inputs to the environmental impact of a building and improving their reliability.

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Sustainable Living? Biodigital Future!

Alberto T. Estévez

1 Introduction

Within the context of this book, entitled "Sustaining Resources for Tomorrow", it can quickly come to mind how and why we got here now: why after millennia of human history it is so necessary to talk about "Green Energy and Technology", within which this writing is framed. Actually, to raise these issues today would seem rhetorical, because at this point of the twenty-first century everyone knows how and why we have reached this point. Even in the most disadvantaged or remote places one can, in one way or another, get access to a television, a mobile phone, the Internet. The fact that we continue to feel the need and urgency to address these issues makes us realize how little resolved are still at the global level. Few are those who act 100% in consequence of such a situation. And we can find so many contradictions in our daily life…

In 1973, the first oil crisis, paradoxically motivated by political issues and not of genuine environmental awareness, was the instance in which society became aware that natural resources are limited. So maybe it was providential, and we have arrived in advance to the knowledge of the problem, of which we might have realized later. Yes, the Organization of Arab Petroleum Exporting Countries stopped the production of oil and established an embargo for oil shipments to the west. Arab exporters reduced production by 30% and prices rose by 17%. This came to quadruple the price of the barrel, causing a crisis with many short- and long-term effects on global politics and economy.

The crisis started the conversation, at first timidly, about ecology. Gradually "the greens" and political parties with environmental programmes were appearing, and other ecological movements, seeing that natural resources are limited, and the damage to nature was beginning to be noticeable on a larger scale, accompanied by

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demographic growth. So until today, “we are eating the planet”, literally. Such a situation is actually not so new in the evolution of humanity. It is not the first time that such a relatively “sudden” phenomenon humanity has to face. Since prehistorical times, societies have suffered different types of sudden changes that have been transformed or not into catastrophes. The most similar to the one we face today was the sudden change in resource exploitation strategies by Palaeolithic inhabitants [9], when they contributed to the extinction of the Eurosiberian, American and insular megafauna. Especially in current Europe, thanks to the demographic increase and the technological improvement of hunting, the Palaeolithic inhabitants literally ate all the large mammals that populated the globe until then. Forced to look for solutions, even if it took them thousands of years, they finally invented agriculture and livestock. This critical fact can be seen as a precedent of current global change that, unlike the previous ones, and for the first time in the history of mankind, we can study, anticipate and try to avoid its possible catastrophic effects. Although it must be something that each individual one on the planet must take as commitment and collaborate, there is no longer lacking information, avoiding the contradictions in which we fall, that make us retreat the steps that we manage to advance.

1.1 Contradictions in the Age of the 4th Industrial Revolution

In the face of current environmental and technological changes, at least, as architects and designers, we need to think about the meaning of the architecture and design in the age of the 4th Industrial Revolution, about the times that we are living, and to think of the contradictions of this age. Referring to these written lines, not only from the point of view of someone dedicated exclusively on theoretical criticism, but from the point of view of someone that is dedicated mostly to the research, practice and teaching of what is happening in our times. Yes, it is true that today we live in a moment of profound and accelerated changes in the way we perceive and interact with the world. But this obligates as also more to think really what is happening: who we are, where we came from, where we are going with this 4th Industrial Revolution, because it seems that we are running crazy, to nowhere, if we do not think about the meaning of all this in which we are involved. Please, let’s stop for a moment for doing that.

The question of what we want our future urban spaces and architecture to look like cannot be separated from what kind of people we aspire to be. We must go beyond the individuals’ right to have access to the resources in order to live with dignity, towards an architecture and design (and the advanced research behind it) that allows it. Knowing and recognizing the contradictions with which we live, that are at the heart of capitalism [10]: its drive, for example, to accumulate capital beyond the means of investing it, it’s imperative to use the cheapest methods of production that leads to consumers with no means of consumption, and its compulsion to exploit nature to the point of extinction.

To exploit nature to the point of extinction is the worst of all the contradictions, which, after all, is reached by a sum of contradictions. Starting, for example, with our self-contradictions and our poor knowledge of how our own thinking works [11]. Indeed, some in the academic and public interest research community are beginning to raise questions about the claims of the emerging conventional wisdom. For example, perhaps the sharing economy is not moving us forward, but is in fact setting us back in terms of economics [19] when the capitalist system needs the continuous expansion of the principle of rationality to solve the problems of organization and efficiency that the operation of the economy demands. But simultaneously, the culture of capitalism increasingly accentuates the values of an opposite sign, such as feeling, personal gratification and hedonism, reactive response to the old ethic of order and work that accompanied the rise of the bourgeoisie [2]. Ending with the human greed, because we've known for a long time that every day the sun bombards us with ten thousand times more energy than we consume. If we could cover one-tenth of 1% of the Earth's surface with solar cells and each cell would achieve only 10% energy efficiency, we could meet all our energy needs using only this source. We do not need oil. Nor would there be carbon dioxide guilty of the greenhouse effect [14].

And the smaller our contradictions seem to us (against the need for planetary sustainability that we have) the more devastating can be the effects because those are more easily multiplied by millions of individuals around the planet every day. The problem is that until the politicians do not force a change with laws in our habits, solutions do not generalize at all. Luckily it seems that little by little seeps the examples of the most sensitive countries that start to forbid something as simple as plastic straws for soft drinks, for example, that 36,500 million are consumed every year only in Europe, when it is not necessary even for drinking. Or the countries where it is already forced to pay for plastic bags in stores, or even seeks to prohibit them. But there is still so much to do… Plastics that can take up to 500 years to decompose in our environment, causing very serious damage to marine ecosystems. Between 40 and 60% of turtles ingest plastics. And in some species of birds that percentage rises up to 93%. More than a million birds and more than 100,000 marine mammals die every year as a result of all the plastics that reach the sea. Up to 12 million tons of plastics enter the oceans every year, drowning ecosystems, causing damage to wildlife and entering the food chain.

It is already known that the demographic increase, and (paradoxically) the industrial technological development and consumerism, is leading to a limit situation of sustainability and planetary survival. It is not that human misery or the differences between rich and poor is something new, because that reality has unfortunately always existed in our history. The reality of our time, and that is what we have to deal with, which is new, of just over half a century, is that if we all live as we currently live in the so-called developed countries, we would need the resources of two whole planets, and it turns out that at short-term we have only one ("One World!").

And this reality is full with contradictions, as, for example, the case that in just two weeks after the call, 78,000 people had signed up to go to a one-way trip to Mars, under the mission of establishing a permanent colony on the red planet. Obviously, this pioneering journey of a handful of “privileged” that should be selected from among those thousands is an exorbitant cost. And it is clear that with that budget it could help the lives of thousands of people, for example colonizing decently the deserts of our own planet without problems of oxygen deficiency, without being at 55 °C below zero on average (with minima of down to −143 °C), or under extremely strong winds and dust storms, which darken the planet for weeks and even months. In addition, being able to see the family again, if it is desired. But it turns out that leaving with all the expenses paid to cross interplanetary space is much “sophisticated” (“cooler”) than not solving the urgent problems that we have just around the corner.

Almost as a “manifesto” on this issue is what led us to design a prototype house in Sahara, the *3D Printed Sahara House Project*, an “integral ecology” example (Fig. 1), digitally designed and digitally manufactured: it would be constructed by printing it with robots on-site, at a scale of 1:1, using part of the building material the desert sand itself. That is, practically the same building type and with the same process of construction as the one that would be done realized on Mars, only without risks and for a very small part of the budget. In the conception of the project are

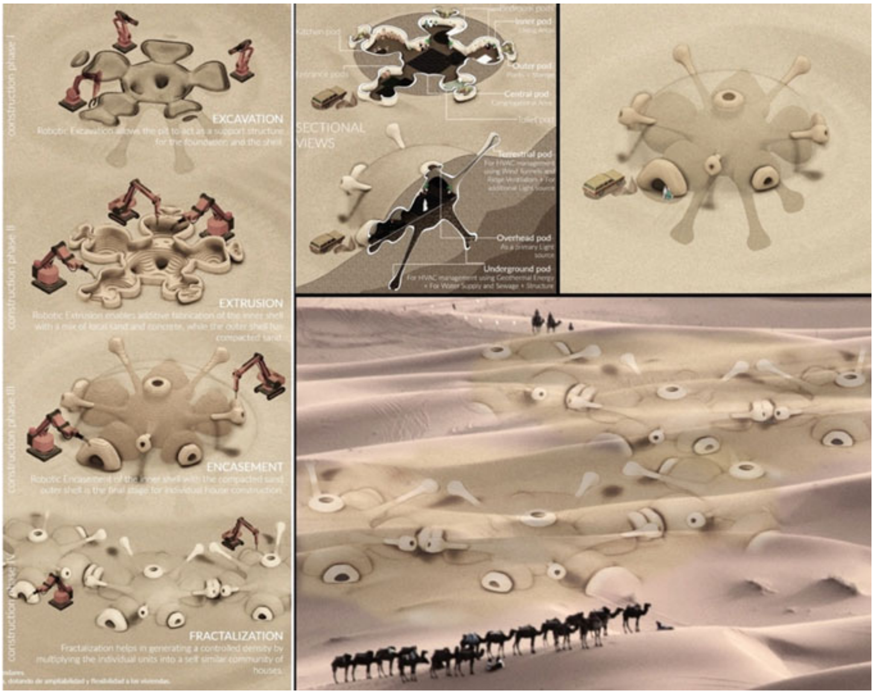


Fig. 1 Alberto T. Estévez (with Angad Warang, collaborator), *3D Printed Sahara House Project*, 2017. Digital design and digital manufacturing: it would be solved by printing it with robots on-site, at a scale of 1:1, using as part of the building material the desert sand itself, abstracting in the conception of the project typical elements of the typologies of vernacular architecture

included also elements of the vernacular architecture typologies, in its form, ventilation, distribution of rooms around larger spaces and central open patios. Of course, thinking with simple systems of geothermal conditioning, semi-buried, and the necessary solar energy exploitation, with building climate control by means of passive systems.

It is expected that expenses such as those planned for the planet Mars of the year 2029 will not leave us the planet Earth as it is "painted" for the year 2049 in the last film of Blade Runner 2049 [22]. Would that be our reality? Yes, and worse, an absolute collapse, if we don't do our part.

Let's see the present, right now, that urgently demands our responsibility. That is our reality, our reality in the whole world. It is enough to see the shocking images of overpopulated cities that stretch tight to the horizon. We live in the largest anthill of the known universe. Immense interconnected colony to which we all have to contribute our grain of sand for their survival. The problems become planetary, and some pay the irresponsibility of the others.

For example, New Zealand, which, being one of the most respectful countries as for the environment, is nevertheless the one with the highest rate of skin cancer. Since it has been his luck to be under the ozone hole of the atmosphere in which we have all participated. They can't leave their houses without a hat, nor can they go to the beach in a swimming suit, but only fully clothed.

"Do not eat cherries at Christmas", was the laconic answer from Jorge Wagensberg years ago to my question about what we could do to avoid the alarming proliferation of jellyfish in the Mediterranean, since I liked to bathe in the sea. Definitive, since that day I stopped taking fruit that was not seasonal and of nearby origin: tons of goods move every day polluting the entire planet simply to satisfy unnecessary whims. Our own responsible action and the teaching should be attentive to all those tremendous contradictions in our daily life.

2 Research Presentation

So, these pages will introduce (more as method for the discussion) a brief presentation of projects, taking as example one project of each moment of the architectural ideas evolution of recent times. Thus, from the different understandings of the architecture of each example, all of them remain as an excuse to discuss the concepts of sustainable architecture that every construction should consider today, as a commitment but also taking one of each type of climate. Following then, a chronological thread that spreads from the beginnings of our professional practice until the latest investigations of our current biodigital projects, with biological and digital design strategies, biomanufacturing and digital manufacturing, based also on our outcomes with the scanning electron microscope (SEM), to produce images of samples by scanning surfaces and sections with a focused beam of electrons. What follows our investigation in genetics applied to architecture [6], and our research in computation applied to architecture [7].

The research for the architectural application of cutting-edge biological and digital techniques (with the benefits that come from the inclusion of genetics: efficiency, economy, renewable use, self-replication), is crucial, relevant and urgent before it is too late for our planet which has reached the limits of its sustainability. "We have, because human, an inalienable prerogative of responsibility which we cannot devolve" [18].

2.1 The First Steps: The Influence of Rafael Serra

Everyone can participate in improving the world with, for example, simply planting a tree throughout his/her life. I already did it, and I will do it again to replace those who didn't. Of course, what the Cuban poet says could happen: "I had a tree but it dried up". However, as every day approximately 372,960 people are born in the world, every 3 s 13 trees could be planted, a huge forest full every day! And the good thing about being a teacher is that, besides, planting a "tree of knowledge" you can go much further in space and time.

This is what Rafael Serra (1942–2012), architect and professor in Barcelona, did. In a different architectural approach from that of the "official" and dogmatic, of the realism and rational-functionalism, of the so-called "Barcelona School", anchored in the *Neue Sachlichkeit* of the 20s and 30s, he was the only one that in the 70s and 80s had a vision of what is even fashionable today, the attention to environmental issues, the use of alternative energies, passive solar architecture, etc. "Good architecture by definition is sustainable", he told us in class. For instance, I will always remember how he showed us a project of a complex, something "hippie", built in the middle of the countryside, as a protest and example in front of a nuclear power station: it was clear that no cable was coming to the project, because he revealed how all the electricity and the necessary air conditioning were solved in a self-sufficient way.

This, nowadays, can no longer surprise anyone, but at that time no one else taught these things, which I found very inspiring, full of common sense and full of reason, which made me sign up for his courses. So, as soon as I graduated as an architect, as soon as I began my professional career, from my first house built (House G., Sigüenza, 1983–85), I intended to apply those principles that I learned from him. In fact, I was the only one of my generation who then followed his postulates of passive solar architecture. Then, when about 15 years later the words ecology and sustainability became more fashionable, little by little others of my generation were already approaching such understandings.

From the origins of humanity, architecture has fulfilled as a first function the protection against atmospheric elements. Buildings are barriers against rain, wind, shelters against the cold or filters against heat or light. Among other things, Rafael Serra was the most advanced in teaching how to build in the best sustainable and self-sufficient way possible, according to the variety and complexity of climatic situations

[15, 16]. In any climatic condition, what architecture always seeks is to achieve a certain degree of comfort. The attainment of a certain level of well-being results, in practice, as a complex phenomenon involving numerous parameters that are not always quantifiable. And yet now we have the duty not to squander resources, energy, to achieve such comfort. And maybe we can't rule out that we even have to lower our level of comfort, towards the planetary sustainability. As less comfortable is having to separate waste and take them to the appropriate recycling place, or having to dress more warmly at home in winter to have to heat less.

So we can now go through some chosen projects, to briefly review the different principles applied. Then we will see how the sense and the sensibility that moved us to get into those paths of sustainability is just what led us to conclude in biodigital architecture.

2.2 *Three Houses, Three Principles and Something Else*

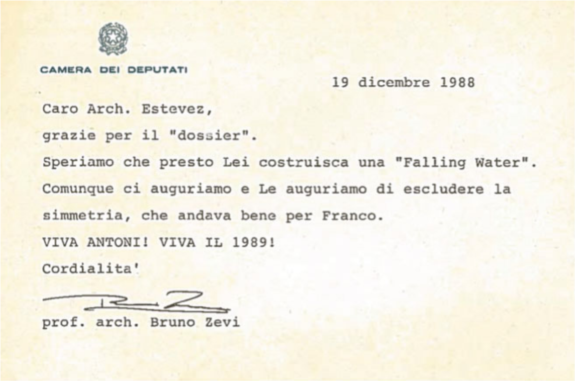
To begin with, three examples of three small houses that explain how, with a low budget, you can also create easily buildings that provide some sustainability benefits.

I started designing the first building of my generation with considerations of passive solar architecture at the end of my architecture studies, when I was still 22 years old (Fig. 2). Very open to the south, with a narrow greenhouse of fine glass in front, flush with the facade, as a gallery, of the optimum depth, for a better "greenhouse effect", and insulating glass behind. Very much closed and protected to north, with only one opening with double-insulating window, not to miss the beautiful views of the valley. Closed fireplace with heat recuperator in the centre, capable of heating the whole house, with stones also inside to accumulate thermal inertia, in a cold climate in winter which—fortunately—does not need air conditioning in the summer. Due to the technological limitations of the place and the early time of the project, solar panels were not yet available, nor other advances that were easier to obtain later. Although due to municipal regulations, the roof had to be covered with Arabic tiles.

Fig. 2 Alberto T. Estévez, *House G.*, Sigüenza, 1983–85. Views from the south and from the north

Of course, in view of this work is that, and fleeing from the rational-functionalist and realistic dogmatism that all the students were forced to design in the famous School of Barcelona, my first professional steps were in the dazzling Vienna of the postmodern epicentre years, fascinated by their big protagonists, as Hans Hollein (HSAK), Gustav Peichl (AKBILD) and Rob Krier (TUWIEN), with personal encounters: there, I also started my academic career, teaching my first classes at the university.

However, this "postmodern pull" was short-lived, because, raised before as child in the shadow of the buildings of Antoni Gaudí in Barcelona, as a young architect it occurred to me to send something to Bruno Zevi, who in just few words radically changed my vision:



CAMERA DEI DEPUTATI

19 dicembre 1988

Caro Arch. Estevez,
grazie per il "dossier".
Speriamo che presto Lei costruisca una "Falling Water".
Comunque ci auguriamo e Le auguriamo di escludere la
simmetria, che andava bene per Franco.
VIVA ANTONI! VIVA IL 1989!
Cordialita'

prof. arch. Bruno Zevi

CHAMBER OF DEPUTIES
19 December 1988

Dear Arch. Estevez,
thanks for the "dossier".
We hope that soon you build a "Falling Water".
However we hope and wish to exclude the
symmetry, which was fine for Franco.
HURRA ANTONI (GAUDI)! HURRA THE 1989!

Friendly'
prof. arch. Bruno Zevi

And on the other hand, little by little, the pure, simplified, abstract geometry of people like Donald Judd was also more striking: exemplified in this other project (Fig. 3), resolving it conceptually with the minimum possible lines. And nevertheless collecting basic principles, like closed to the north winds of winter, with a circle as a good way to repel such winds, and with high trees there against them, stone walls with greater thermal inertia, creating a microclimate in the patio, all the house covered with solar panels to south, water-pool in the south to humidify the environment with the south winds during the summer (necessary for the climate in which this project was located), centred chimney, and also a narrow greenhouse-gallery, which opens in summer and becomes a shaded porch.

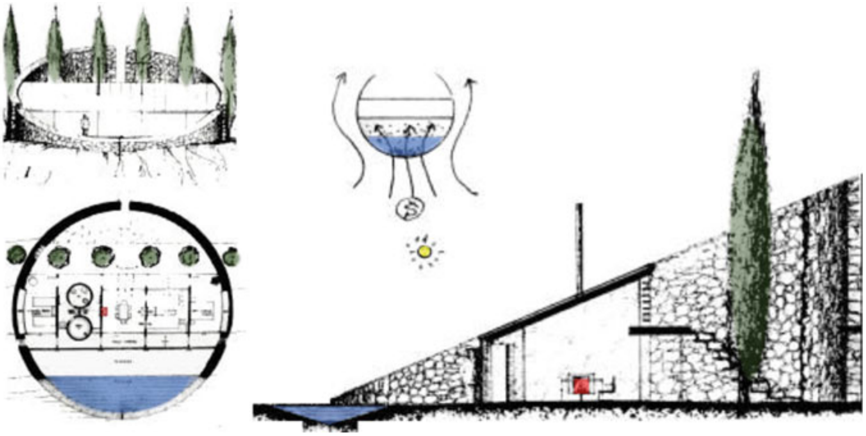


Fig. 3 Alberto T. Estévez, *House P.*, Cervià de les Garrigues, 1989. Greenhouse to the south, water for the south winds, closed to north with a patio microclimate, with high trees against the north winds, and with solar panels on the roof

Later, once experienced the design strategies of maximum reduction of appearances, once exhausted by the work of the application of the famous motto "less is more" of Ludwig Mies van der Rohe, it comes a moment in which another types of possibilities appear, as those that open new ways. This is how one would arrive to the following case from this trio of initial examples of this writing (Fig. 4): a house that breaks, plastically and expressively, in broken lines of acute angles, a house that is "sharp", alive, looking for dynamic and emphatic movements.

The turn that is seen in the main floor is also due to face the south, which is at 45° in relation to the plot. This allows to install the greenhouse-gallery well oriented. And at the same time let to protects the house more from the west sun, which in the case of the climate of this work is more critical, hot in summer. For this reason, narrow galleries are built on each side, open from the top. This permits a constant circulation

Fig. 4 Alberto T. Estévez, *House M.*, Almerimar, 1993–95. Green roofs, main floor with greenhouse turned 45° to face south, with water in the south, closed to north, with open side galleries, and lower floor half-buried and aerated

of air, always without direct sun impact on the walls of the interior spaces. And with the possibility that also air circulation is available underneath, through a half-buried whole floor, which opens behind in an open ditch-gallery. Ahead, water-pool to south, to humidify the environment when hot winds blow. While still protected to the north, with a thicker wall, with earth inside as cheap thermal insulation and higher thermal inertia.

Here, finally, a dream came true: a whole house, really build, with green roofs, soil and grass. Having been again the first house of my generation to be built in such a way, and the first of all in that geographical area. Nowadays, things have become easier, and there are many specialists on these solutions, so it should be almost always appropriate to build green roofs: cheap and good thermal insulation for both summer and winter, and ecological, natural, simply made with earth. With the vegetal leaves that (like the hairs on the head) they do not let the sun's rays hit the deck directly. And with a better possibility of self-management of rainwater. A roof that instead of overheating in summer it produces oxygen, it retains pollution and dust, and offers a pleasant surface to be used, and to live. The advantage in this case is also having the green roofs connected directly to the surrounding garden, as it is sloped down.

In short, basic principles, simple, not so difficult to apply in reality, and yet so poorly applied. Although it is true that, compared to 25 and 35 years ago that is when these houses were built, little by little more architects are aware of all this. But, it is not known if it is in a greater proportion or not, because the number of architects has skyrocketed in the last decades.

These three examples participate of the evolution of ideas in architecture: architecture is a living entity, dynamic in conceptualizations and experimentations. And we can see how basic principles of passive solar architecture are applicable under different architectural approaches and considerations. Something that constitutes movements, and trends: post-modernism at the beginning of the 80s, (neo-)minimalism at the end of the 80s, and (neo-)expressionism at the beginning of the 90s. All of them were avant-garde movements at their time, although up to this day, there are so many architects who follow them. All those tendencies (as happens with contemporary art) are here to stay, indifferent to the fact that the avant-garde is always moving forward.

2.3 Green Architecture

This is how, finally, at the turn of the century and the millennium, the main goal of the cutting-edge projects was the integration of real green elements in architecture starting with the green roofs, as the easiest application of green. This, taken on a larger scale, should already been a rule in every urban area. Ideal to combat the superheated thermal islands of large cities, pollution, dust, electrical overload of air conditioning devices in winter and summer (Fig. 5).

Fig. 5 Alberto T. Estévez, *Green Barcelona Project*, Barcelona, 1995–98: hug interconnected park on the roofs of the buildings, when Barcelona is also the city with fewer parks

As an example, the Green Barcelona Project (Barcelona 1995–98) presents the creation of a huge interconnected urban park, landscaping the roofs of the entire city, which fortunately in Barcelona are usually flat terraces. Thus, the project is improving the thermal inertia of attics, with the consequent energy saving, both in winter heating and summer air conditioning reducing the increment of the temperature of the urban zones, in short, making the whole building more pleasant.

This project was presented to two successive mayors of the metropolis, and they seemed very interested about it, but at the end it only remained dozing on the table of the bureaucrats. Politicians have to legislate, to direct the planet towards its sustainability. When day by day the headlines seen in the media hurt. Between hundreds and hundreds, the following are samples, randomly taken, by day and by newspaper (in this case, *La Vanguardia*, Barcelona, 2011-today):

The forests of our planet lose twice
the area of Portugal each year

ENVIRONMENT
Each year 16 million hectares of trees disappear due to large industry.

CO2 is 40% higher than in the pre-industrial era,
absorbed by 30% of the oceans, causing acidification

ENVIRONMENT
The increase of the level of the oceans and the acidification
of the water create a dangerous scenario for the ecosystems.

The concentration of greenhouse gases in the
atmosphere has grown to unprecedented levels

ENVIRONMENT
The effects of climate change are close to the point of no return: part of
the CO2 emitted will remain in the atmosphere for at least 1,000 years

Meanwhile, an underground and/or green architecture is an alternative to return to a planet entirely covered with living nature, which is the best self-regulating system of sustainability: life. Something that can be solved for whatever building type or functional use would be: a hotel (Fig. 6), for example, or a cow farm (Figs. 7 and 8). In both cases, a green roof solution has been achieved, and also the continuity of the vegetal mantle, alive, as semi-buried architecture, with all its benefits of thermal insulation and thermal inertia. In addition to recreate natural landscapes, is certainly more easily perceived as humanly pleasant environments, instead of stacks of "boxes" artificially constructed, which unfortunately is the aspect of our cities and neighbourhoods.

The earth itself is the resource. The integration of life in the architectural concept is to obtain more advantageous results at all levels, physical and psychic—plant life in this case, whose introduction is always automatically accompanied by greater integration of animal life. In short, semi-buried buildings and green roofs are apparently a certain improvement for climate and landscape.

After all, this follows the same understanding applied to the architecture as contemporary painting and sculpture conquered: the fusion of the figure and the background. Contemporary art and architecture, for decades, are beyond the creation of

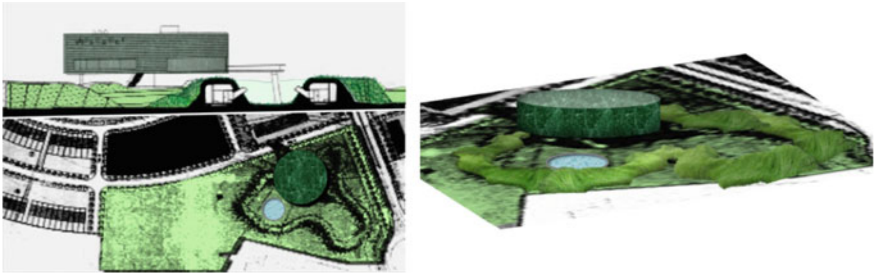


Fig. 6 Alberto T. Estévez, *Hotel*, Salou, 1999: the rooms are inside of a continuous green grass "hill", around a central open space with the pool and solarium

Fig. 7 Alberto T. Estévez, *Cow Farm*, Paraguay, 2007. The mysterious "crop circles" serve as inspiration for the geometrical landscaping of the complex, which organizes the land with continuous green roofs, pergola of solar panels as an open-air warehouse, and a wind turbine at the other end of the project

Fig. 8 Alberto T. Estévez, *Cow Farm*, Paraguay, 2007. General view and view of the guard house

differentiated objects from their environment. As Umberto Boccioni proclaiming, "the absolute and complete abolition of the finite line and the closed statue. Let's open the figure wide and enclose the environment in it" [4]. The finite physical limits of artistic and architectural objects have been erased in relation to what surrounds them. The closed object is faded, being both the figure and the background, as a single artistic and architectural object. It is a green continuous tapestry of nature that from all the surroundings not only climbs above architectural spaces, but actually creates them. It is not only surrounding them. It is part of the architecture itself. Where can it really be seen where the building begins or, and where the landscape ends? Everything must already be one, everything must be designed at the same time, everything must work together.

One step further would be with that integration of life seen or called for in other ways. As it would be the case of applying it also in vertical walls. But it is always about looking for a simple way that really is a solution for our global planetary problem,

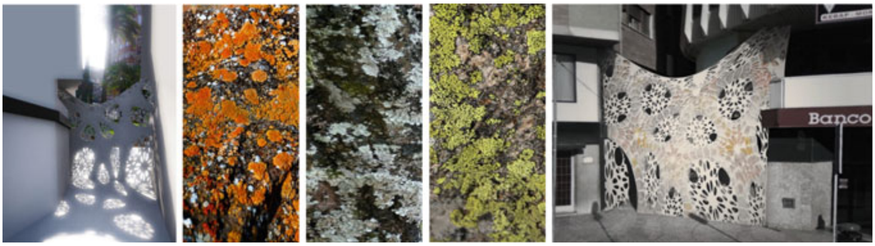


Fig. 9 Alberto T. Estévez-GenArqOffice, *Urban door*, Castellón, 2011. In the centre, views of lichens of different colours to be applied on the surface of this structure, prepared for it

applicable equally for rich and poor, expensive or cheap. It is then necessary to always discard sophisticated solutions, of high technology, only for the privileged, or with difficult maintenance. It can't be that the "alleged" planetary solutions are more costly for the economy and for the environment than doing nothing. Therefore, it should follow a way non-horizontal architectural elements can be covered with life without requirements of irrigation facilities, which add complexity. One could think, for example, about lichen, as a living being that would fulfil such requirements of simplicity and autonomy. Therefore, this is integrated into the design presented here (Fig. 9), involving the colour variations that are specific to lichen.

And entering the twenty-first century as it is, the research about the use of digital tools for the design and manufacture of architecture and objects becomes almost something unavoidable. Therefore, as shown in these projects, they will now follow the processes and take the forms that such advanced tools allow, taking advantage of the benefits that are offering, for its conception, development, control and execution. Thus, the conjunction of the biological and the digital reaches the possibility of the birth of the biodigital architecture. And therefore, we must adapt to the times. Making the effort to get out of our comfort of doing things "as always". Discovering the new freedom that corresponds to this era.

It is not difficult to understand. The introduction of steel and concrete in the architecture of the last century led to a radical change of construction systems, and thus forms. And vice versa, because we should not just think that the forms go behind existing systems and materials. Not always the technical possibilities allow certain creations. On the contrary it also works: the longing for certain ideas, materialized in designed forms, also propitiates and accelerates the arrival of the systems and materials that allow them. Thus, the introduction in the present century of the digital constructive systems and the computational design possibilities of controlling have also to expect a radical change in the architecture. An architecture that, in this way, fulfil the need to work only with green energy and technology, perfectly suited for sustaining resources for tomorrow.

2.4 Biodigital Architecture

And once entered fully into the conformations that only digital technologies allow, it is clear that the will to integrate basic and simple principles of passive solar architecture must be maintained, together with other possible extracted inputs from vernacular architecture. This, after all, is to take into account the "trial-error" evolution of hundreds of years of human habitat in that particular place, as nature does. Nature adapts to its surrounding reality, to the climate of each region. Living beings are different according to the climatic regions in which they live. With architecture and design should happen the same. But instead, we see how today buildings are usually equal on all continents. So, starting from the corresponding climate begins the study to optimize the possibilities of insolation that the environment allows, conditioned by an urban situation or not (Fig. 10). Consequently, the architectural forms are emerging, as guided by the sun, as would any living vegetable. Greenhouses are installed in the sunny areas, and non-sunny areas are well insulated, ventilation and air flows are strategically planned, geothermal use is also created, and green roofs are built.

Meanwhile, in the line of biolearning (now that everywhere the discussion is machine-learning), the research of primigenial and genesiac structures with an electron microscope becomes relevant for an architect: the moment when the amorphous masses of living and growing cells genetically start to order themselves. An order which resists (in the most efficient and economical way, as nature always does) gravitational external forces and the own weight of the respective living being. There, then, appear different systems and complex geometries that must find a response with the corresponding graphic strategy and digital conception [7]. In this case, an apartment building in Innsbruck (Figs. 10, 11 and 12), it was decided to be developed based on a Voronoi structure.

Thus, in its maximally efficient growth, in the trinomial of a good relationship between quantity of material used, energy expended with it and satisfaction of the function (structural in this case), both plants and animals integrate in their structures this complex geometry of Voronoi (Fig. 12). Today, thanks to digital tools, it can be designed and controlled without too much difficulty. And for that reason it can be built in reality. With the plus of rational and emotional interest that has a complex,

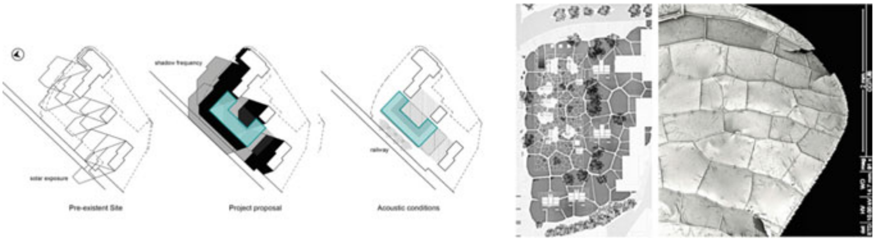


Fig. 10 Alberto T. Estévez-GenArqOffice, *Passive solar housing*, Innsbruck, 2014. From left to right, previous studies of the building's location, its ground floor with 2D Voronoi, and dragonfly wing on the right (91x) with 2D Voronoi

Fig. 11 Alberto T. Estévez-GenArqOffice, *Passive solar housing*, Innsbruck, 2014. Above, general view of the building. Below, from left to right, natural structures of bees and vernacular structures of Innsbruck, urban agriculture in roofs, flowers in balconies as it is usual in this area, scheme of the passive solar performance of the building, urban beekeeping and interior Voronoi space with hanging orchards

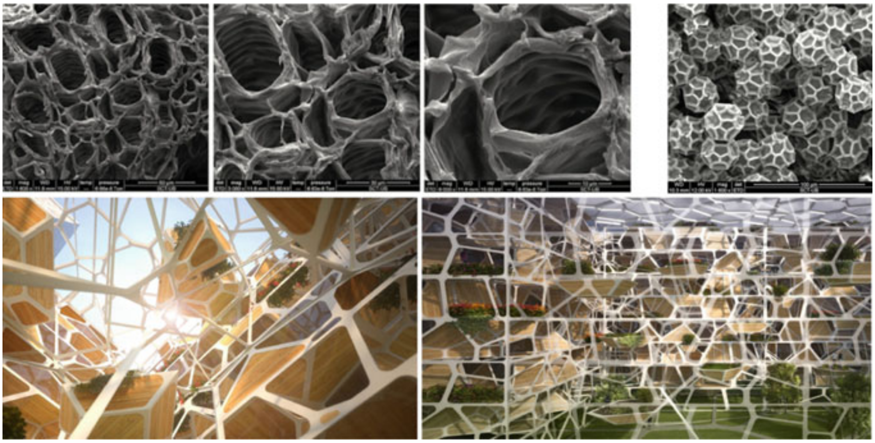


Fig. 12 Alberto T. Estévez-GenArqOffice, *Passive solar housing*, Innsbruck, 2014. Above, cactus section (1600x, 3000x, 6000x) and pollen grains (1600x) with interior and exterior 3D Voronoi, respectively (photographs: Alberto T. Estévez). Below, views of the Voronoi 3D structures of the residential building, which support urban orchards, kitchen-gardens and hanging gardens

unitary, harmonic, organic and continuous structure like this one. Then, the floors of the project are designed in 2D with this geometry. Voronoi that is scaled in three levels, one within the other, according to the size in plan or the function to solve. Then, consequently, the same geometry is developed in space, in 3D, configuring its interior and exterior structure, and a large central open space to obtain a microclimate. There, on roofs, balconies and terraces, agriculture and urban beekeeping will be available. All this is in pursuit of the energy and resource self-sufficiency.

Being in the line of an idea of self-sufficiency, of passive solar architecture, sometimes having additionally some proper learning from vernacular architecture is aligned with an idea of low technology, which, after all, is closer to a more "natural" way, more sustainable, more economical, and even more "democratic".

This would be the ideal to build, in a tendency to search for self-sufficiency, where each house, each building, each city, tend to self-sufficiency. And therefore to the self-management of their resources: to get models of buildings that only need the fire of the sun, the wind of the air, the water of the rain (or of the humidity), and the heat of the earth. These would be the genuine "sustaining resources for tomorrow", the four classic elements [21], the usual ones. With the same words before said, also applicable to resources: the most "natural", sustainable, economical and democratic resources, renewable and ecological. And on the other hand, applying intelligence, to think housing modules that could act almost like companies that manage their resources (and wastes) that are produced by them.

Understanding that the economy that nature teaches us (biolearning), after millions of years "testing" natural structures with survival objectives, with maximum efficiency and sustainability, looking for optimal ways of survival in the environment that corresponds to it, it turns out that we also arrive to a discovery of the organization of the cells in different levels of fractality. Of course, there are examples of fractality that are seen with the naked eye, in different plants for example. But even the sustainability of the planet must also be achieved "fractally", with the sustainability of each country, each region, each city and each house.

Something definitive is to see that there is also such fractality at the microscopic level. For this reason, we continue the work with the electron microscope, discovering how at a microscopic level the structures are replicated in a fractal patterns, up to three successive levels. For example, a bamboo is made up of small "little bamboos", which, so to speak, are made up of microscopic "little bamboos". Or a sea sponge is made up of small "little sea sponges", which are made up of microscopic "little sea sponges" (Fig. 13). The structures created in this way are what we should always consider in our works, and being not massive, as has always been. This acquires a greater resistance with less material and with less energy spent in its construction. And again, now, with digital technology design and manufacturing, using large-scale 3D printers that are already starting to exist, it can now become a reality.

Then, the fractality opens the possibility of becoming itself a design strategy and is applied in the following project presented here (Figs. 14, 15 and 16).

By means of a digital design development, the whole structure emerges, by such fractal development that captures the values of complexity, unity, harmony, organicity and continuity: the values of beauty. The structure will support everything necessary

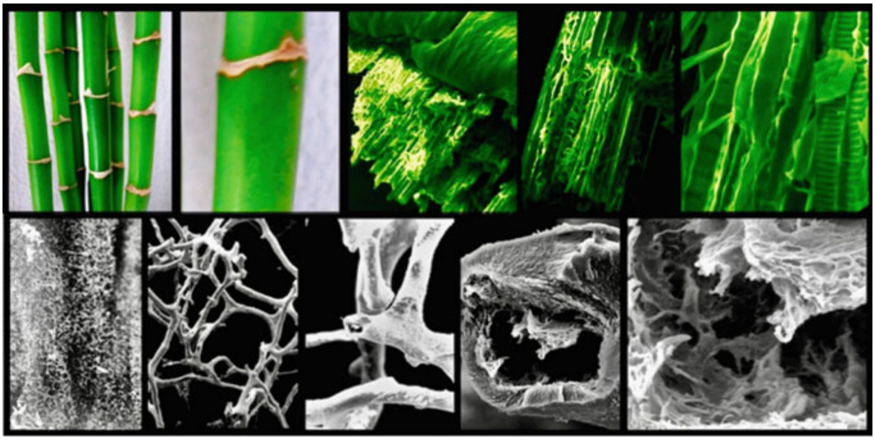


Fig. 13 Alberto T. Estévez. Above, bamboos (x1, x1, x200, x400, x3000) and, below, sea sponges (x1, x100, x400, x3000, x7000), 2008–09: photographs taken with scanning electron microscope that allows to appreciate the structural fractality

Fig. 14 Alberto T. Estévez-GenArqOffice, *Antenna Tower*, Santiago de Chile, 2014. Instead of appearing on the top the typical telecommunications tower, here is offered as an alternative a crown, a bright (Bruno Taut's) "Stadtkrone"

for its function as a telecommunications antenna and belvedere overlooking the city. And in parallel is offering the possibility of energy self-sufficiency, by incorporating spherical solar collectors (Beta Torics) in its last level of fractal development. There are also planned parabolic and linear antennas. As well as spherical luminaries that at night create (on the top of the mountain where this building is located) the image of "the crown of the city", following the idea of the "Stadtkrone" of Bruno Taut [20]. That same effect is given during the day with the brightness of the aforementioned spheres (Fig. 16), a crown, instead of one of those telecommunications towers that populate the mountains and skylines of cities.

On the other hand, all that structure of hollow tubes, with fans inside, will inhale the surrounding contaminated air through its interior, so that filtrated air comes out purified to the central zone, where is located the area for the entertainment of the people who go up to the top of the mount. In fact, thanks to being a "decontaminating

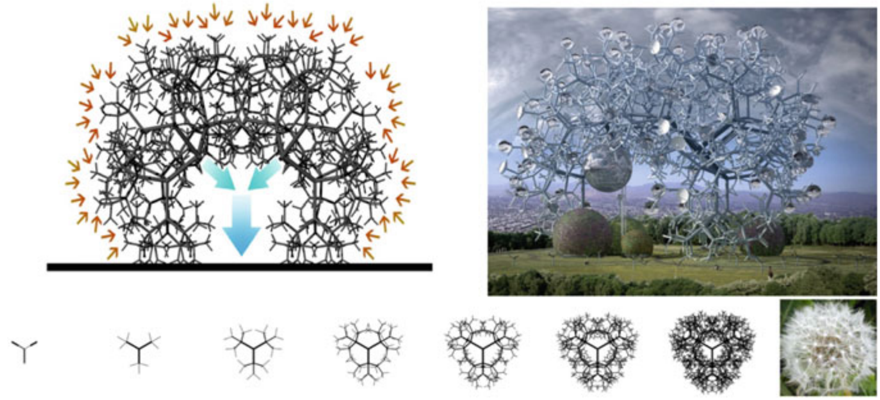


Fig. 15 Alberto T. Estévez-GenArqOffice, *Antenna Tower*, Santiago de Chile, 2014. Developed digitally and fractally, which at the same time is a "purifying air machine". Although its uniqueness is only a symbolic fact, because the acute contamination suffered by Santiago de Chile, where the project is located (right, a meadow of dandelions around)

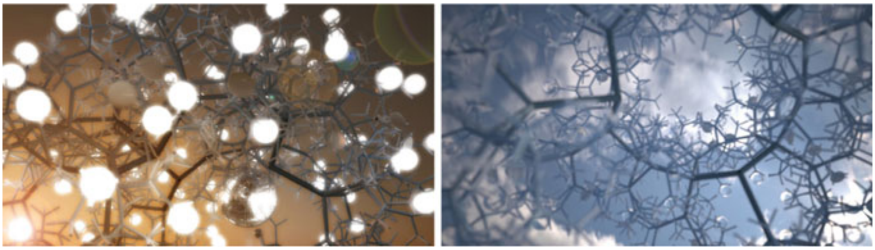


Fig. 16 Alberto T. Estévez-GenArqOffice, *Antenna Tower*, Santiago de Chile, 2014. At night, spherical luminaries surround the building's surface at its last fractal level. By day, spherical solar collectors of the same size and placed on the same level will also offer their brightness as a "crown" of the landscape

machine", the whole project is symbolically presented as "environment healing". For this reason, it is also surrounded by a meadow of dandelions, a well-known medicinal plant, a small-scale poetic participant of the building fractality.

In conclusion, all buildings should be designed today as self-sufficient. There is no longer any technical excuse against this. Everyone should start from a fine design of sustainability. Learning from nature (biolearning), in biological symbiosis with it, and the use of digital tools for a proper adaptation to our time, from the conceptualization of its design and architecture: biodigital architecture.

2.5 Genetics

Within biology, genetics also offers us paths to explore, which applied to architecture can offer unimaginable sustainability benefits. Benefits as powerful as are the almost infinite potentials intuited in genetics. The precarious state of our world even obliges us having the responsibility to search into this field, without delay due to laziness, myopia or a very closed mindset. For the moment, genetics is only applied to health and nutrition. But humans have one more basic need, its habitat. For this reason, we created in year 2000 the Genetic Architecture Research Group and the (official) University Master in Biodigital Architecture, as well as a Doctorate Programme. For the first time in history, geneticists and architects begun to collaborate and to set genetic research objectives applied to architecture: building, light and heat would be the general goals to be followed to satisfy the basic human need for habitat. Thus, the first real result occurred on our bioluminescence research (Fig. 17).

So, in 2005, seven lemon trees with the GFP gene (Green Fluorescent Protein) began to illuminate the planet (years later other people in different parts of the globe also took this idea that we started of bioluminescence applied to the domestic and urban space). In addition, in 2008, the first house in history was illuminated with "living light", biolamps of different design were placed throughout the house, that made the installation of electric light unnecessary (Fig. 18). Nevertheless, we continue with other possible solutions, like introducing the genes responsible for bioluminescence in various types of ornamental plants, or those genes from other species, whose results could be more effective and durable for the required use.

As has been said before, and with genetics it can also be said that "the longing for certain ideas, materialized in designed forms, also propitiates and accelerates the arrival of the systems and materials that allow those ideas to come true". Thus, the introduction in the present century of the biological constructive systems and their possibility of control by means of genetic design, suggest a radical change in the

Fig. 17 Alberto T. Estévez, *Genetic Barcelona Project*, 2003–2006. Left, the magic light of the GFP lemon trees. Centre, image of a possible world. Right, comparison between a lemon tree leaf with GFP and another without GFP from the same tree type: above photograph taken with conventional reflex camera, and below photograph taken with special UV camera

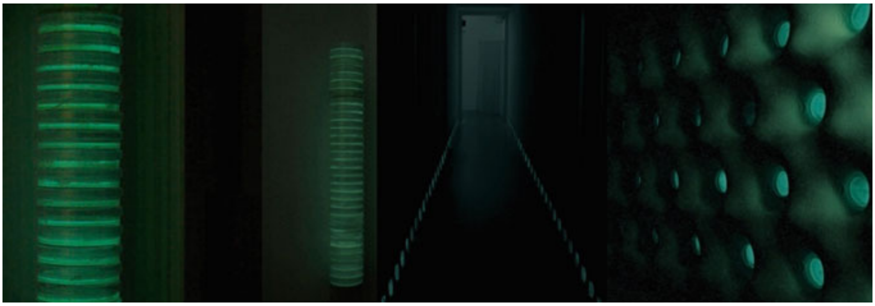


Fig. 18 Alberto T. Estévez, *Bio-lamps*, 2007–2008: the first systematically fully illuminated apartment with living light (human eye view: photographs by the author, taken with a conventional reflex camera)

architecture. An architecture that in this way can fulfil the need to work only with green energy and technology, perfectly suited to sustaining resources for tomorrow.

Having today that possibility in the scientific and technological horizon, it is clear that sooner or later the necessary genetic research will be developed enough, in parallel with architectural and constructive objectives, so that a house can be “planted” and will grow alone, in the most “natural” way, more sustainable, more economical, and even more “democratic” (as it has been stated before for biodigital architecture paradigm): having greater possibilities of freely reproduction. In addition, the possibility of genetic creation of new species can stop the dramatic disappearance of the ones that we have propitiated.

Specifically, working in genetic research to obtain living elements, building materials and useful living spaces for architecture. One more example, illustrated with figures, is the *Sporopollenin Houses* (Fig. 19). Architectural objectives with the application of genetics. Research is being carried out into the genetic control of growth, to develop living cells that are converted into building materials and habitable space. “Directed” by means of their specific genetic design, thereby are producing architecture that is 100% ecological and sustainable, with maximum energy saving throughout the construction process and with no need for manual labour, as its growth is naturally emerging.

Fig. 19 Alberto T. Estévez, *different views of Sporopollenin Houses*, 2009–10: genetic research on growth control which makes live cells grow for architectural material and habitable spaces

From the same research on cellular structures by means of scanning electron microscope, this project of the *Sporopollenin Houses* (Estévez [5] emerged as well as single-family houses that grow alone formed of sporopollenin, the material of pollen grains, the material most durable, that does not rot, or rust, or fall apart, even if thousands of years pass. Here is when durability is a requirement of architecture.

3 Conclusions: Biodigital Future

So, at this point, looking at our results and the results of all the other colleagues, that are working being aware of the 4th Industrial Revolution we are crossing, a possible conclusion is to think about what is the authentic meaning of all these efforts—a critical moment to ask whether we are really working for something that is absolutely useful for mankind.

We know that the answer is in nature and nature is the answer. The more science advances, the more we know of what we call nature and the more we understand that nature is the answer. But, “if nature is the answer, what was the question?” [23]. We are exploring and interrogating “the question”, through interdisciplinary endeavours involving fields such as biology, genetics, computation, art, architecture, design, civil engineering. We are exploring the frontiers of knowledge… One main interdisciplinary cross-point in this exploration is the point where genetics meets biology and the digital, applied to architecture and design in our case (and similar to art or civil engineering, etc.). This is the cross-point at which we find ourselves, and also this writing is about. This is the scene, in which to create architecture and design, we join forces with geneticists and philosophers focused on architectural objectives, together researching the fusion of biological and digital techniques.

It all started with a word. And after, let’s say, an infinite succession of words, which started emerging as calls from the darkness of nowhere, this word, “biodigital”, emerges [8]. Truthfully, more and more, no doubt about the way forward, today, we can see in our own results how biodigital is the future: the houses, the cities, the landscapes, will be 50% biological and 50% digital, and the fusion of them both. It is certainly the great potential of new biological and digital techniques that can lead to the sustainable and social efficiency the planet needs, so the human being can have a future.

Biodigital has in itself its own set of words. At the same time, each one of them is related (at least, neurologically) to many others. In this manner, around the term biodigital we can include others such as biology, life, computing, nature, cybernetics, genetics, mathematics, DNA, algorithms, emergence, morphogenesis, artificial intelligence, surrealism, digital organicism, genetic architecture, robotics, biomanufacturing, digital production, biolearning, programming, scripting, parametric, among others. This cloud of words, in constant change depending on how one aspect or another is intensified, like if it were a pointillist mosaic, ends up illustrating what the term biodigital really is and what it can be. Biology and digital, if we understand working with DNA as if it were a natural software, and with software as if it were an artificial DNA: those are the new materials of the future, as concrete and steel were for modernism.

How can we visualize future cities and future houses? The city of the future will be 100% biodigital, improved by biological and digital technology, or maybe there will be no future. "Learning from trees" [1]: a city that is more like a forest than like a landscape of shipping containers on the port. After all, where do we prefer to live, surrounded by boxes or by trees? Our cities are destroying nature wherever they grow. We need to assure that every human footprint becomes a creator of life. We need to change our reality with life.

This has a poetic point of view: we will solve our planetary problems with life; but it has also the exactly description of the real and scientific path to follow, through biodigital and genetics, life for saving life. A world view that leads naturally to a philosophy of reverence for life [17]. Marvelled at the mystery of life, the miracle of the self-formation of the delicate, sophisticated and perfect that each living being is, the fascination with the problem of the phenomenon called life: Sherrington began studying the primal cell and curiously this took him on his journey up to the concept of altruism. Not in vain did he impress the scientists and thinkers who followed him: Schrödinger, Atson, Crick and Prigogine, on the one hand, and Loeb, Popper on the other [18].

We live with the contradictions that this age has: where does it is really taking us all this research around AI, digital thinking, digital design, digital manufacturing, big data, BIM, CIM, GIS, CAAD, virtual and augmented reality… Where we are going with these series of disruptive concepts and innovations, like the smart-phone, social networks, online gaming, Internet of things, smart materials, interactive environments, personal fabrication, 3D printing, drones, self-driving cars or the smart cities… which is really this radically new world…

Of course, like in the past, if the world changes, architecture and design cannot remain indifferent. Architects and designers must understand and adapt to the new circumstances. But this declaration is not absolutely true, because, the evolution of the architecture and design, and the novel understandings and technological possibilities that come from this is also a motor of changes. Furthermore, are the digital technologies oriented to what this world really needs right now? When, effectively, digital technologies are at the core of the emerging paradigm. Yes, we have this advantage. So, we have also this ethical responsibility. We must orient all this to the increasingly exigent demands on our planet, and not to what separates, more and more, in two worlds.

In the film *Elysium* [3], and it is not the only one that in recent times illustrates it, appears as in the future humanity is radically divided in two: the film takes place on both a ravaged Earth, and a luxurious space habitat called Elysium. Some people have access to extraordinary advancements in areas like mobile communication, artificial intelligence, big data, cloud computing, blockchain, nanotechnology, biotechnology, facial recognition, robotics or additive manufacturing, and others not (Fig. 20).

But that is not the future, it is already our present, when the human population is already divided into two increasingly separated halves. When one half can live as it lives because the other half can't. That is why all of us have to focus on our research

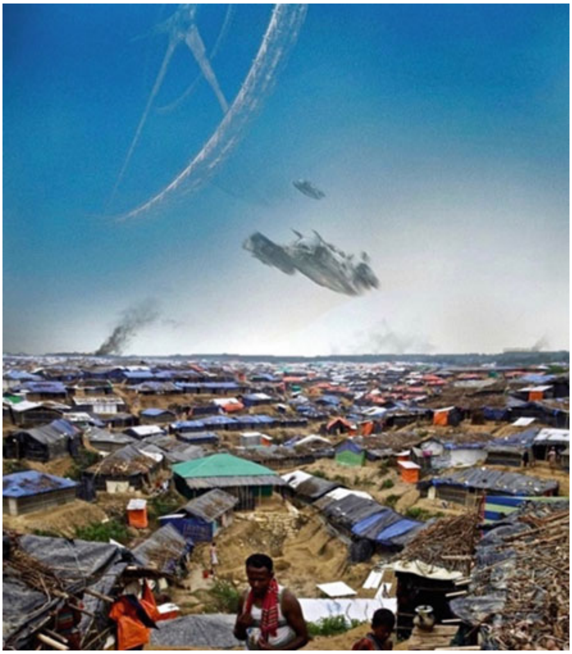


Fig. 20 Symbolic photomontage of an image of the film Elysium with an image of the Rohingya refugee camp in Kutupalong (Ukhia, Cox's Bazar, Bangladesh). Dream and reality: reality and future?

exclusively to achieve this planetary unity of life. And to do this, we have also to put ourselves all in line with an intelligence that integrates the results of cognitive sciences, neurology, artificial intelligence, philosophy; able to direct the behaviour using the information that it captures and elaborates itself; a creative intelligence that discovers new possibilities in reality, selects its goals and executes them, and that therefore is aimed at action [13]. A knowledge of our intelligence that can amplify our efforts in our struggle for the sustainability of the world [12].

3.1 Integral Ecology

In conclusion, since everything is interrelated, and today's problems call for a vision capable of taking into account every aspect of the global crisis, we need to urgently consider the idea of integral ecology, which simultaneously considers as whole indivisible entity its environmental, economic and social dimensions.

Ecology studies the relationship between living organisms and the environment in which they develop. This necessarily entails reflection and debate about the conditions required for the life and survival of society, and the honesty needed to question certain models of development, production and consumption.

Just as the different (physical, chemical and biological) aspects of the planet are interrelated, so living species are part of a network too, which we need to explore and understand, and genetics is the most advanced tool for it. Even a good part of our genetic code is shared by many living beings. It follows that the fragmentation of knowledge and the isolation of bits of information can actually become a form of ignorance, unless they are integrated into a broader vision of reality.

When we speak of the "environment", what we really mean is a relationship existing between nature and the society which lives in it. Nature cannot be regarded as something separate from ourselves or as a mere setting in which we live. We are part of nature, in constant interaction with nature. Recognizing the reasons why a given area is polluted requires a study of the society, its economy, its behaviour patterns. Given the scale of change, it is no longer possible to find a specific, discrete answer for each part of the problem. It is essential to seek comprehensive solutions which consider the interactions within natural systems themselves and with social systems. We are faced with one complex crisis which is both environmental and social. Strategies for a solution demand an integrated approach for protecting nature and at the same time combating poverty.

We, as architects and designers, have the personal responsibility to achieve a vision of architecture and design that helps to develop sustainable and safe societies. And this goal, in our present reality, is not only relevant but also urgent. Hence, we have the personal responsibility to create and engage ideas of environmentally responsible architecture, that means at the same time socially responsible architecture; and the biodigital integration, biology and digital, is the most advanced tool for architects and designers. Biodigital, as a tool, but, before that, as an approach, is an understanding of architecture and design. While we are at this work, little by little, almost as if by magic, the understanding about what our times demand will grow. In an integral two-sided reality, on one side, seeing that architecture and design can improve the world by improving the lives of the least fortunate; on the other side, learning from nature's laws (biolearning) and finding computation as the most powerful tool to really solve problems.

Yes, the path to follow is clear, in a world where everything is already connected, with an intimate relationship between the poor and the fragility of the planet when it is necessary to develop critical thinking towards the new paradigm and the forms of power resulting from technology and when it is necessary to search for new ways of understanding economy and progress, the value of each person, and the human sense of ecology. When there is an urgent need of sincere and honest debates, there exists a great responsibility in terms of politics both at an international and local scale. Ultimately, when it is convenient to have a new lifestyle, this is all what the *Zeitgeist* calls us to do, when in sight of all are the signs of our times.

At least this world is our common home that sustains us, and that we must guarantee its own sustainability, that it is ours too. Everything that discriminates the integral ecology will not prevent the ruin of our entire world. There will only be a real future if there is one for all. Only working for an integral ecology, with, of course, proportional generosity and sacrifices on the part of each and every one, which means fighting against the contradictions of our era, we will find together a real salvation of our beautiful Blue Planet.

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Energy Security and Efficiency Analysis of Renewable Technologies

Fazıl Gökgöz and Mustafa Taylan Güvercin

Abstract Global conflicts in securing the energy resources and the climate change have propelled the investment in renewable energy (RE) research and deployment in the last two decades. This chapter statistically confirms the relationship between renewable research and energy security and benchmarks the efficiency of the R&D efforts in different RE technologies. Our findings reveal that the inexpensive and abundant natural gas in energy markets restrained the research on energy technologies particularly after 2010. This bears a risk for the diminished capacity of the countries in energy security, especially in bull energy markets. The results of the super-efficiency model of data envelopment analysis (DEA) reveal that the wind and biofuel technologies are the efficiency leaders in R&D, where each dollar spent on their research has a bigger impact on energy security than other RE types. The countries should continue investing on renewable research and develop collective innovation and commercialization strategies, especially in solar, geothermal, and ocean technologies in order to achieve sustainable energy efficiency levels for providing the energy security.

1 Introduction

Securing the energy sources and routes is crucial for the economic development of all countries and is one of the primary reasons of international conflicts, at all times. As the international competition for accessing the energy resources increases, renewable energy (RE) comes to the fore as a crucial aspect of the discussions on energy security. RE brings the right ascension to four dimensions of energy security, which are *availability, accessibility, acceptability,* and *affordability* [1]. Being generated

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from natural resources that replenish continuously, RE is available and accessible locally. Since RE is environment-friendly, it is acceptable by the society. Furthermore, global researches on RE technologies persistently reduce the unit generation costs of RE and make it affordable [2]. Dependency on fossil fuel exporters and higher level of energy security diminishes accordingly as the share of RE in the energy mix[1] of the countries increases.

Within this context, efficiency analysis of RE is getting bigger attention in the international research platform in the last decade. For example, Menegaki [3] has focused on 31 countries in Europe and benchmarked their efficiency regarding the renewables during the period between 1997 and 2010. Likewise, Chien and Hu [4] have made a research on the energy efficiency of 45 countries, during which they identified that the member countries of OECD do not only have bigger shares of RE within their energy-mix than the other countries but also have higher efficiency levels. Halkos and Tzeremes [5] have made a firm-level analysis of the efficiency of RE companies in Greece.

There is also a previous research on RE efficiency from an energy security point of view. Researchers like [6–10] conceptually emphasized the association between energy security and renewables, while others utilized simulations or case studies. For instance, Lund [11] has analyzed the Denmark case for the challenges against developing sustainable growth strategies that utterly depend on RE. Similarly, Gan et al. [12] have identified that the countries implement RE policies with the motivation of attaining higher levels of energy security while reducing the gas emissions. Likewise, Blazejczak et al. [13] have run simulation models for the RE generation in Germany. Their RE expansion scenario has confirmed significant amount of savings from the fossil fuel imports of Germany 2030 (i.e., 33 Billion Euros).

In a recent study, Gökgöz and Güvercin have analyzed selected EU countries in terms of their efficiency and productivity scores regarding the RE deployment from an energy security standpoint [2]. The authors have identified that the RE and the energy security are statistically related, whereas the average efficiency and productivity scores of the EU countries regarding energy security increased between 2005 and 2014. In addition, the authors found out that the key component of the productivity growth in RE is innovation (technological progress).

In a similar vein, this chapter elaborates further on the RE innovation by examining the impact of research and development (R&D) on RE generation and by benchmarking the efficiency of the global R&D investment in different RE technologies. By utilizing the methods of data envelopment analysis (DEA) and panel data analysis, this chapter is intended to find empirical answers to the following questions:

- What was the change in the global expenditures on energy R&D between 2000 and 2016?
- Is there a pattern in the popularity of different RE technologies in the global research platform?

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[1] Energy mix is the mixture of the main energy sources which are utilized to generate electricity (e.g., renewables, fossil fuels, or nuclear).

- How was the growth in power generation from various energy sources, particularly from renewables throughout the above period?
- Is there a statistical support regarding the impact of renewable R&D on energy security?
- Is there any significant variance in the efficiency scores of the R&D investment in different RE technologies?

This chapter comprises six sections. Utilized empirical methods are explained in Sect. 2, while data, data sources, and descriptive statistics are provided in Sect. 3. R&D expenditures on energy and RE generation are summarized in Sect. 4. Section 5 explains and discusses the results of empirical work. The last section contains the conclusions.

2 Methodology

2.1 Data Envelopment Analysis (DEA)

Data envelopment analysis (DEA) is a non-parametric mathematical model, which is extensively used for exploring the efficiency and productivity changes of a set of decision-making units (DMU). Using the actual data, DEA draws a frontier line, which indicates the possible maximum production with the available technology. DEA is a popular method in academia and business, since it allows any number of input or output parameters and does not impose a particular production function [14]. For the output-oriented models, DEA aims to achieve maximum level of output relative to the fixed input levels [15]. On the contrary, maximum possible decrease in inputs is the objective of the input-oriented models with the constant levels of output. Relative efficiency scores in DEA are reported as a number between 0 and 1. The DMUs with the score of 1 are considered as efficient units in the group, while scores below 1 indicate inefficiency. As shown in Eq. 1, the efficiency score is calculated by DEA as the weighted sum of outputs divided by the weighted sum of inputs.

$$\text{Max}\ \frac{\text{Weighted sum of outputs}}{\text{Weighted sum of inputs}} \tag{1}$$

The original DEA model is developed by Charnes, Cooper, and Rhodes (CCR) in 1978 [16]. The CCR model has the basic assumption of constant returns to scale (CRS), with the postulation that all DMUs operate under the optimal scale. Equation 2 shows the formula of input-oriented CCR model [17]:

$$\max \theta_o = \sum_{r=1}^{s} u_r y_{ro} / \sum_{i=1}^{m} v_i x_{io} \tag{2}$$

subject to

$$\sum_{r=1}^{s} u_r y_{rj} / \sum_{i=1}^{m} v_i x_{ij} \leq 1 \quad j = 1, 2, \ldots, n$$

$$v_i \geq 0 \quad i = 1, 2, \ldots, m$$

$$u_r \geq 0 \quad r = 1, 2, \ldots, s$$

In Eq. 2, the vectors of x (x_1, x_2, …, x_m) and y (y_1, y_2, …, y_s) represent the inputs and outputs, respectively, while θ_o is the efficiency score of DMU$_o$ which shall be maximized. The letter "n" denotes the total number of DMUs in the set, whereas weight assigned to inputs and outputs are shown with the vectors of v and u. Equation 3 shows the linear program which basically replaces the fractional program of Eq. 2 [17].

$$\max \theta_o = \sum_{r=1}^{s} u_r y_{ro} \tag{3}$$

subject to

$$\sum_{i=1}^{m} v_i x_{io} = 1$$

$$\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \leq 0 \quad j = 1, 2, \ldots, n$$

$$v_i \geq 0 \quad i = 1, 2, \ldots, m$$

$$u_r \geq 0 \quad r = 1, 2, \ldots, s$$

In order to calculate the relative efficiency scores of all DMUs, the linear program in Eq. 3 is compiled "n" times, while each DMU in the set would select the input and output weights that are going to maximize the efficiency score.

In 1984, Banker, Charnes, and Cooper (BCC) relaxed the CRS assumption to variable returns to scale (VRS) and introduced a new DEA model [18]. Due to market impurities like government interventions, imperfect competition or limitations of finance, the BCC model of DEA presumes that firms do not work under optimal scale. Equation 4 exhibits the input-oriented DEA with the VRS assumption [18].

$$\max \theta_o = \sum_{r=1}^{s} u_r y_{ro} + w \tag{4}$$

subject to

$$\sum_{i=1}^{m} v_i x_{io} = 1$$

$$\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} + w \leq 1 \quad j = 1, 2, \ldots, n$$

$$v_i \geq 0 \quad i = 1, 2, \ldots, m$$

$$u_r \geq 0 \quad r = 1, 2, \ldots, s$$

$$w \text{ free}$$

The newly added parameter w in Eq. 4 loosens the CRS assumption, which imposes the frontier line to pass through the point (0,0). Figure 1 illustrates the BCC and CCR models of DEA, where the dissimilarities are also revealed. For example, if the inputs get increased in CRS surface, the outputs will have a proportional increase, whereas the VRS surface permits non-proportional changes [17]. Covering the DMUs on the CRS surface as well, the VRS line envelops the DMU set by linking the outermost DMUs. Since VRS frontier line has more DMUs on it, it calculates the efficiency scores higher than or equal to the CCR model.

In Fig. 1, the line which navigates from the points B, C, and D is the VRS efficient frontier line, which envelops all the other DMUs in the set. Within this context, DMU A should increase the level of output and/or decrease the input and move to the point A’ to became efficient.

DEA allows the scale efficiency score to be calculated by dividing the score of CCR model into the score of BCC model. The score of 1 means that the DMU is efficient in scale [17].

It is not possible in classical DEA models to benchmark the efficient DMUs which get the score of 1 and take place on the frontier line. Fortunately, the super-efficiency DEA model provides a solution to this issue, which generates efficiency

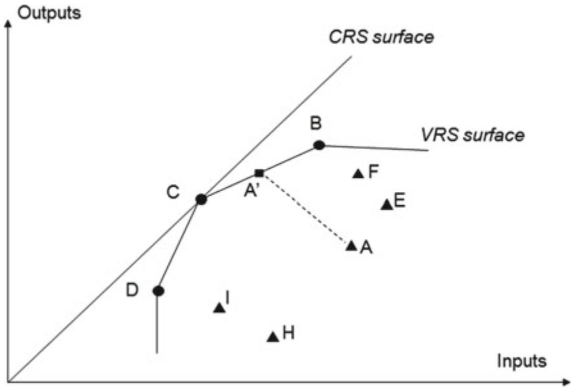

Fig. 1 Envelopment surfaces of the CCR and BCC models of DEA [17]

scores beyond 1. The model calculates the efficiency score of a particular DMU in a setting that original reference group does not include the assessed DMU [19]. As a result, super-efficiency let the researchers sort the efficient DMUs.

Within the context of this chapter, super-efficiency DEA model is utilized to calculate R&D efficiency of the renewable technologies with the energy security point of view.

3 Presentation of Data

3.1 Data and Data Sources

Table 1 presents the data that are provided throughout the chapter. The R&D data are retrieved from the online data services of International Energy Agency (IEA) [20]. IEA has utilized the renewable R&D data of 27 countries and the respective Table 9 is provided in the Appendix herein. Regarding those 27 countries, the power generation data, gross domestic product (GDP) and gross electricity demand data for the same period are collected from the United Nations databases [21]. Annual nominal price of natural gas is obtained from US Energy Information Administration (EIA) [22].

3.2 Descriptive Statistics

Descriptive statistics of the data for the period between 2000 and 2016 are provided in Table 2. The numbers reveal that the average R&D budgets of the sample countries on nuclear energy exceed the research investment in other energy sources. Throughout the analysis period, 213.89 million US dollars (m$) were spent on researches for nuclear energy, while this figure is 83.09 and 56.57 for renewable and fossil fuel technologies, respectively.

With the average of 32.90 and 29.75 m$, solar and biofuel generation have been a larger research area compared to other renewable technologies, followed by wind (12.75) and geothermal (7.11). Interestingly, hydro technologies have received limited research budget (i.e., 3.25 m$), while providing almost 20% of the gross electricity demand in sample countries. Becoming a more popular research area, especially in the USA, the UK, South Korea, Ireland, and France through the second half of the analysis period, ocean generation technologies have attained only an average of 3.30 m$.

In terms of power generation, Table 2 reveals that a significant percentage of the gross electricity demand is met by fossil fuels. In the whole analysis period, an average of 61.45% of the electricity demand in sample countries has been provided by means of combustion generators, while 36.62 and 34.76% have been provided by

Table 1 Presentation of the data

Data name	Description	Unit/calculation
GDP	Gross domestic products	Constant 2011 billion US $
GROSS_DEMAND	Gross electricity demand	Million kilowatt hours
SOLAR_RD	R&D budget for solar energy	Constant 2007 million US $
WIND_RD	R&D budget for wind energy	Constant 2007 million US $
OCEAN_RD	R&D budget for ocean energy	Constant 2007 million US $
BIOFUELS_RD	R&D budget for biofuels	Constant 2007 million US $
GEOTHERMAL_RD	R&D budget for geothermal energy	Constant 2007 million US $
HYDRO_RD	R&D budget for hydro energy	Constant 2007 million US $
TOTAL_RE_RD	Total R&D budget for renewables	Constant 2007 million US $
FOSSILS_RD	R&D budget for fossil fuels	Constant 2007 million US $
NUCLEAR_RD	R&D budget for nuclear energy	Constant 2007 million US $
RATIO_SOLAR	Gross demand met by solar energy	Solar generation divided by gross electricity demand
RATIO_WIND	Gross demand met by wind energy	Wind generation divided by gross electricity demand
RATIO_OCEAN	Gross demand met by ocean energy	Ocean generation divided by gross electricity demand
RATIO_BIOFUELS	Gross demand met by biofuels[a]	Biofuels generation divided by gross electricity demand
RATIO_GEOTHERMAL	Gross demand met by geothermal energy	Geothermal generation divided by gross electricity demand
RATIO_TOTAL_RE	Gross demand met by renewables	Renewable generation divided by gross electricity demand
RATIO_FOSSILS	Gross demand met by fossil fuels	Fossil fuel generation divided by gross electricity demand
RATIO_NUCLEAR	Gross demand met by nuclear energy	Nuclear generation divided by gross electricity demand
PRICE_NATGAS	Annual natural gas price	US $ per million cubic feet

[a] Biofuel category includes the electricity generated from fuel wood, municipal waste, animal waste, and biogas

means of renewables and nuclear power plants, respectively. With a rate of 19.21%, the hydro technology has constituted the biggest share of the average RE generation in subject countries, followed by biofuels (12.79%), wind (2.91%), and geothermal (0.49%). Average power generation from solar has been around 0.23% of the gross electricity demand in both periods, while the generation from oceans was only 0.055%.

Table 2 Descriptive statistics

Data name	Mean	Median	Std. dev.
GDP	1,527	432	2,912
GROSS_DEMAND	354,534	123,171	773,467
SOLAR_RD	32.90	12.56	47.97
WIND_RD	12.25	3.99	19.01
OCEAN_RD	3.30	1.63	4.29
BIOFUELS_RD	29.75	13.22	58.75
GEOTHERMAL_RD	7.11	1.70	12.48
HYDRO_RD	3.25	1.45	4.17
TOTAL_RE_RD	83.09	43.15	130.44
FOSSILS_RD	56.57	10.32	106.00
NUCLEAR_RD	213.89	24.60	512.29
RATIO_SOLAR	0.00230	0.00125	0.00231
RATIO_WIND	0.02913	0.00954	0.04826
RATIO_OCEAN	0.00055	0.00060	0.00064
RATIO_BIOFUELS	0.12789	0.07608	0.14896
RATIO_GEOTHERMAL	0.00491	0.00309	0.00615
RATIO_HYDRO	0.19211	0.08269	0.26319
RATIO_TOTAL_RE	0.36629	0.23474	0.30982
RATIO_FOSSILS	0.61454	0.67286	0.33681
RATIO_NUCLEAR	0.34764	0.30030	0.21604
PRICE_NATGAS	10.80	10.75	1.77

Note Mean is the geometric mean of the average of sample countries between 2000 and 2016

4 R&D Expenditure on Energy and the Change in Energy-Mix

4.1 R&D Expenditure on Energy

In concordance with the increasing concerns about energy security, the R&D budget on energy has increased globally between 2000 and 2016 in general. As shown in Fig. 2a, the average R&D expenditure made by subject countries on energy increased from 6.7 billion US dollars (b$) in the beginning of 2000s to over 10.7 b$ in a decade. However, starting from 2010, the average R&D expenditure by the subject on energy had a sharp fall to 7.5 b$ during the 2015–2016 period.

Figure 2b shows the decomposition of average energy R&D budgets reserved for different sources (i.e., renewables, fossil fuels, nuclear). Average annual R&D expenditure of subject countries on renewable technologies has increased more than threefold from 0.98 b$ in 2000–2002 to over 3.57 b$ in 2009–2011. Nevertheless,

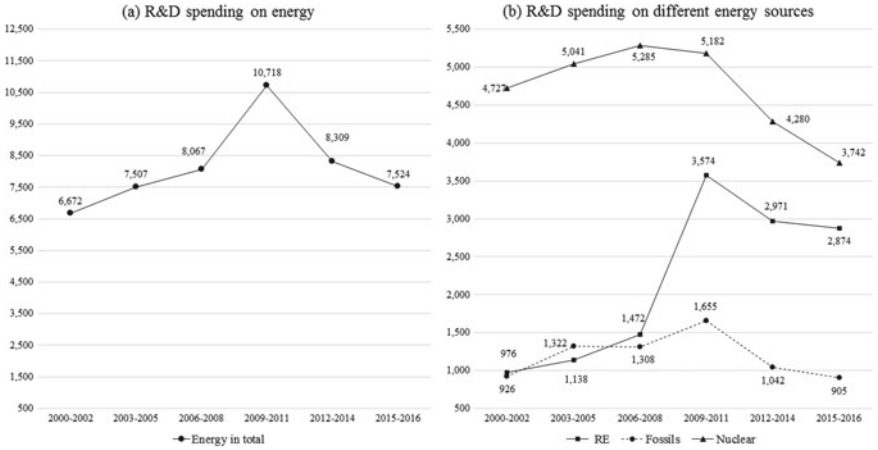

Fig. 2 R&D expenditure on energy

same as the other energy sources (i.e., fossils and nuclear), the average R&D in renewables makes a sharp fall down to 2.87 b$ in the period of 2015–2016.

Despite the on-going discussion around nuclear energy, the nuclear energy has taken the biggest share of the energy research budget on average. Nuclear energy R&D has peaked up to 5.2 b$ in 2006–2008, then gradually fell down to 3.7 b$ in 2015–2016, due to the budget cutback mainly in the USA, Japan, and Canada.

Equally important, Fig. 2b discloses that the fossil fuels have been the least popular of the global R&D platform in the last decade. The current technological trajectory, which is propelled with the increasing public awareness against the environmental concerns and dependency on exporter countries, has favored the renewables against fossil fuels. Thus, the trajectory seems to restrain the research on fossil fuels in the new millennium. As shown in Fig. 2b, average budget of fossil fuel R&D is reduced even down to 0.9 b$ in 2015–2016, which is less than 1/3 of the renewables.

An important finding of this section is that the available budget for the energy research in the subject countries has undergone a serious decline after 2010, where renewable technologies are no exception. One of the primary reasons of this cutback is the sharp reduction in natural gas price starting from 2009, which is visible in Fig. 3. Countries have enjoyed the cheap natural gas in the international markets, which also diminished their motivation and capacity in energy R&D in general.

4.2 R&D Expenditure on Renewables

Solar energy got the lion's share in R&D expenditure on RE technologies in early 2000s. As shown in Table 3, almost half of the RE research budget was spent on solar in P1 and P2, followed by biofuels, wind, geothermal, hydro and ocean technologies.

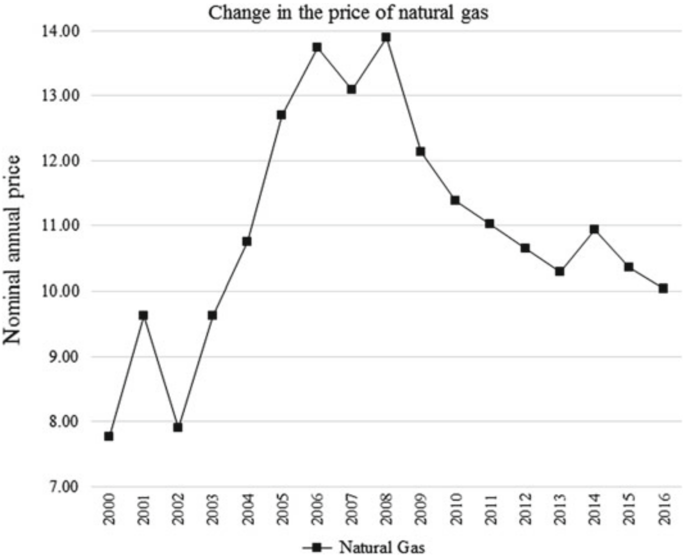

Fig. 3 Change in the price of natural gas

Table 3 R&D expenditure on renewable technologies

		P1[a]	P2	P3	P4	P5	P6
Solar	Expenditure[b]	483	547	586	1,115	1,010	779
	Share (%)	49.4	48.1	39.8	31.2	34.0	27.1
Wind	Expenditure	134	154	175	463	407	613
	Share (%)	13.7	13.5	11.9	13.0	13.7	21.3
Ocean	Expenditure	9	8	23	107	141	116
	Share (%)	0.9	0.7	1.6	3.0	4.7	4.0
Biofuels	Expenditure	244	337	607	1,521	1,151	1,077
	Share (%)	25.0	29.6	41.3	42.6	38.7	37.5
Geothermal	Expenditure	79	62	54	185	164	157
	Share (%)	8.1	5.4	3.7	5.2	5.5	5.5
Hydro	Expenditure	26	25	17	104	94	118
	Share (%)	2.6	2.2	1.1	2.9	3.2	4.1
Total RE	Expenditure	976	1,138	1,472	3,574	2,971	2,874
	Share (%)	1.0	1.0	1.0	1.0	1.0	1.0

[a] P1: 2000–2002, P2: 2003–2005, P3: 2006–2008, P4: 2009–2011, P5: 2012–2014, P6: 2015–2016
[b] Expenditures are in million US dollars

Table 4 Renewable R&D expenditure of top ten countries

	Solar	Wind	Ocean	Biofuels	Geothermal	Hydro
USA	3,145	1,118	317	6,563	1,034	242
Japan	1,826	850	37	872	138	39
Germany	1,434	700	4	506	295	14
France	883	85	62	965	102	20
South Korea	916	523	83	209	91	60
Italy	1,107	72	17	290	92	24
Canada	249	123	81	710	22	223
UK	277	426	215	397	17	15
Netherlands	457	243	10	603	25	6
Spain	524	297	35	284	14	6

Notes Values are in million US dollars and represent the total expenditure of each country between 2000 and 2016

While the amount spent on solar research has increased, the share of solar gradually decreased and ended up with 27% in P6. As shown in Table 4, with 3,145 m$, the USA is the biggest investor in solar R&D between 2000 and 2016, followed by Japan (1,826 m$), Germany (1,434 m$), and Italy (1,107 m$).

As the popularity of alternative RE technologies grows, biofuel technologies seized the leadership in R&D expenditure by P3. The huge investment of 1,521 m$ in biofuel research was 42.6% of the total research budget on renewable technologies in P4. However, biofuel R&D expenditure has actually been decreasing in terms of both share and value after its peak in P4. Table 4 confirms that the top countries investing heavily on biofuel researches are the USA (6,563 m$), France (965 m$), Japan (872 m$), Canada (710 m$), and Netherlands (603 m$).

It must be noted that the research budget of wind technologies has increased remarkably between 2000 and 2016, so has its popularity. Started with 134 m$ in P1, the total R&D expenditure on wind exponentially increased throughout the analysis period and hit to 613 m$ in P6. In the last period, wind technology received more than one-fifth of each dollar spent on renewable research within the subject countries. Table 4 shows that along with the USA (1,118 m$), Japan (850 m$) and Germany (700 m$), South Korea (523 m$) and UK (426 m$) have been the top investors on wind energy research.

Table 3 shows that the ocean energy is under the spotlight of international research community, particularly after P4. Although significantly increased throughout the analyzed timeline, ocean research was able to pull a modest budget compared to solar, biofuels, or wind. In P6, the total R&D expenditure on ocean generation technologies received 116 m$. As Table 4 indicates, the USA has been the research leader in ocean energy by far with the total expenditure of 317 m$ between 2000 and 2016, followed by the UK (215 m$), South Korea (83 m$), Canada (81 m$), and France (62 m$).

Interestingly, hydro was not able to attract the research funds as other renewables, although it has been one of the main sources of power generation. With a total of

118 m$, hydro research could only get 4% of the total renewable R&D budget of subject countries in P6. Moreover, as seen in Table 4, most of the hydro research has been done by two countries only. The USA and Canada have spent 242 and 223 m$ on hydro R&D between 2000 and 2016 in total, which is 65% of the total hydro research of the subject countries. South Korea (60 m$), Japan (39 m$), Italy (24 m$), and France (20 m$) have also financed the hydro innovation.

4.3 Change in the Electricity Demand and the Supply Sources

Table 5 shows the change in GDP and the gross electricity demand of subject countries between 2000 and 2016.[2] Confirming the positive relationship that is identified by the previous research in [2, 23–25], the increasing average GDP of the subject countries has boosted the gross electricity demand during the analysis period. GDP is among the underlying drivers of the investment in renewable deployment and research [2], thus the electricity demand. Subsequently, this section presents how the increasing electricity demand in subject countries was met by different energy sources during the whole analysis period.

Table 6 exhibits that the total RE capacity has grown steadily in subject countries between P1 and P6. The RE generation has leaped from 1,697 billion kilowatt hours (BKWH) in P1 to 3,120 in P6, which constitutes 31.6% of the gross electricity demand. With a slight increase from 1,276 in P1 to 1,358 BKWH in P6, hydro has been the RE leader, which covers 13–14% of the gross electricity demand almost constantly during all periods. Equally important, biofuel is the second-largest RE source of generation, which has gradually reached up to almost 10% in P6. Furthermore, wind (5.73%) and solar (2.08%) have met the significant portion of the electricity demand of subject countries in the same period. In contrast, it is obvious that, with the shares below 1%, both geothermal (0.32%) and ocean (0.01%) generation need to gain ground in order to be classified as mature technologies.

Table 6 underlines that both the volume and the share of nuclear generation have decreased starting from P4, which is mainly due to the removal of nuclear capacity in Japan and Germany. The nuclear power generation in Japan decreased from 288 in

Table 5 GDP and gross electricity demand of subject countries

	P1[a]	P2	P3	P4	P5	P6
GDP[b]	36,359	36,983	37,851	38,876	40,053	41,171
Gross electricity demand[c]	8,943	9,044	9,229	9,399	9,565	9,721

[a] P1: 2000–2002, P2: 2003–2005, P3: 2006–2008, P4: 2009–2011, P5: 2012–2014, P6: 2015–2016
[b] GDP is in billion US dollars
[c] Gross electricity demand is in billion KWH

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[2] To make it easier to analyze and understand, the total analysis timeline is divided into six periods.

Table 6 Electricity generation from different sources and their share in subject countries

		P1[a]	P2	P3	P4	P5	P6
Solar	Generation[b]	2	3	8	34	119	205
	Share[c] (%)	0.02	0.03	0.08	0.35	1.21	2.08
Wind	Generation	36	74	148	268	429	566
	Share (%)	0.40	0.79	1.51	2.76	4.37	5.73
Ocean	Generation	0.53	0.51	0.48	0.49	0.76	1.01
	Share (%)	0.01	0.01	0.00	0.01	0.01	0.01
Biofuels	Generation	359	471	583	698	843	957
	Share (%)	4	5	5.9	7.2	8.6	9.7
Geothermal	Generation	23	25	26	26	29	32
	Share (%)	0.25	0.26	0.26	0.27	0.29	0.32
Hydro	Generation	1,276	1,276	1,290	1,322	1,367	1,358
	Share (%)	14.3	13.6	13.2	13.6	13.9	13.8
Total RE	Generation	1,697	1,851	2,058	2,355	2,791	3,120
	Share (%)	19	19.7	21	24.2	28.4	31.6
Fossils	Generation	5,846	6,234	6,557	6,407	6,434	6,270
	Share (%)	65.4	66.3	66.9	65.8	65.6	63.5
Nuclear	Generation	2,256	2,285	2,290	2,189	1,949	1,951
	Share (%)	25.2	24.3	23.4	22.5	19.9	19.8

[a] P1: 2000–2002, P2: 2003–2005, P3: 2006–2008, P4: 2009–2011, P5: 2012–2014, P6: 2015–2016

[b] Generation is the total power generation of the subject countries from each source type in billion KWH

[c] Share is the percentage of the generation in the gross electricity demand of subject countries

2010 to only 18 BKWH in 2016, while these figures were 140 and 84 for Germany. In contrast, Canada, South Korea, and the UK have continued to invest in deployment of nuclear generation capacity during the same period. For example, in 2010, the nuclear generation of Canada was 90.7 BKWH, which has increased to 101.1 in 2016. Similarly, South Korea has expanded its nuclear generation from 148.6 BKWH to 161.9 in the same period while these figures were 62.1 and 71.7 for the UK.

Despite the environmental issues and vulnerabilities in energy security that they trigger, fossil fuels have been the primary sources of electricity generation in subject countries. Table 6 shows that the amount of electricity generated by using fossil fuels has floated in a narrow band between 5.800 and 6,600 BKWH throughout the whole timeline, which represents circa 65% of the total gross demand in the subject countries. As identified in the previous sections, the low cost of natural gas in the energy markets has resulted in the utilization of their installed capacity of combustion generators in subject countries, if not new plants have been built. For example, the power generation from natural gas in the USA has increased from 22.8% in 2009 to 31.9% in 2015. Similarly, over 39% of the total power was generated from natural gas in Japan and Italy in 2015, while this ratio was 42.2% in the Netherlands, 29.7% in the UK, 22.4% in South Korea, and 18.9% in Spain.

The findings in this section lead into two important inferences. Firstly, the cyclical market conditions in fossil fuels, particularly natural gas, have restrained the decommissioning of the fossil generators, unlike nuclear plants. Secondly, subject countries have followed continuous policies for increasing their RE deployment throughout the analysis period.

5 Empirical Analyses and Discussion on Findings

5.1 Panel Data Analysis for the Effect of R&D on Energy Security

The relationship between energy security and R&D in RE is conceptualized in Fig. 4. R&D will result not only in pushing down the unit cost of the RE generation [26] but also in increasing the conversion efficiency of the RE technologies [27]. Cheaper and more efficient RE generation will increase the ratio of gross electricity demand met by renewables. Thus, a positive relationship is expected between R&D expenditure on RE and the share of renewables in gross electricity demand. In other words, the more percentage of gross electricity demand is met by renewables, the less dependency on fossil fuels and on the exporter countries occurs. As a result, energy security increases.

The regression model in Eq. 5 mimics the relationship between R&D and the share of renewables in electricity demand for the RE technologies. It must be underlined that technology diffusion and knowledge spillover take place in RE, where the technological progress is utilized in wider geographies than the originating countries [2]. From this point of view, the aggregated R&D expenditures of the subject countries on each RE technology (RE_RD) is selected as the independent variable of the regression model while the share of each RE technology in the aggregated gross electricity demand (RATIO_RE) is the dependent variable.

$$\mathrm{RATIO\_RE}_{\mathrm{it}} = \alpha_{\mathrm{it}} + \beta_1 \mathrm{RE\_RD}_{\mathrm{it}} + \varepsilon_{\mathrm{it}} \tag{5}$$

where the vectors of $t = 1, \ldots, T$ and $i = 1, \ldots, N$ denote time periods and the panel members, respectively, while $\varepsilon_{\mathrm{it}}$ is the error term.

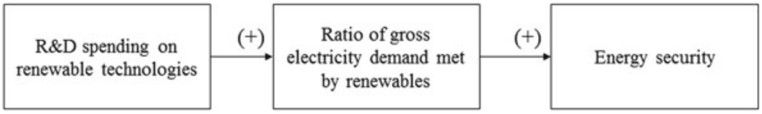


Fig. 4 Conceptualization of the relationship between R&D expenditure on RE and energy security

Table 7 Outcome of the panel data analysis

Model 1: fixed-effects, using 85 observations
Included 5 cross-sectional units. Time-series length = 17
Dependent variable: RATIO_RE
Robust (HAC) standard errors

	Coefficient	**Std. error**	***t*-ratio**	***p*-value**
Constant	0.00766615	0.00301641	2.541	0.0639*
RE_RD	2.89649e−05	7.28186e−06	3.978	0.0164**

Mean dependent var.	0.019664	S.D. dependent var.	0.027613
Sum squared resid	0.007685	S.E. of regression	0.009863
LSDV *R*-squared	0.880008	Within *R*-squared	0.403712
Log-likelihood	275.1134	Akaike criterion	−538.2268
Schwarz criterion	−523.5709	Hannan-Quinn	−532.3318
rho	0.848863	Durbin-Watson	0.410211

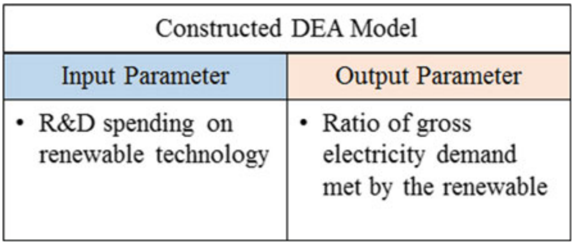
* and ** refer to statistical significance with the confidence of 95% and 99%, respectively

Panel data regression is utilized to statistically test the relationship modeled in Eq. 5. Panel data of five RE technologies (i.e., solar, wind, ocean, biofuels, and geothermal) for the years between 2000 and 2016 are used in the fixed-effects panel analysis. Since hydro has a more mature technology than other renewables and its generation capacity is almost fixed, it is excluded from the analysis. In order to determine whether fixed or random effects panel model should be used, the Hausman test is applied to the ordinary least square (OLS) model.

As the results of panel analysis in Table 7 confirm, there is a positive and statistically significant relationship between the R&D of subject RE technology and the share of gross electricity demand met by that RE. This signifies that the research is a critical enabler in RE deployment and making bigger investments in renewable R&D results in higher energy security.

5.2 *Efficiency of the Renewable Technologies*

This section benchmarks the efficiency of the R&D investments in different renewable technologies. Utilizing the super-efficiency model of DEA, the efficiency of each penny invested in the renewable research is benchmarked for five RE technologies (i.e., solar, wind, ocean, biofuel, and geothermal). Therefore, the decision-making units (DMU) of DEA are these five renewable technologies. As the relationship between renewable R&D and gross electricity demand met by the renewable is statistically confirmed, the same are used as the input and output parameters of the DEA model. Figure 5 visualizes the constructed DEA model.



Constructed DEA Model	
Input Parameter	Output Parameter
• R&D spending on renewable technology	• Ratio of gross electricity demand met by the renewable

Fig. 5 Constructed DEA model

Table 8 shows the super-efficiency scores of the renewable technologies from an R&D point of view. The super-efficiency scores are calculated by means of the output-oriented CCR model of DEA.

Table 8 exposes that the wind energy is the leader in research efficiency among the subject renewable technologies. With an average of 1.22 between 2007 and 2016, wind is the only technology which has higher score than 1.00 in the whole analysis period. That means that each dollar invested in wind R&D has resulted in the highest increase in the share of gross electricity demand met by the renewables. In other words, compared to other RE technologies, the research on wind has a bigger impact on the energy security of subject countries in general.

Biofuel is the second-most efficient renewable among five RE technologies with an average efficiency score of 0.82. The efficiency of biofuel research is 0.978 and 0.945 in 2015 and 2016, respectively, which are nearly on the efficiency line of 1.00. This shows that the R&D investment made by the subject countries in biofuel technologies leverages their energy security almost efficiently. In contrast, the efficiency scores in Table 8 indicate that solar energy has been an overrated research field compared to wind and biofuels. Between 2007 and 2011, the relative efficiency of solar research could not reach even 0.1. Poor efficiency scores are the expected results of high R&D spending, on one hand, and the limited power generation, on the other hand. For example, in 2008, the solar research consumed 42.6% of the total RE R&D budget of subject countries, while providing only 0.12% of their aggregated gross electricity demand. Nevertheless, the efficiency of solar research turned into an upward trend after 2014, due to not only the significant cutback of subject countries in the R&D expenditure on solar but also to the slight increase in their solar generation capacity.

The research efficiency of the geothermal technology has a declining trend throughout the whole analysis window. The average efficiency of geothermal was 0.39 in the first five years between 2007 and 2011, which decreased down to 0.19 in the second five years (i.e., 2012–2016). The reason of this negative slope lies behind the R&D and generation figures of geothermal technology. In 2007, the R&D expenditure for geothermal technologies was 46 m$ as the total of subject countries while the total power generation was 25.8 BKWH. Later in 2016, the total R&D budget of geothermal was almost quadrupled to 163 m$, whereas the total generation increased only up to 32.6 BKWH.

With an average score of 0.008 throughout the analysis period, the ocean energy is at the last place in the efficiency race of renewable research. The investment on

Table 8 Results of super-efficiency analysis

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	AVG[a]
Solar	0.017	0.016	0.036	0.059	0.069	0.104	0.103	0.130	0.262	0.310	0.073
Wind	1.085	1.074	1.592	1.162	1.087	1.358	1.329	1.645	1.022	1.058	1.224
Ocean	0.029	0.012	0.010	0.007	0.007	0.004	0.006	0.005	0.008	0.012	0.008
Biofuels	0.922	0.931	0.628	0.861	0.920	0.736	0.752	0.608	0.978	0.945	0.817
Geothermal	0.686	0.363	0.099	0.488	0.313	0.190	0.146	0.163	0.239	0.203	0.246

[a] AVG refers to the geometric mean between 2007 and 2016

ocean R&D was 133 m$ per year on average between 2010 and 2016, whereas the average annual generation was only 0.77 BKWH. The low-efficiency figures indicate a commercialization problem in ocean energy technologies.

6 Conclusion

This chapter examines the relationship between renewable research and energy security, analyzes the efficiency of the R&D efforts on the different renewable energy (RE) technologies, and benchmarks the impact of each dollar invested in RE research on energy security.

Increasing concerns in energy security and the public awareness on climate change have propelled the funding in renewable research and deployment on global scale. The average annual R&D expenditure of subject countries on RE had increased from 0.98 to 3.57 b$ between the start and end of the first decade of the new millennium. Consequently, the share of gross electricity demand met by renewables had increased from 18 to 25% during the same period.

However, mainly due to the inexpensive and abundant natural gas in the energy markets, the average research budgets on RE have started to shrink after 2010 and gradually ended up around 2.8 b$ in 2016. Given that the innovation is the key driver of RE productivity [2], this finding underpins an important future risk in energy security on global scale. As statistically confirmed by our panel data analysis, research is a key enabler in RE deployment and it impacts the energy security. Consequently, instead of cutting the renewable R&D expenditure, countries should leverage this era to redirect their savings from the inexpensive natural gas into the renewable R&D budgets and get prepared for the future. Eventually, fossil fuel reserves of the world will be depleted.

The super-efficiency analysis of this chapter on the renewable research exposes that the wind technology is the efficiency leader of subject renewables, followed by biofuels. In other words, every penny spent on wind or biofuel research has a bigger impact on energy security than other types. Despite the high funding, the efficiency of solar research has been quite low during the analysis period. This fact indicates that the solar has been an overrated research area compared to the wind and the biofuel. Equally important, the poor efficiency scores of geothermal and ocean research indicates a commercialization issue in these technologies.

We may conclude that the renewable R&D has a direct influence on energy security and the countries should continue to invest on RE research regardless of the temporary market conditions. Besides, collective smart strategies should be developed for achieving better efficiency scores, especially in solar, ocean, and geothermal technologies through innovation and commercialization.

Appendix

See Table 9.

Table 9 List of the countries the data of which are used for empirical analyses

			R&D expenditure[a]			Gross electricity demand met with		
No	Country[b]	GDP[a]	Fossil fuels	Nuclear	Total RE	Fossil fuels (%)	Nuclear (%)	Total RE (%)
1	USA	17,269.67	184.61	891.52	875.84	66.8	20.2	17.4
2	Japan	4,861.67	186.62	1,142.19	385.88	82.6	1.8	17.9
3	Germany	3,658.90	0.00	275.49	235.12	64.6	15.2	57.4
4	UK	2,578.52	16.33	170.59	147.55	62.3	21.2	46.9
5	France	2,544.86	61.09	514.61	194.80	10.3	83.2	28.9
6	Italy	2,101.06	87.75	106.64	88.10	68.6	0.0	52.1
7	Turkey	1,888.94	5.67	0.33	69.78	67.4	0.0	34.9
8	South Korea	1,794.65	29.26	96.05	167.37	68.5	30.3	6.1
9	Canada	1,568.02	95.05	119.73	93.73	21.7	17.3	80.9
10	Spain	1,548.87	0.00	14.78	61.68	41.3	21.9	45.2
11	Australia	1,077.22	10.72	11.97	37.15	86.9	0.0	16.3
12	Poland	988.58	21.63	95.98	24.31	90.8	0.0	24.0
13	Netherlands	805.02	8.81	7.88	79.24	87.9	3.4	31.5
14	Switzerland	480.81	4.05	42.38	93.22	6.2	33.7	85.4
15	Belgium	476.87	0.88	110.96	18.70	36.8	50.1	38.8
16	Sweden	462.10	0.24	1.24	46.23	9.7	45.6	111.2
17	Austria	388.47	1.44	1.93	35.92	27.9	0.0	107.0
18	Norway	335.84	76.10	10.46	53.14	2.1	0.0	113.7
19	Czech Rep.	331.14	0.82	13.41	6.41	64.0	37.8	36.1
20	Ireland	300.67	0.00	0.00	0.00	76.6	0.0	34.8
21	Portugal	280.07	0.00	0.00	0.00	49.6	0.0	64.4
22	Denmark	263.44	0.71	2.84	44.18	55.6	0.0	131.3
23	Greece	260.91	0.00	0.00	0.00	73.1	0.0	26.5
24	Hungary	251.87	0.00	1.76	0.00	45.8	38.0	27.5
25	Finland	217.94	8.53	16.67	42.37	38.4	27.4	77.5
26	Slovakia	158.65	0.00	1.96	19.22	25.9	54.1	39.9
27	Estonia	36.99	20.82	0.42	1.85	94.8	0.0	71.9

[a] In constant 2011 billion US dollars
[b] Sorted by GDP

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Small Wind: A Review of Challenges and Opportunities

Alberto Álvarez Vilar, George Xydis and Evanthia A. Nanaki

Abstract This chapter investigates the challenges that small wind market would face, in order to exploit its potential possibilities to keep growing, becoming a relevant asset for the energy production sector worldwide. Despite its name, small wind market is actually large and relies on several different possibilities for energy production through different types of devices (from the ‘classic’ horizontal-axis wind turbines and vertical-axis wind turbines to ‘retrofitting innovative designs’ such as the cross-axis wind turbines or building augmented wind turbines). The scope of application of this market is also wide, from small-scale ‘classic’ wind turbines in semi-urban areas to the installation of different designs in the domestic sector (building rooftops and surroundings) or integrated in the building design. The different possibilities for energy production of the small wind market and its scope of application are reviewed through this chapter, so as to gather enough information to assess the maturity of this technology and its match with the energy consumption needs. The objective is to test the possibilities of the small wind market in now and in near future. An open-source wind turbine calculation software, QBlade, was used to describe the relationship between the design of the airfoil and its performance, under the specific conditions that usually small wind market devices are exposed to.

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1 Introduction

Addressing climate change while meeting future world power demand is a challenge, which demands a significant change in human behaviour. The energy sector is one of the key elements of this change, as it has historically been one of the most important contributors to human-made greenhouse gas emissions via the burning of fossil fuels [1]. Thus, the target is to reduce the energy dependency on fossil fuels by focusing on renewable power sources [2]. Several sources of energy fulfil the requirements to serve this purpose. Among them, probably both solar energy and wind energy have the greatest potential, due to their abundance [3]. 'Wind power is now successfully competing with heavily subsidized incumbents across the globe, building new industries, creating hundreds of thousands of jobs and leading the way towards a clean energy future' according to the Global Wind Energy Council (GWEC) Secretary General Steve Sawyer, and claimed for 'the need to get to a zero-emissions power system well before 2050 if we are to meet our climate change and sustainable development goals'. Figure 1 illustrates the evolution of annual installed wind capacity, globally during the period of 2001–2016; whereas Fig. 2 presents the global cumulative installed wind capacity.

In order to reach zero emissions, installed wind capacity should keep the growing trend. Several scientific papers focus on forecasting trends of wind capacity installation in the short term, and a large majority of them agree on the likelihood of keeping the growing trend. For instance, *Market Forecast for 2015–2019* expects the total capacity of wind power will exceed 665 GW by the end of 2019 [4] and GWEC has published in its *Global Wind Report: Annual Market Update* the expected 800 GW by the end of 2021 [5]. Despite the fact that a majority of researchers agree on the growing trend of wind capacity installations for the years to come, it is more difficult to predict how that growth will be continued, as the wind energy market is wide by itself and technology development leads to improved and retrofitting designs which allow higher efficiency, enabling different and new paths to convert the kinetic energy to electric energy. This fact broadens the scope of application of wind energy sector adding small wind market solutions to the current big commercial offshore and onshore wind turbines.

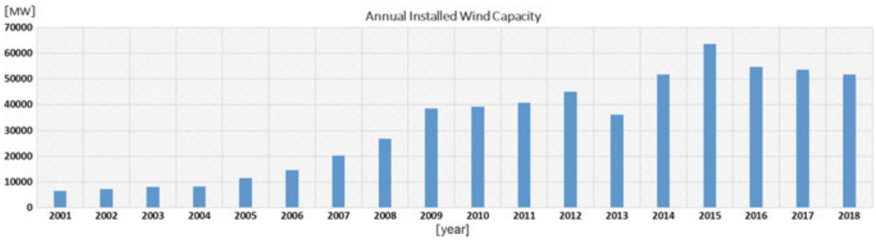


Fig. 1 Global annual installed wind capacity 2001–2018. *Source* Global Wind Energy Council

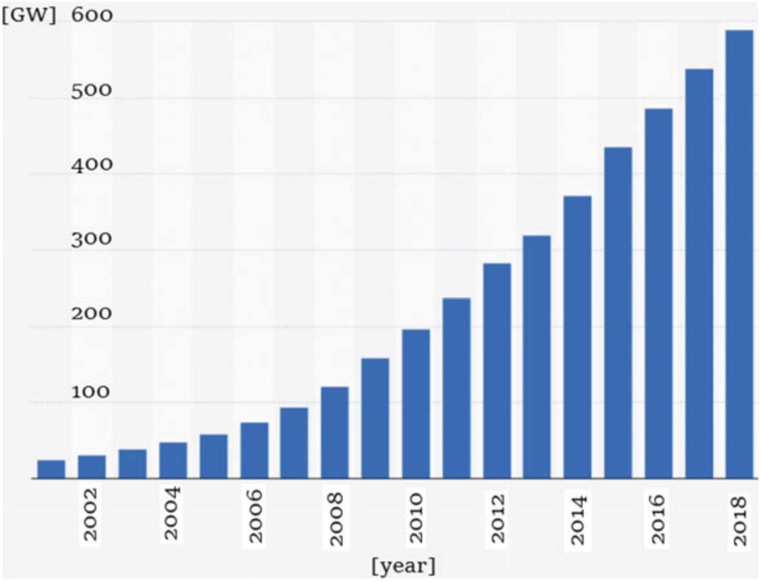


Fig. 2 Global cumulative installed wind capacity 2002–2018. *Source* Global Wind Energy Council

1.1 Current Situation

The USA, in a paper published by its Population Division, states that ‘in 2016, an estimated 54.5% of the world’s population lived in urban settlements. By 2030, urban areas are projected to house 60% of people globally and one in every three people will live in cities with at least half a million inhabitants’ [6].

Power generation relying on wind energy has been considered for many years as not promising in urban and semi-urban areas, due to ‘insufficient wind’ conditions—the existing turbulence in the shade of surrounding obstacles and insufficient wind speeds—and several aspects related with the unlikely match between urban life and wind turbines operation. However, the global small wind market is expected to grow 20.2% by 2022 [7], and several scientific articles recently published are pointing in the direction of overcoming the challenges linked to urban and semi-urban wind conditions through improved and innovative designs of wind turbines [8].

Small wind world market is growing at a slower pace. Following a recovery during 2014, the world market for small wind has overcome the small growth of 2015 in terms of units and significant growth in terms of installations. The major markets, China, USA and UK, suffered a decrease in a number of units installed per year. A new giant in the small wind sector, the Italian market, has ‘saved the day’ (practically saved the year) for many in the industry. As of the end of 2015, a cumulative total of at least 990,000 small wind turbines were installed worldwide. This is an increase of 5% (8% in 2014 and 7% in 2013) compared to the previous year, when 944,000 units were registered. China is leading the market in terms of installed units—43,000 units were added in 2015. Around 20,000 less than in 2014, reaching 732,000 units were installed by the end of 2015. The Chinese market now represents almost 74% of the world market in terms of total installed units and 93% of the new installations in 2015. The small wind industry in the USA saw a similar number of new installations than in the previous year. 1695 units were sold during 2015, 95 more than in 2014. USA is the second-largest market with total cumulative units installed of 160,995, clearly behind China, but well ahead of a number of medium-sized small wind markets. Italy has become the most important medium wind market worldwide, especially for the over 50 kW range as 115 new SWTs were installed during 2015. Germany, Canada, Japan and Argentina are all medium-sized markets with a total number of small wind turbines between 7000 and 14,500 units [5, 8].

As there is a limit to the number of adequate sites for wind turbines—the so-called good wind sites —, a part of the strategy to keep the development of wind energy sector on a high level is to reach wind turbine designs efficient enough to overcome 'bad wind' conditions. As the 'good wind' sites enable the opportunity to generate enormous amounts of electric and make profitable the investment in large-scale wind turbines, small wind market seems to be doomed to deal with 'bad wind' conditions. However, this does not necessarily mean that they have no possibilities.

A literature review was carried out in this work, in order to throw light on the possibilities of small-scale wind turbines to enable the expected growth of small wind market, overcoming the 'bad wind' conditions. QBlade tool was used to refer to 'bad wind' conditions analysing the performance of different blade designs for small-scale wind turbines. QBlade is an open-source wind turbine calculation software distributed under the General Public License (GPL), which, among other possibilities, shows the fundamental relationships of design concepts with turbine performances.

2 Research Methodology

Research has been carried out following two different approaches. In the first place, literature review has been performed, in order to gather information about the wind energy sector as well as about the small wind market.

As wind energy industry has evolved rapidly within the last few decades, literature review has been carried out through several recently written scientific articles, to ensure reliability of the data avoiding out-dated researches and opinions.

3 Different Types of Turbines

3.1 Wind Turbines

Wind turbines are those devices, which allow the kinetic energy present in the wind to be converted into mechanical energy and ultimately into electrical power. The origins of wind turbines date back to around 200 B.C. somewhere in Persian Empire territory, but the first recorded functional wind mills date back to seventh century A.C. in the Middle East [3]. Many years later, the first electricity-generating wind turbine was used in 1887 in Scotland [9]. In North American farms, wind mills have been effectively utilized for several uses, from the historical applications such as pumping water or grinding grain, to producing electricity, since 1930's [3]. A couple of decades later, in 1951, a wind turbine was effectively connected to a utility grid for the first time in UK [10].

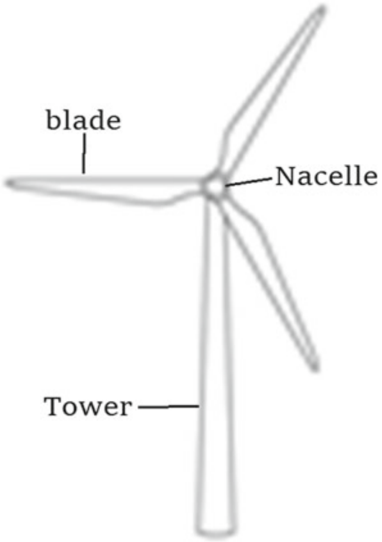
There are different types of wind turbines and they can be classified according different criteria. For instance, in regards to location two types of turbines can be distinguished: onshore and off shore wind turbines. One of the most widespread classification of wind turbines is based on its axis of rotation, as described below:

- **Vertical-Axis Wind Turbine (VAWT)**: Vertical-axis wind turbines are those whose rotor is in vertical direction. There are different types of VAWT based on the type of rotor. The most relevant are listed here below:
  - Darrieus Rotor: Based on lift forces.
  - Savonius Rotor: Based on drag forces.
  - H–Darrieus Rotor: Based on lift forces.
- **Horizontal-Axis Wind Turbine (HAWT)**: Horizontal-axis wind turbines are those whose rotor is in horizontal direction (Fig. 3). These are the most widespread type of turbine within the wind industry. In this type of turbine, the rotor need to be aligned in the wind direction, thus they have a tail (passive yawing) or a yaw motor (active yawing). This type of turbines works based on lift forces.

As this study focuses on small wind market, the most relevant classification is made according to the size of the wind turbine, i.e. the rotor diameter. In order to meet their growing energy needs, large-scale wind farms—both on shore and offshore—are being installed in several countries all around the world. Despite the fact that large-scale wind farms are one of the cheapest, safest and most effective ways to generate electricity without greenhouse gas emissions, and hence one of the greatest solutions to fight climate change, the effect of large wind farms on weather conditions it is a matter of concern for several wind energy experts.

Several researchers have studied the impact of large-scale wind farms on the weather conditions. Wang et al. [11] used a three-dimensional climate model to perform simulations, in order to study future large-scale wind farm installation potential weather impact over land and ocean. The simulations were performed globally for an extensive period (60 years), as fluctuations in temperature do not show the gradual

Fig. 3 Horizontal-axis wind turbine



effect immediately. They conclude that the installation of wind turbines to achieve 10–15% of global power needs might involve surface warming (on land) and increasing the temperature by 1 °C. Similar conclusions have been extracted for the raise in temperature by 1 °C over the oceans, but further research should be carried out for its validation.

Similarly, Fiedler et al. [12] used a regional climate model to simulate 62 warm seasons. Based on their observations, it emerged that the precipitation rate was increased by 1%. It was also observed that the larger the size of the wind farm, the greater the rate of precipitation was registered [13, 14]. Tummala et al. [3] interpreted that building large-scale wind farms might generate serious weather changes, so the need to harness wind energy without generating negative impact in the environment arises. An alternative for wind energy exploitation, less impactful on weather conditions, is pointed by Tummala et al. [3] by decentralizing the grid system, which necessarily leads to small-scale wind turbines.

Apart from the qualitative approach of this literature review, there are two mathematical expressions that should been mentioned, to identify the key elements of power generation via wind turbines [15].

$$P_{\text{in}} = 1/2 \rho A v^3 \tag{1}$$

Equation 1 indicates that the power present in the wind is function of air density (ρ), the blade swept area (A) and the cube of the wind velocity (v). This means that for a determined location (specific air density and wind velocity), the amount of energy contained in the wind crossing the turbine depends on the blade swept area, i.e. depends on the rotor diameter.

$$P_{\text{out}} = P_{\text{in}} \times C_{\text{p}} \tag{2}$$

Equation 2 shows the relationship between the power in the wind and the actual electrical power produced, by the power coefficient (C_{p}) which is an indicator of turbine's efficiency. Besides the Betz' limit, mechanical and electrical losses are added to the process of electricity generation. Thus, even though C_{p} varies for different types of wind turbines, a majority of modern large wind turbines achieve values between 40 and 50%, while urban wind turbines usually reach much lower values for C_{p} due to restrictions implemented during its design process in order to make them suitable for urban environment (noise generation, visual impact, safety issues, etc.). The C_{p} varies with the tip-speed ratio (λ)—as indicated in Eq. 3.

$$\text{TSR} = \lambda = \Omega/v = \omega r/v \tag{3}$$

Equation 3, suggests that tip-speed ratio (TSR) is the relation between the tip speed (Ω) and the wind speed (v).

The tip speed is calculated by the multiplication of the rotational speed (rad/s) and the radius of the rotor (m).

3.2 Small Wind

There are various definitions of small-scale or small-sized wind turbines. The International Electrotechnical Commission (IEC) is considered as the most relevant international standardisation organization, defines small wind turbines in standard IEC 61400-2 as '*those whose blade swept area is less than 200 m*^{2}*, equating to a rated power of approximately 50 kW generating at a voltage below 1000 V AC or 1500 V DC*' [16]. It is worth mentioning that this publication dates back to 2013 and, besides this standard, several definitions of small wind have been set-up by different countries. The discrepancy of the upper capacity limit of small wind ranges between 15 and 100 kW.

Nowadays, the most commonly accepted upper limit of small wind capacity units is, in practise, 100 kW [17]. The World Wind Energy Association (WWEA), in its 2017 Small Wind World Report, claims to agree a standard definition of small wind in order to reach a healthier small wind market share. In this study, 100 kW is temporarily chosen as the reference point for the upper limit capacity for small-scale wind turbines. However, the definition requires a wider agreement until a harmonised and accurate global definition is achieved. Through this literature review, a high difficulty to clearly represent the current state of small wind sector has been observed not only because of the lack of a global agreement on small wind definition, but also because of data inequality. The widespread household purpose of small wind turbines affects information accuracy, due to lack of available information related with off-grid installations. Despite the need for a global agreement on small wind definition standardization and shortage of data in some cases, there are several researchers and organizations that have been collecting and analysing relative information.

As already mentioned, the leading market of small wind sector with a wide difference over the rest is China, followed by USA and UK. In regards to the size of the units installed, enormous contrast is noticed among different countries (from the 0.56 kW of the average Chinese turbine to the 5.1 kW of UK or 37.1 of Italy). However, an increasing trend on the average size of small wind turbines can be observed globally: 0.66 kW in 2010, 0.77 kW in 2011, 0.84 in 2012, 0.85 in 2013, 0.87 in 2014 and 0.96 kW in 2015 [17].

As far as the technology is concerned, the *horizontal-axis wind turbine* technology has dominated to the market for over 30 years. The Wind World Energy Association has performed a study within 327 small wind manufacturers by the end of 2011. The WWEA observed that 74% of them invested in horizontal-axis wind turbine technology, while only 18% leaned towards the vertical-axis wind turbine technology and 6% of the manufactures decided to develop both options. Thus, it is obvious that the percentage of market share for small VAWT remains significantly smaller than small HAWT.

However, VAWT technology success is directly linked to urban wind energy implementation, as fluctuation of wind direction is one of the major challenges for wind power in cities, and VAWT is less dependent on wind direction than HAWT. In spite of this advantage, the average rated capacity of VAWT is estimated to be 7.4 kW with a median rated capacity of merely 2.5 kW, which are significantly lower values than HAWT [17].

The trend of global small wind market over the last two years shows a slow growth. However, the expectations for an increasing trend are high. The World Wind Energy Association have anticipated a minimum growth rate of 12% for the next year and the industry is expected to achieve approximately a cumulative installed capacity of about 1.9 GW by 2020 [17].

3.3 Urban Wind Turbines

Within the following lines challenges and opportunities of small wind market will be reviewed the years to come, through the analysis of the different main paths the researcher community is pointing out. From different locations for wind turbines such as on top of buildings or integrated into their structure to stand-alone small-scale wind turbines based on the ground, on the surroundings of buildings. From the already mentioned 'classic' designs (Horizontal-axis wind turbine and vertical-axis wind turbine) to innovative designs such as the cross-axis wind turbine (CAWT) and the building augmented wind turbine (BAWT).

In order to define accurately the concept of wind turbines in urban areas, it is worth mentioning again that within this study, 100 kW has been temporarily chosen as the reference point for the upper limit capacity for small wind turbines. However, a distinction should be made between small wind turbines and urban wind turbines.

The latter, are those devices specifically designed for urban environment usage. This implies that the urban wind turbines have been designed for the wind conditions in the built environment and are capable, theoretically, to perform efficiently overcoming wind gusts and turbulences, and noise pollution as a result of its performance has been taken into consideration. The shape and size of the turbine have been adapted to reduce the visual contrast with the surroundings. The upper limit for the installed capacity of these urban wind turbines is commonly around 20 kW [18]. However, this is just an orientation for the maximum installed capacity for urban wind turbines. The location of the turbine plays an important role regarding this upper limit, as less density in the urban environment usually enable greater sizes of wind turbines and hence higher installed capacity.

Despite the fact that four main designs are mentioned in the following lines as examples of possible urban wind turbine designs (HAWT, VAWT, BAWT and CAWT), it is relevant mentioning that the range of designs available is significantly varied due to the importance of being adjusted with the specific needs taking into consideration the surroundings and wind conditions. Thus, even for those ‘classic’ designs such as HAWT, ‘new retrofitting’ designs are considered. In spite of the mentioned in previous sections regarding the predominance of horizontal-axis technology over the vertical-axis wind turbines in small wind turbines, the situation is different regarding urban wind turbines. For this specific case of small wind turbines, the distribution is relatively well balanced with 65% HAWT and 35% VAWT [19]. Actually, a more balanced distribution can be expected in the short term, or even VAWT overtake HAWT might be a reality in the near term urban wind market, as vertical-axis wind turbines, in respect to horizontal-axis technology, might be considered a better option for urban wind exploitation due to smaller size, lower turbulence sensitivity, lower noise production and the lacking of yaw control need [20].

Besides the widespread HAWT and VAWT designs, building augmented wind turbines (BAWT) can be considered as great potential option [21]. However, the implementation of this type of devices has a significant handicap compared to the others, as it is not feasible to implement this technology in existing buildings. BAWT should be designed before the construction of the building and in harmony with its architecture. Despite the fact that these are not widespread, there are several successful examples that take this technology into consideration, such as the Bahrain World Trade Centre, consisting of two towers which obtain around 35% of its energy requirements through wind turbines [22].

Innovative retrofitting designs such as the cross-axis wind turbine (CAWT) should also be taken into consideration [23]. As either HAWT or VAWT had to be chosen forcing to lose the benefits of the non-chosen option, CAWT technology arises a dual option as it performs with both horizontal and vertical wind directions (Fig. 4). This technology is focused on versatility, hence is designed to perform as building-integrated device or as a stand-alone turbine [23].

The turbine design and the local weather conditions are the most significant drivers determining the energy production. The energy present in the wind increases with the cube of the wind speed (see Eq. 1, in wind turbines section), hence slight variations in the wind conditions may have notable impact on the electrical power yield.

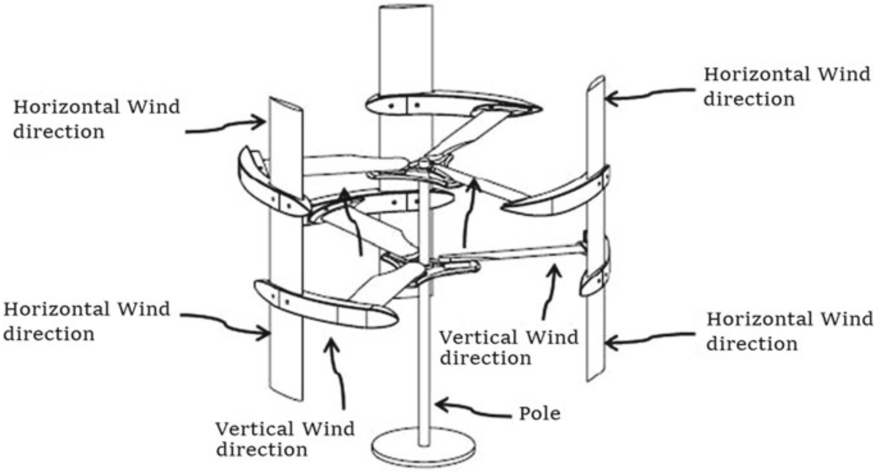


Fig. 4 CAWT operation under bi-directional flow. *Source* [23]

The minimum recommended average wind speed varies depending on the source of information. From the 5.5 m/s recommended by Cace et al. [18] to those researchers focused on the so-called micro wind turbines with low power generation but with low requirements to perform either. For instance, Panda and Tan used a 4-bladed horizontal-axis wind turbine with a 6 cm diameter rotor to generate 7.86 mW at a 3.62 m/s velocity with a 9.5% efficiency [24].

It can be stated that wind 'choses' the path based on the lowest resistance. Thus, wind 'goes around' obstacles such as hills or buildings [22]. The presence of obstacles in urban environment is mentioned as one of the most relevant challenges for urban wind turbines implementation. It has been described that obstacles create turbulences and enhance the difficulty to predict wind flow patterns in a specific area. However, an opportunity might be hidden behind this challenge. This is due to the fact that wind speed and air density reach higher values when 'passing' along the edges of obstacles [22].

When the wind flow 'finds' an obstacle changes its behaviour depending on the shape of the obstacle. The area below the boundary layer, the so-called separation cavity, has lower pressure than the undisturbed wind. There is no wind in that area, rather turbulence. In the area right above the boundary layer pressure is higher, then air density and wind velocity are higher either. This phenomenon might be seen as an opportunity to boost wind turbines performance [23], as the wind speed immediately above the boundary layer increased by 20–40%, which means a 2.2–2.7 times higher energy present in the wind that in the undisturbed flow [22]. Figure 5 shows a two-dimensional representation of the wind flow over a building.

The wind profile depends on the roughness of areas, which increases with obstacles. 'With air flow perpendicular to the wind-ward wall, the height of the roof cavity above the ground may be approximately 2.0 to 1.3 times the building or the obstacle

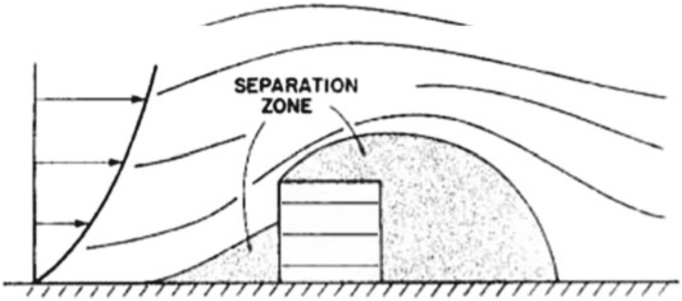


Fig. 5 Wind flow behaviour over a building-shape obstacle. *Source* Peterka et al. [25]

height (Fig. 6). Such a ratio must be used with caution, however, the cavity height can be considered independent of building height within certain limits' [26].

There are several ways of sitting within complex urban terrain. However, since every city's ground-cover is different, the various spaces between different land covers (roughness areas) are those that wind turbines should be installed. The spaces should be mostly taken into consideration are those which the wind conditions right above the boundary layer can be improved. The length of the cavity is considered to take values around three times the obstacle height [26]. The idea is just creating a comparison of the cavity size with the obstacle size, which will extend over the whole roof surface for many buildings. For very long obstacles (in the wind direction), the wind flow will attach to the roof at some point. It is worth mentioning that size and shape of the wind flow contour and cavities keep relatively unaffected from the wind speed. However, the variation of pressure is clearly related to wind speed [26].

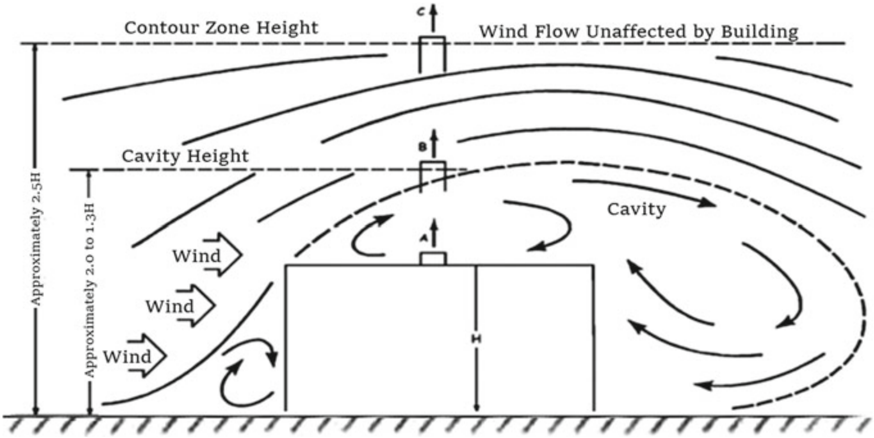


Fig. 6 Wind flow representation: cavity and contour zone representation. *Source* Clarke [26]

4 Centralized Versus Decentralized Generation

There are several different names to the same concept of decentralized generation; distributed generation, on-site power and cogeneration, among others. There are several existing definitions, but one has been wider accepted above the rest; Ackermann et al. [27] described distributed generation as 'an electric power source connected directly to the distribution network or on the customer site of the meter, without being part of a centralized generation system'.

Currently, electricity is primarily produced at large centralized generation stations and then shipped through the transmission and distribution grids to the end-users. However, the search for power efficiency and the need for greenhouse gas emission decrease has led to taking into consideration alternatives to the current generation system and improve its overall performance. In this scenario, one of the best alternatives to complement or even substitute the existing system is decentralization of the generation paradigm by producing electricity next to the end consumers [28].

Benefits of distributed generation have been pointed and numerous articles. The major advantages are listed below:

- Exploitation of resources in areas not suitable for large centralized generation stations. Hence, the possibility of bringing efficiency and effectiveness to the overall power generation system arises [28].
- Significant decrease of losses associated with power transmission and distribution [29].
- Economical viability [29].
- Lower vulnerability in case of a natural disaster or a terrorist attack [29].

Despite these benefits, there are several challenges to overcome such as:

- Technical issues. In case of on-site power implementation, there is need for reinforcement of transmission and distribution to increase its capacity. Control and protection mechanisms should be incorporated [28].
- Regulatory barriers. Significant effort in regarding regulation should be carried out [28].
- Adding difficulties in maintenance and operations due to an enormous number of stations [29].
- Environmental issues. Distributed generation does not mean clean energy. If energy generation is allowed as a particular activity, control over health, safety and environmental protection would be more difficult to achieve [28].

Overall, there is a need for a change regarding energy generation system. However, any global change must be preceded by significant changes in regulations and logistics. Decentralized generation arises as an opportunity within the scope of this change. Probably not as an alternative. Centralized and decentralized generation systems are likely to co-exist in the long run, turning the energy generation into a dual system, combining centralized and decentralized stations.

5 Case Study: Urban Wind Resource Assessment Using Computational Fluid Dynamics (CFD)

5.1 Computational Fluid Dynamics (CFD)

One of the main constraints in understanding wind flows in urban areas is the lack of adequate field measurements, which could help characterize urban wind and understand its effect on turbines [30]. It has been suggested, that key considerations such as wind resource assessment, turbine siting, turbine specification, energy production and safety and reliability of the turbines should be incorporated during the technical evaluations of urban SWT. The on-site atmospheric measurement was suggested as the best option for the quantification of wind resource. Nonetheless, accessing the wind resource in the built environment is a challenge.

For medium- to large-scale wind projects such as wind farms, the local wind resource and its characteristics are studied by producing detailed, high resolution and accurate wind maps, as well as by identifying uncertainties and turbulence related to the wind resource [31]. In addition, the measurement of wind data is relatively difficult for complex terrains due to the stochastic nature of wind, which does not follow any known statistical distribution and demands a high-temporal resolution of logged data to be able to capture the significant additional energy present in the turbulent wind resource in urban locations [32]. Limited budget and lack of site-specific measurements increase the level of uncertainty during the performance assessment of the SWTs making further analysis of the interactions of the WTs with the local loads and distribution network even more difficult [31]. Such constraints are addressed by employing numerical simulation of wind flow and turbulence with the help of different computational fluid dynamics (CFD) tools.

A significant part of CFD models uses large eddy simulations (LES) to solve the flow field [5]. Although LES models have a high level of fidelity when simulating turbulent flows, their use is still limited by the extensive computational resources they require to solve the flow equations. The vast majority of CFD models are instead based on Reynolds-averaged Navier-Stokes (RANS) equations to solve the flow field. The use of this time-averaging procedure reduces the computational cost of the simulations, but creates the need for additional turbulence models to ‘close’ the system of equations. A CFD simulation is based in three basic components such as the computational domain, meshing and the boundary conditions (for inlet, outlet and walls). Currently, the usage of CFD models to simulate wind behaviour around obstacles such as buildings is widely extended. Task is also very time consuming. The time needed for the application of this model increases with the size of the area the wind flow is been calculated over. In order to obtain valid results, high requirements are needed for the computational tools to generate complex domain’s geometry. Thus, CFD models are not always suitable for simulations around large-sized areas. Nevertheless, several new commercial tools have been developed recently within the CFD industry. A significant number of those tools are particularly focused on urban simulations [33].

5.2 Methodology, System Design and Data Used

QBlade, an open source wind turbine calculation software, was used, in order to design a small wind turbine based on existing airfoils and on the findings of literature review, so as to assess via a CFD approach, its expected power output. QBlade, software is distributed under the General Public License, presents the fundamental relationships of design concepts and turbine performance. It is a one-solution tool for both design and aerodynamical computation of wind turbine blades.

It is noted that despite the benefits of technology used to obtain data, the quality data is limited to that level this software methods provide. In this regard, QBlade guidelines state that has been developed and released without any warranty, distributed for personal use only and not as a professional product.

Data acquisition—based on literature review—has been carried out by gathering knowledge relying purely on ‘white’ sources, due to insufficient resources for collecting knowledge from ‘grey’ sources and to an ethical decision not to collect any information from ‘black’ sources. The first forecasting activity meeting the scope of this study was based on trend extrapolation analysis, which takes the extrapolators point of view [34]. Patterns in the development of technologies used within small wind sector, and other important drivers determined in the literature review, are used to forecast the possibilities for that element. The analysis was based upon both quantitative and qualitative data.

Since future of small wind market development cannot be accurately foreseen for all the factors affecting it, alternate scenarios were proposed and examined through the scenario-axis technique [34, 35]. The different scenarios were based on the most impactful and uncertain key drivers. Multiple scenarios were proposed and analysed.

Among the available airfoil designs, NACA 2415 and NACA 6412 have been selected (Fig. 7). The selection was done based on their match for small wind requirements. Figure 8 illustrates the relationship between wind speed and the expected power outcome for two small wind turbines (2.2 m diameter) based on the mentioned airfoils and optimized to perform under low wind speed conditions. Table 1 summarizes the characteristics of both airfoils.

It is shown that both can achieve 50 W generation with wind speeds below 5 m/s. For winds speeds above 5 m/s NACA 2415 turbine reaches greater production than NACA 6412, the opposite is also true for wind speeds below 5 m/s.

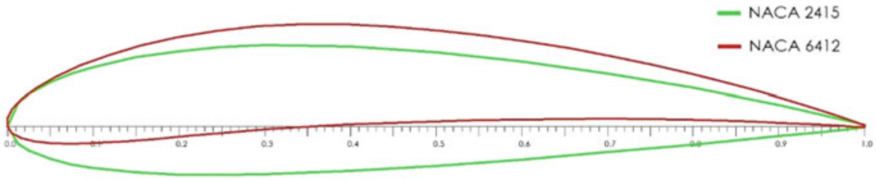


Fig. 7 Airfoils selected for blade design: NACA 2415 and NACA 6412

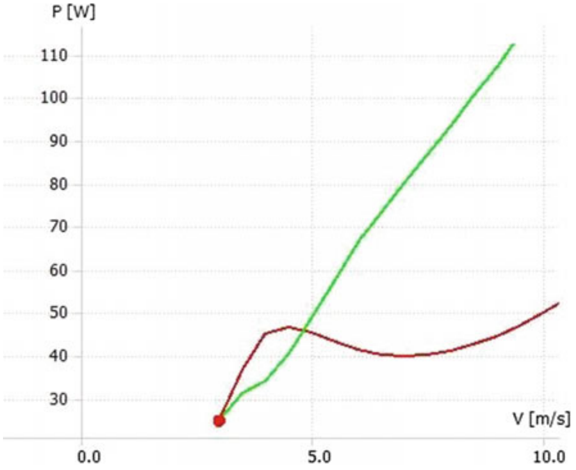


Fig. 8 Power-wind speed graphs for NACA 2415 and NACA 6412

Table 1 Characteristics of airfoil designs

Name	Thickness (%)	At (%)	Camber (%)	At (%)
NACA 2415	15.00	30.00	2.00	40.00
NACA 6412	12.04	29.21	6.00	39.61

5.3 *Results and Discussion*

As mentioned, one of the forecasting tools used was trend extrapolation. Thus, there is a need for gathering data about the recent past and the current state of small wind. This has been done through literature review, which led to the first analysis of this sector summarized below:

- There is need for a globally accepted definition. Discussions about size and upper limit capacity should be carried out in order to reach to some agreement.
- Data quality is still an issue due to lack of off-grid registration in many cases.
- There is a necessity for a big regulatory effort for the small wind sector to widely succeed, as despite the fact that this technology has not reached the optimum level of maturity, regulation, in many countries, remain behind papulation demand in this regard.
- Lack of standards. Thus, all the benefits of standardization are missing.

This front-end analysis works as a first general approach to challenges identification on the short term. However, a analysis follows below:

- There is a low amount of reliable information available on urban wind turbines, which account for a significant percentage of the possibilities for small wind industry. This is due to the fact that most information is given directly by the manufacturer, without a third external actor testing that information.

- There are no norms for quality of small wind turbines. This is true for HAWT, but the issue receives greater attention regarding VAWT, BAWT and of course every innovative design such as CAWT.
- Urban wind turbines are often placed in not suitable locations [18].
- The administrative costs, which in many cases account for 50% of the total investment are high and out of proportion compared with equipment and installation. The administrative costs are sometimes responsible for as much as the half of the total investment [18].

Lack of agreement among researchers about basic topics within small wind such as viability to install wind turbines on the rooftops point in the same direction. The predominance of HAWT over VAWT when a vast majority of researchers' states that vertical-axis technology suits better urban wind conditions argue also for lower level of maturity with respect to large-scale wind, where HAWT seem to be the ideal device to extract the energy present in the wind.

Far from having a negative impact on the expectations for small wind in the short term, low maturity level means the opportunity to still achieve improved designs, regarding safety, noise pollution and overall performance. Gathering data has allowed to implement trend extrapolation, based on the recent historical data and the current state. Hence, growth of small wind market can be expected in the short term, at least at the same level of the previous year. This forecast is aligned with uncountable experts' opinions [3, 7, 8, 17].

The knowledge acquired through the literature review has enabled the identification of the challenges listed above. Overcoming those challenges by maturing small wind until the optimum level would unlock the opportunities of small wind mentioned constantly in the previous sections such as:

- Green electricity generation.
- CO_2 savings.
- Exploitation of wind resources in urban areas, which are not suitable for large wind farms. Thus, higher effectiveness of the overall generation system through an improved exploitation of the resources available.
- Significant decrease of distribution losses associated with the power transmission from the large generation stations to end consumers.
- Stimulation of environment-friendly attitude, as self-producers are commonly more energy efficiency aware.
- Less dependency on energy prices and utility companies.
- Pave the way to a zero emissions power generation system.

Following the methodology described in previous section, the most relevant challenges will be evaluated by assessing its uncertainty and impact (Fig. 9).

It can be observed that there are two challenges with greater uncertainty and impact than the rest. This is due to the others are consequence of the immaturity of the small wind. But, as already forecasted, it can be expected an increasing trend for maturity levels in within the next years. However, regulation is very high in uncertainty and definitely the most impactful challenge, as is playing a double role in the sector:

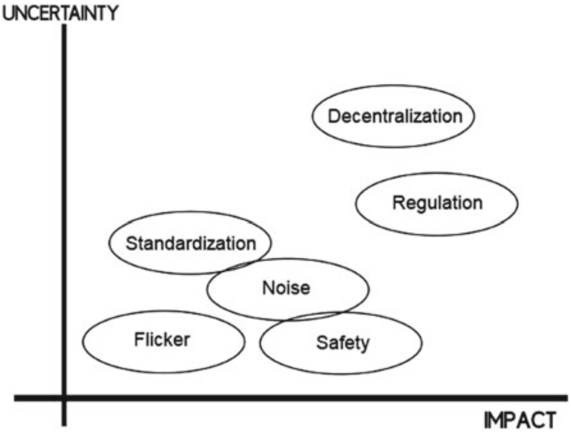


Fig. 9 Uncertainty and impact challenges assessment

- By restrictions.
- By allowance systems.

Decentralization is also a key driver because without enabling decentralization, small wind turbines have no role to play in large-scale wind farms, where large-sized wind turbines are the most suitable option. Identification of the two more relevant key drivers within small wind, the scenario-axis technique can be applied (Fig. 10).

Based on Fig. 10, the following conclusions can be drawn:

- Regulation combined with a centralized generation system would be not favourable at all to small wind market development. Actually, this scenario would mean disappearance of small wind.

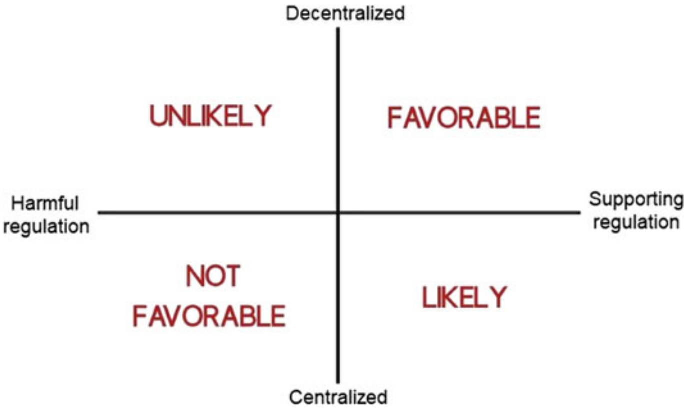


Fig. 10 Scenario-axis technique applied to small wind market

- It does not make sense evolving to a decentralized generation system while implementing ‘harmful’ regulations. Thus, it is unlikely to happen in the short term. By all means, this scenario would not be favourable either.
- As the maturity of small wind is expected to increase, regulation will most probably follow that trend, responding to the market pull based on consumer’s demand. Hence, this scenario is most likely to happen and even though decentralized generation system will not replace the opposite, coexistence of both will enable the forecasted growth of small wind in the short term.
- Supporting regulation combined with a decentralized generation system is less likely to happen on the short term, due to the difficulties associated with a quick change in the generation system. However, this scenario would be the perfect one to boost small wind market.

6 Concluding Remarks

As small wind turbines have nothing to do in large wind farms due to a greater performance of large-scale wind turbines, their scope of application is limited mostly to urban environment or often off-grid applications. Urban environment has very specific conditions regarding wind flow patterns, which could be both a challenge and an opportunity. Despite the fact that obstacles such as buildings can lead to poor performance, if studied properly wind flow behaviour over obstacles can boost the energy production with small wind turbines.

Due to its specific conditions, urban environment requires specific designs to exploit the wind efficiently in the cities. As a consequence of greater maturity of large-sized wind turbines, in recent history, many small wind installations were simple adaptations of large wind technology to ‘bad wind’ conditions. However, small wind technology is still maturing which means that there is still a place for improved designs and a greater understanding of urban conditions and its connected threats and opportunities.

The low maturity level proves that there are still basic assumptions to discuss, and its discussion will lead to a more mature technology. Nevertheless, there are no possible discussions about the existing opportunities associated with small wind, if the challenges are some day completely overthrown. Besides its maturity elements (noise, safety, flicker and standardization), there are two main key drivers which are (a) regulation, playing a double role by setting up restrictions and guiding the sector with financial aids and (b) decentralization of the energy generation system. Overall, based on: (i) knowledge gathered through literature review relying on white sources, (ii) trend extrapolation analysis and (iii) scenario-axis forecasting technique small wind is expected to at least maintain its growing trend, or even boost it. Despite of the unlikely complete decentralization of the power generation system, meeting the population energy needs while fulfilling the reduction of greenhouse gas emissions seems to lead to a balanced system, where centralized generation might be helped with small decentralized stations next to consumers, and in specific regarding wind energy, large-scale wind farms might be supported with extra power generation relying on small wind turbines operating in the urban environment.

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Supercapacitor for Future Energy Storage

Giancarlo Abbate, Eugenio Saraceno and Achille Damasco

Abstract The research and application of renewable energy sources and electromobility implies a subordinate but not negligible problem, the energy storage. The most important sources of clean energy, related to solar and wind power plants, are in fact intermittent and therefore require their management in energy collection, even more in the long term. Additionally, electromobility and several other applications may need huge peak power. All this kind of problems cannot be solved always by electrochemical batteries. An alternative to them is represented by supercapacitors (SCs), energy storage devices specialized in high power, exhibiting also a very long life cycle. In this chapter, we will illustrate the state of the art of their operation, typologies, applications and all that a wide-ranging interdisciplinary literature offers us about how this type of technology could be used more and more in the near future.

1 Supercapacitors: State of the Art

1.1 Overview

A supercapacitor (SC) is a capacitor in which the capacitance can be of some orders of magnitude bigger than a usual capacitor (1 to thousands of Farad versus μF or mF) thanks to materials with high specific area as electrodes and free ionic charges as counter-electrodes. For these reasons, the usual capacitor is also called "electrostatic capacitor", while the SC is also called "electrochemical capacitor" or "ultracapacitor". In a first approximation, SCs follow the same capacitance law as every capacitor does:

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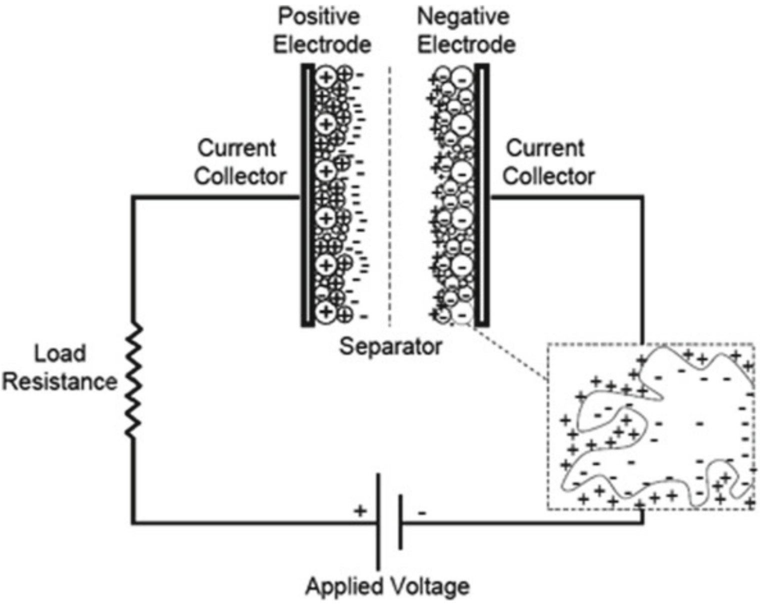

Fig. 1 Scheme of a SC (EDLC) in its simpler configuration in a circuit with only a constant applied voltage and a load resistance [1]

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \tag{1}$$

where the surface area A is given by all the insets of a porous conductive material and d is the distance between the porous electrode and the respective counter-electrode, i.e. the layer of ionic charges, of the order of molecular size (see Fig. 1).

We specify that in Fig. 1 we show a specific kind of SC, the so-called EDLC (electric double-layer capacitor), where the charging process (so, the formation of the layers) is completely electrostatic. A separator (in general, a special sheet of paper) prevents electric contact between opposite electrodes.

Despite their name, SCs are used for their outstanding specific power (W/kg) instead of their specific energy (Wh/kg), i.e. mainly as fast energy delivers. In fact, the energy stored in a SC follows the law (2) and the maximum power is given by (3)

$$E = \frac{1}{2} QV = \frac{1}{2} CV^2 \tag{2}$$

$$P_{\mathrm{MAX}} = \frac{V^2}{4 \cdot \mathrm{ESR}} \tag{3}$$

where the ESR is the equivalent series resistance, an internal resistance that includes all the resistance sources of a SC. To make an example, a commercial SC cell (a can-like SC weighting about 600 g) of 3400 F can have an ESR of only 0.28 mΩ, working with a maximum voltage of 2.85 V [2]. So, it can store 3.84 Wh and can supply this energy at a power up to 7250 W. We can use this energy/power combination, for example, to supply a constant current of about 300 A for 15 s or even a 1000 A peak current for few seconds.

The real power a SC can supply is actually below the theoretical value given by (3), as we will explain later, but in any case it is about 100 times greater than the specific power of a lithium-ion battery.

Unfortunately, at the time of writing, the maximum specific energy (energy per unit mass) of a commercial SC is 7.5 Wh/kg, while a lithium battery can store up to 250 Wh/kg. Advantages and detriments of these two kinds of energy storage device have simple but opposite origins: a battery stores energy through chemical reactions involving mass transfer, thus limiting the specific power, while a SC is, in general, purely electrostatic, involving just charge displacements that can be very fast, thus ensuring higher specific power but less stored energy, the last feature depending on the very high surface-to-weight ratio needed for the electrodes.

Due to these two different operating principles, sometimes batteries are called "volume" energy storage devices, while SC are "surface" ones. Thus, if from one hand it is difficult to imagine nowadays a SC application for long-term storage, on the other hand the most striking and useful feature of SCs is the extremely fast recharge time, on the order of tens of seconds.

An overview of the main performances of current electric energy storage devices is shown in the Ragone plot in Fig. 2 (a Ragone plot is a plot with the energy density on the *x*-axis and the power density on the *y*-axis).

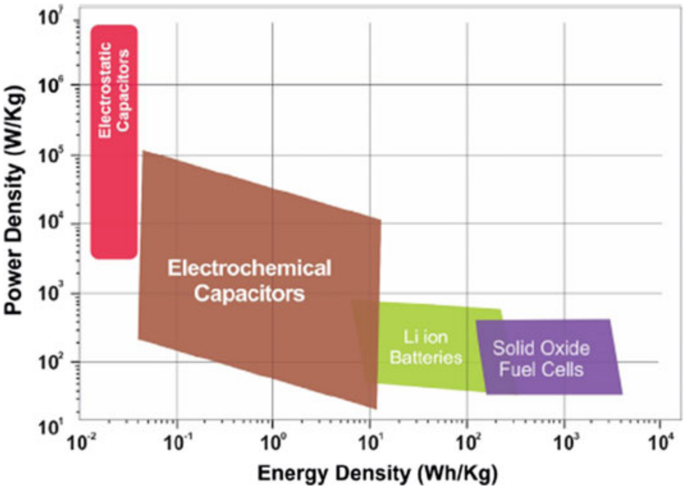

Fig. 2 Ragone plot of the current energy storage devices [3]

As shown in Fig. 2, there is always a trade-off between the energy and the power a single device type can achieve, although researchers are trying to find a device that can stay as high and as on the right as possible in a Ragone plot. This scientific interest can be measured and shown as in Fig. 3.

This exponential trend is not driven only by the search for a possible future substitution of electrochemical batteries with SCs, because quite often the easier and more advantageous solution to a storage problem is to use hybrid systems composed by this kind of devices. In fact, there is a third feature in which the SCs are complementary to the batteries, the life cycle.

Even though a SC can be purely electrostatic, there are always some sources of ageing after a large number of charge and discharge cycles, the most relevant being the degradation of the electrode material and the electrolyte. However, from a quantitative point of view, the life cycle of a SC is outstanding, easily reaching the remarkable value capacitance of about 1,000,000 cycles in a commercial SC (by definition, the life cycle is the number of cycle of charge/discharge before the capacitance becomes the 80% of the rated capacitance and the ESR doubles its initial value). This performance is about one thousand times bigger than the batteries one so that at least in principle a SC can last more than its application. Of course, a SC life depends on the working current and this kind of devices are charged more often than a battery exactly because they can be recharged in few seconds or minutes, but however we can say they can last from 10 to 30 years.

To complete the overview, we can mention two other features.

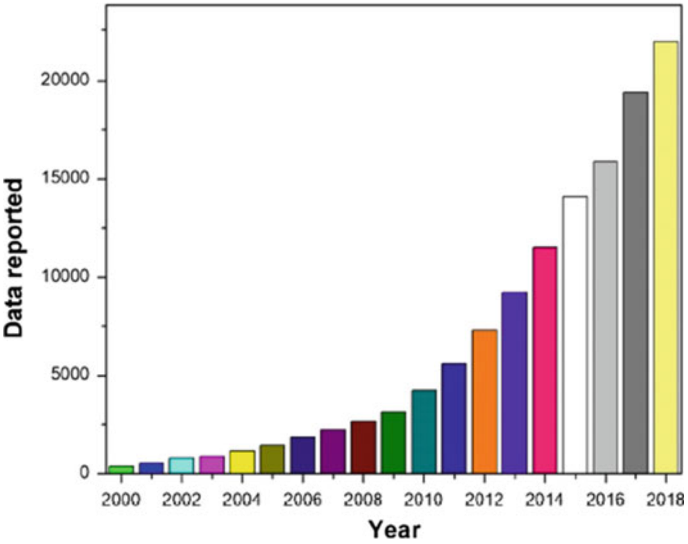

Fig. 3 Number of publications including articles, books and other authentic open literature (2000–2018 (predicted)) from a search using supercapacitor as a keyword in Google Scholar

A SC can withstand a deep discharge (a discharge of all the stored energy) unlike an electrochemical battery, so it has more efficient energy storage. Finally, a standard commercial SC can work in a wide temperature range (−40 to +60 °C) that can be largely extended for specialty applications.

Environmental aspects are more complex to deal with and still need research efforts for the following reason. The SC electrode materials, aluminium and carbon, are abundant and safe and do not rise any disposal issues like battery materials do. Moreover, as we said before, SC substitution is a rare event due to its long life cycle, so we should consider reusing it after the application end-of-life, rather than recycling its materials. Unfortunately, the most common solvent used for the electrolyte, namely acetonitrile, is toxic and flammable, so research activity is looking for alternative solvents, also for this reason.

Nowadays, SCs represent just a niche market within the whole electric energy storage panorama, with a small number of manufacturing companies, mainly in USA, China, Japan and few in EU (Germany, Estonia). The growing interest for specific power applications, the scientific research and technological advances will probably involve a spreading of these devices. It is worth noting that in 2016 the SC global revenues reached 600 M$ that corresponded to about 1% of the total electric energy storage market, while in 2018 the SC market topped 1 G$. Major consulting companies foresee a large growth rate still for next years and estimate 2 G$ total SC market revenues in 2022; this is the expectation based on the present SC/EDLC technology, with the usual small periodic improvements. However, the scientific results from one side and the introduction of SC technologies different from the standard EDLC may push the performances and consequently the market much quicker than expected. For instance, hybrid capacitors are somehow a middle way between ELDCs and batteries, or a combination of both technologies in a single device that can exhibit intermediate performances and thus could reach different or larger market niches. We will describe different possible types of SCs in the next sections.

An overview of the present SC applications is given in Sect. 2, with a particular focus on those dealing with renewable energy sources and environmental issues; then, some recent scientific results are described in Sect. 3, and a view on the future, as a conclusion.

1.2 The Supercapacitor Family

In the following picture (Fig. 4), we show a scheme of the SC hierarchy according to the two main charging mechanisms: electrostatic movement of charges (EDLC), redox reactions (pseudo-capacitor), with all the hybrid combinations of these two ways.

We will give a special attention to the activated carbon-based EDLCs, because they are the most common commercial SCs, while the other types mainly remain in the scientific research area (see Sect. 3).

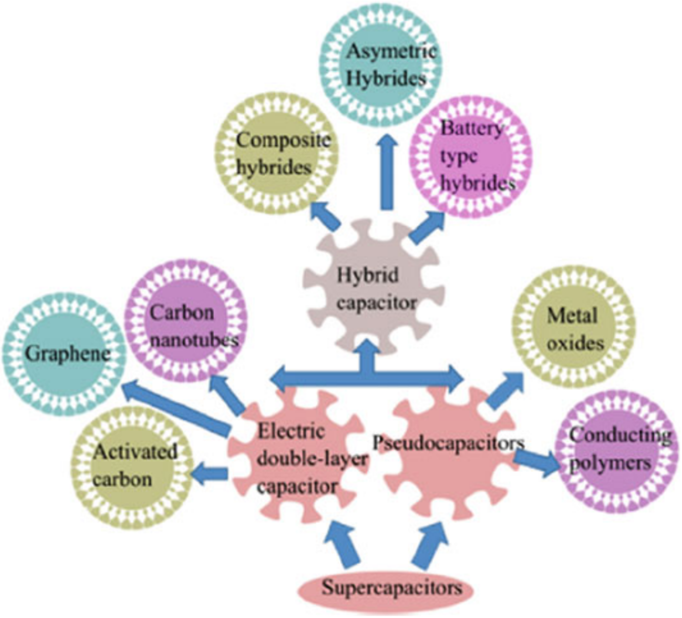

Fig. 4 SC hierarchy with three main categories in the centre and their subtypes according to the possible materials [4]

1.2.1 Electric Double-Layer Capacitor

An EDLC is made of two conductive surfaces, the current collectors, usually in aluminium, coated with a porous material, in general a kind of carbon called “activated carbon”, forming the electrodes. The latter are electrically separated by a “separator”, a sheet of paper, and filled with an electrolyte. During the charging phase, electrons and holes move from the collectors to the carbon electrodes, while the ions pass through the separator and the solvent to go insides the inlets of the carbon (see Fig. 1).

The term “double” in the acronym EDLC refers to the formation of two Helmholtz double layers, one with negative ions next to the positive solid electrode and the other with positive ions next to the negative electrode so that an EDLC is actually made of two capacitors connected in series, in each of which the separation of charge (d) is less than 1 nm. Thus, the equivalent capacitance of the SC cell is one half of the single double-layer capacitor. Now, let us enter in some detail.

The capacitance of an EDLC depends “in a first approximation” on the separation distance d and the specific area (m^2/g) of the carbon material. However, the effective area to put in the (1) is the accessible area for the ions of the electrolyte (this process is called adsorption). In other words, it is very important that the pore areas and for that often the pores of an electrode material are divided in three groups: micro-pores (<2 nm), mesopores (2–5 nm) and macropores (>5 nm). Choosing the right pore size

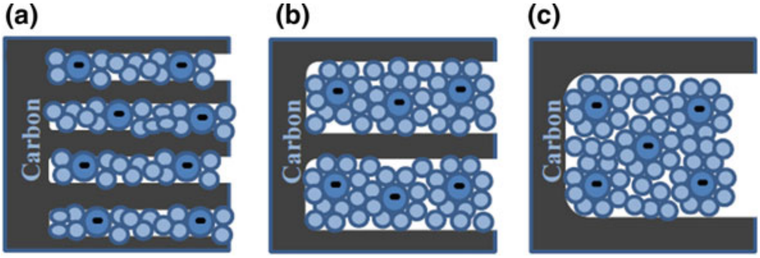

Fig. 5 Scheme of the adsorption of ions in carbon micro-pores (**a**), mesopores (**b**) and macropores (**c**) for an electrolytic solution [5]

for an activated carbon electrode is not an easy task. The ideal, most effective size would be slightly larger than the diameter of the dissolved ions in the electrolyte so that such ions can enter in the pores losing the solvation sphere made by the solvent molecules. In this way, the available surface is used as effectively as possible. In general, wider pores can host more easily an ion, but they exhibit a lower specific area and vice versa, as we can understand viewing Fig. 5. In practice, the situation is quite different from the simplified one depicted in Fig. 5, and one should take into account the pore size distribution in the actual materials used. Thus, the optimal choice of the material can be made only after experimental tests on the specific capacity (F/g) that can be obtained.

In average, the specific area of an activated carbon is between 1000 and 1600 m^2/g, while the specific capacity is in a range of 10–100 F/g, where the minimum is the present value of commercial SCs, while higher values belong to the scientific literature (see Sect. 3). The great advantage of activated carbon is that the starting material is very cheap, e.g. coconut shells which are easily carbonized and then “activated” (i.e. made porous) through thermal or chemical methods.

It is also known and commercially exploited a variant of the EDLC called AEDLC, where the “A” means “asymmetric”. This device is an EDLC where the positive electrode is made with more carbon, and the respective capacitor has a larger capacitance than the negative one. This is made because some positive ions can sustain, before degradation, a greater voltage than negative ones and the voltage drop distribution across the two capacitors in series is no more symmetric, resulting inversely proportional to the respective capacitance. Eventually, the overall electrochemical stability window (ESW, the maximum voltage that can be applied to a SC) is enlarged and in some laboratory experiments resulted up to 1 V wider. This phenomenon is depicted in Fig. 6, where w_+/w_- is the mass ratio between the two electrodes, which is roughly proportional to the capacitance ratio.

The second main element of an EDLC is the electrolyte. Currently, electrolytes are aqueous or organic solvent-based, even though solid electrolytes attract significant research work.

The most common commercial solvent is the organic acetonitrile, because it can sustain a voltage up to 2.85 V, while water has a maximum working voltage of 1.1 V. In

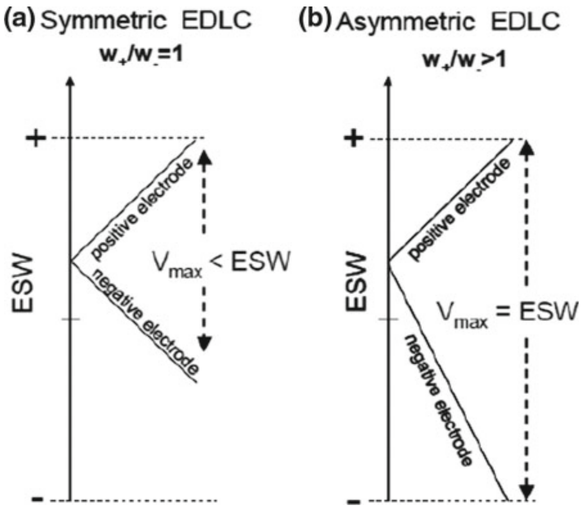

Fig. 6 Diagram of the potential excursion in the symmetric (**a**) and asymmetrical configuration (**b**), where ESW is the electrochemical stability window [6]

fact, after that voltage, the water electrolysis takes place, causing electrolyte breaking. The typical organic salt dissolved in acetonitrile is the tetraethylammonium tetrafluoroborate (TEATFB), but scientific research is active also to find better-performing electrolyte components.

Summarizing, we can state that the theoretical SC capacitance depends on the electrode material and its maximum operating voltage ESW on the electrolyte, but in real cases we must consider also that the actual capacitance depends on the effective adsorption of the ions by the carbon, and the ESR depends mainly on the ions mobility close to and inside the pores. In any case, the ESR of a typical SC is very small, for instance being 0.28 mΩ in the SC cell used in the example worked out at Sect. 1.1, thus giving to SCs their best feature of safely managing very large electric power.

However, the maximum power given by Eq. (3) should be considered as a theoretical limit that can be attained for pulsed or short-duration (few seconds) applications. In most industrial applications, the actual maximum power is also limited by thermal issues. In fact, according to the industrial standard, the maximum allowed constant current for the actual operating time is limited by the requirement to maintain the SC temperature increase within 15 °C. In conclusion, environmental context and thermal features of the electrolyte concur with the SC ESR to determine the real operating power limit. Of course, tropicalized devices designed for special environments or weather situations, and even for extreme conditions, can easily overpass this limit [7]. It is worth noting that the electrolyte affects significantly most of the crucial SC features, including the final cost of the device; thus, it attracts a lot of scientific research work, focused in both directions of increasing performances and reducing cost.

An aqueous electrolyte is an interesting and increasingly tested alternative to organic ones. It contains water, of course, and sulphuric acid or potassium hydroxide, both very common and cheap components. Moreover water is the most ecological and non-toxic solvent. Furthermore, aqueous electrolytes are more conductive than organic ones, thus allowing higher specific power. However, for the usual trade-off power versus energy of the electric energy storage sector, to maintain the same energy performance the specific capacity of a water-based SC should be much greater than that of an organic one (by a factor between 6 and 8). And this is not an easy task. The need for a greater capacitance comes from the smaller voltage that an aqueous electrolyte can sustain before water molecules being damaged. A comparison between typical organic- and aqueous-based electrolytes is shown in the Ragone plot of Fig. 7.

Two SCs with the same electrode, then with the same pore size, can have different capacitances when filled with different electrolytes, because ions may have different sizes and can fit into the pores more or less effectively. In general, ions in aqueous solution are smaller and can better fit into the pores, resulting in a greater capacitance, so partially compensating the decrease in energy given by the reduced working voltage.

The working temperature range is another relevant parameter for real SC applications: the water-based SC range is between 0 and 100 °C and for acetonitrile is between −40 and 80 °C (theoretical) or −40 and 65 °C (operational).

If a special application needs SCs tolerating higher temperatures, it is possible to use a special solvent, like propylene carbonate (PC), an organic solvent with a lower working voltage (2.5 V) but a higher boiling point (242 °C) than acetonitrile. The same salt (TEATFB) can be dissolved equally well in both solvents.

An issue of the organic solvents that requires special care, in particular in industrial manufacturing, is their hygroscopic behaviour: they tend to absorb moisture from

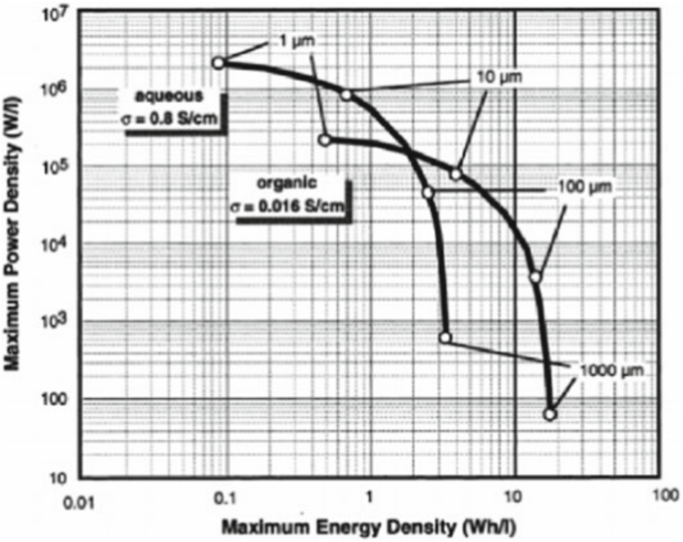

Fig. 7 Comparison of Ragone plot for SCs using aqueous and organic solvent for the electrolyte [8]

the air, which therefore becomes an aqueous impurity. This water causes undesired chemical reactions during the charge of a SC, once the voltage goes above 1.1 V. This problem is dealt with proper insulation systems in research laboratories, for instance a glove box or a dry room, and with controlled sections of the production line in industrial manufacturing plants. Of course, aqueous electrolytes are free from this problem.

Beyond electrodes, electrolyte and electric current collectors, the two other relevant components of a SC are the separator and the binder.

The separator sheet between the two electrodes has the scope to avoid contact between them, while allowing ions crossing. The last feature permits that all the ions in the solution, and not only those close to the respective electrode, take part to the charge/discharge processes, maintaining good SC performances.

Moreover, to prevent unnecessary increase of weight and volume, a good separator should be as thin as possible, with a strong but porous structure.

The most frequent commercial choice is a nonwoven fabric, e.g. like Rayon, frequently used as a filter, that meets quite well all the previous requirements.

Last significant component of a SC is the binder, i.e. the material used to bind the carbon electrode to the current collector (the aluminium foil).

A binder is in general a glue (a polymer), and it has to fulfil at least four prerequisites:

1. It must bind adequately the carbon to the aluminium (especially for a so-long-life-cycle device).
2. It must work with an as-small-as-possible percentage respect to the carbon (to not affect the ESR).
3. It must be compatible with the electrolyte; if possible, it should be relatively conductor (in polymers environment).
4. Preferably, it should be water-based (a glue in which the dispersant is water, for ecological reasons).

Some binders employed in commercial SCs are styrene butadiene rubber (SBR), polytetrafluoroethylene (PTFE), polyvinylidene difluoride (PVdF) and polyacrylic acid (PAA).

As it is clear from the number of scientific publications, there is large room for improvement and optimization of each and every above-described components (electrode, electrolyte, separator and binder) and even for manufacturing process and the final device geometry. We notice that presently the most popular SC geometries are rolled cylindrical and planar (Z-folded or overlapping) carbon-coated aluminium foils; see Fig. 8. The main lines of the scientific research on all these aspects will be presented in Sect. 3.

1.2.2 Pseudo-capacitor

A pseudo-capacitor is a SC whose charging process occurs thank to the reversible redox reactions among the electrolyte and the electrode. This kind of charging is

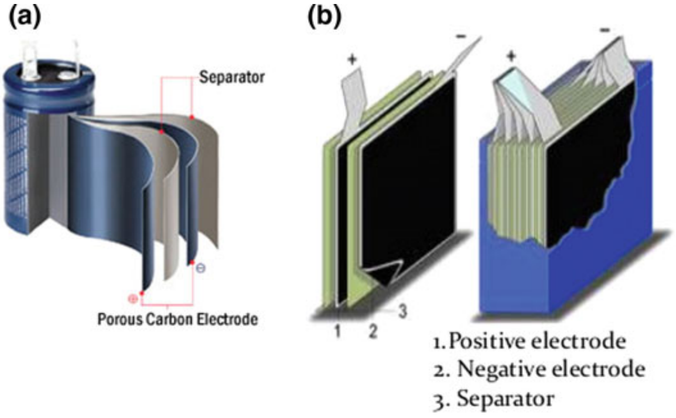

Fig. 8 Main two SCs geometries, **a** cylindrical and **b** planar [9, 10]

called "faradic" (and vice versa the EDLC is called non-faradic). The main purpose of this kind of SC is to achieve more specific energy with a contained loss in power performance.

Many reactions are known involving oxides and sulphides of transition metals, such as RuO_2, IrO_2, TiS_2, or their combinations. These reactions are accompanied by electro-adsorption and intercalation processes.

Let us recall what a redox reaction consists of. An oxidant (suffix -ox) and a reductant agent (red-) react according to the form $ox + ze^- \leftrightarrow red$.

In addition to a redox reaction, an ion adsorption takes place, i.e. accumulation of ions to form a single layer on the electrode substrate. This is a reversible process that results in a faradic charge transfer and gives rise to a pseudo-capacitance, without breaking or forming of chemical bonds.

In Fig. 9, we show a comparison between the operating mechanisms of an EDLC and a pseudo-capacitor. In particular, we can notice the different mechanism of charge separation.

The charge transfer process in a pseudo-capacitor is much faster than that of batteries but slower than the double layer forming in EDLC; thus, its specific power is less than the EDLC one but still much greater than that of batteries.

On the other side, the specific energy of the pseudo-capacitors is less than the battery one, but much greater than that of the EDLC. The present pseudo-capacitors exhibit specific energy values between 10 and 50 Wh/kg, and specific capacity between 300 and 1000 F/g.

Again, due to its physical working mechanism, intermediate between those of EDLCs (pure electrostatic charge transfer) and of batteries (chemical reactions involving mass transfer at the electrodes), a pseudo-capacitor has an intermediate life-cycle duration. It can attain a life cycle of the order of 100,000 cycles, which is about 10 times less than that of EDLCs and 100 times greater than that of a battery.

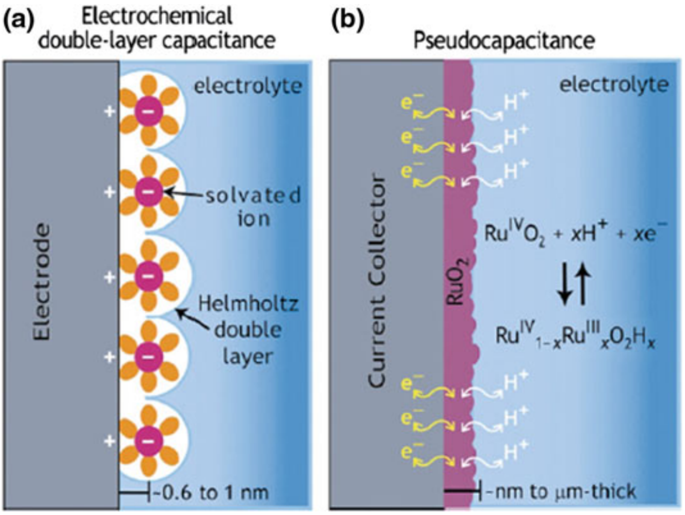

Fig. 9 Scheme of the conservation of the charge mechanisms in an **a** EDLC and in a **b** pseudo-capacitor [11]

Pseudo-capacitors can be made with several types of electrodes, in particular with conducting polymers or metal oxides.

Conducting polymers are one of the main research focuses of modern electrochemistry. Generally, polymers are insulators, but we can make electrochemical reactions occur in double-bond systems, such as polyaniline, polythiophene and polyacetylene. These reactions can be reversible; thus, they can be used in SCs. It is possible to make a conductive polymer thanks to processes called "electrochemical doping of polymers" by anions or cations, in analogy with semiconductors.

Conducting polymers have a relatively high capacitance and conductivity, and a relatively low ESR. Moreover, their cost is comparable to carbon-based materials. The downside is their limited stability limits after many charge and discharge cycles, due to mechanical stress on the conducting polymers during redox reactions. This is the physical reason of the pseudo-capacitor reduced life cycle with respect to the EDLC one, above reported.

Alternative materials for pseudo-capacitors electrodes are metal oxides.

Because of their high conductivity, metal oxides have been deeply studied as possible materials for pseudo-capacitor electrodes. The most relevant scientific works concern ruthenium oxide (RuO_2), because it shows the highest specific capacity.

The excellent capacitance of ruthenium oxide (1358 F/g) and its good electrical conductivity (3×10^2 S/cm) are obtained through the insertion and removal or intercalation of protons in its amorphous structure, according to the following reaction:

$$RuO_2 + xH^+ + xe^- \leftrightarrow RuO_2(OH)_X \quad (4)$$

where $0 \leq x \leq 2$. In the hydrated form ($RuO_2 \cdot xH_2O$), its capacitance (720 F/g) still exceeds those of carbon-based materials and conductive polymers. In addition, also the ESR of hydrated ruthenium oxide is better performing than that of other electrode materials. Furthermore, in the tubular arrangement of porous structures of $RuO_2 \cdot xH_2O$, an even higher specific capacity value (1300 F/g) can be achieved.

Unfortunately, the success of ruthenium oxide has been limited by its prohibitive costs. A cheaper alternative is represented by manganese oxide (MnO_2). It has a theoretical specific capacity of 1370 F/g, a low cost and a good environmental compatibility. The charge conservation mechanism for pseudo-condensers with MnO_2 is based on cation surface adsorption (e.g. K^+, Na^+ or Li^+, generally indicated with C^+) as well as the incorporation of protons according to the following reaction:

$$\mathrm{MnO_2} + x\mathrm{C}^+ + y\mathrm{H}^+ + (x + y)\mathrm{e}^- \leftrightarrow \mathrm{MnOOC}_x\mathrm{H}_y \tag{5}$$

However, the theoretical capacitance is rarely reached in the experiments, mainly due to the low electrical conductivity of the manganese oxide (~10^{-6} S/cm), which limits high power performances and therefore hinders its applications in energy storage systems.

Metal oxide electrodes can only be used with aqueous electrolytes, thus limiting the voltage applicable to the cell. The gain in power density coming from the lower resistance is then offset by the loss due to the lower working voltage.

To summarize the discussion on electrodes for both EDLC and pseudo-capacitors, Fig. 10 shows the specific capacities achieved by various materials.

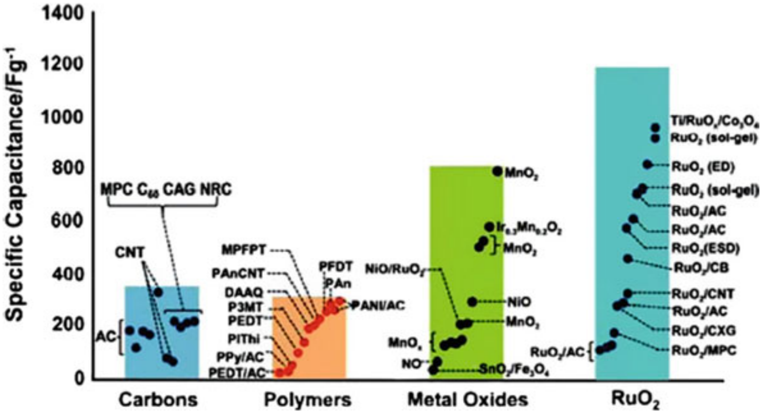

Fig. 10 Capacitance performance for both EDLC with carbon electrodes and pseudo-capacitor electrodes (including transition metal oxides and conductive polymers) [12]

1.2.3 Hybrid Capacitor

Hybrid SCs are SCs where carbon and faradic electrodes are combined to increase the specific energy.

The scientific base for the transition to a hybrid SC was presented in a work on conducting polymers by a research group of the University of Bologna [13]. It was found that a high concentration of polymer cannot be achieved at the negative electrode, but a positive electrode can be effectively realized with the conductive polymer. Thus, a hybrid structure was realized with activated carbon at the negative electrode and conductive polymer at the positive one. The obtained device can be thought as a double-layer capacitor with a pseudo-capacitor in series.

The results of this work are summarized in the Ragone plot of Fig. 11: the triangles represent the hybrid SC, while the circles represent the EDLC (carbon) one. The numerical values written on the side of the points are the electric current density in mA/cm^2. We notice the large improvement in specific energy thanks to the transition to the hybrid solution.

The much higher storable energy is therefore the main advantage of the hybrid SCs with respect to the EDLCs, and then their specific energy goes up to 10–20 Wh/kg. This is a net gain because also the power density is greater than that of the EDLC (see Fig. 11). The drawback, due to the presence of the faradic component, is the reduced number of life cycles, which however still remains much higher than that of batteries going up to 100,000. A further advantage over batteries is the easier manufacturing process.

Depending on electrode configuration, hybrid SCs are divided into composite, asymmetric and battery type.

Composite electrodes integrate carbon-based materials with conductive polymers or metal oxides and incorporate both physical and chemical charge-storage mechanisms into a single electrode. An interesting example of composite electrode is given by nanostructured hybrid materials. In the structure formed by carbon nanotubes

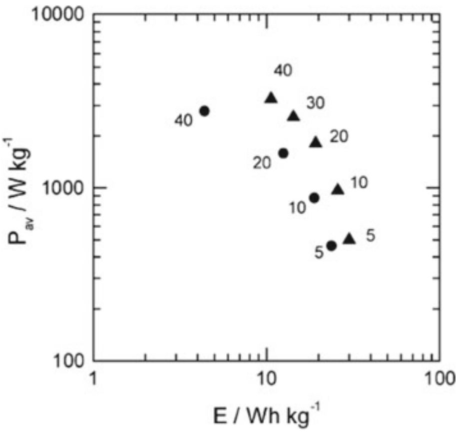

Fig. 11 Ragone plot of a hybrid (triangle) and of a carbon-based (circle) supercapacitor. Numerical values on the side of the points are the respective electric current density in mA/cm^2 [13]

and conducting polymers, the strong nanotube interweaving reduces the mechanical stress caused by the insertion and removal of the ions in the conducting polymers, thus preserving the quality of the electrode surface. This results eventually in cycle stability comparable with that of the EDLCs.

It is also possible to make hybrid ternary structures formed by conductive carbon (e.g. carbon nanotubes), pseudo-capacitive metal oxides and conductive polymers. Figure 12 shows a scheme of a ternary material consisting of a carbon nanotube skeleton, coated with manganese oxide and then with a conductive polymer, PEDOT-PSS.

The key advantages of nanostructured materials therefore include short electron and ion transport paths, large area surfaces exposed by the electrode to the electrolyte, and new reactions which are not allowed in the bulk material. In few words, the specific capacity of the hybrids is greater than the sum of those of the individual components. The main disadvantages include the increase of unwanted reactions at the electrode–electrolyte interface, among those allowed by the large area, and more complex synthesis processes, with corresponding higher manufacturing costs.

Asymmetric hybrids combine faradic and non-faradic processes by coupling an EDLC electrode with a pseudo-capacitor one. These capacitors mitigate the contrast between achieving greater specific energy and power, generally observed in a Ragone plot, being in a region to the right (more energy) but not lower (not less power) than the EDLC one. Furthermore, they have better cyclic stability than pseudo-capacitors.

Finally, the third category of hybrid SCs is the battery type. Like the asymmetric hybrids, the battery-like hybrids couple two different electrodes, the first being an EDL and the second that of a battery. Research has focused mainly on using nickel hydroxide, lead dioxide or LTO ($Li_4Ti_5O_{12}$) for one electrode and activated carbon for the other.

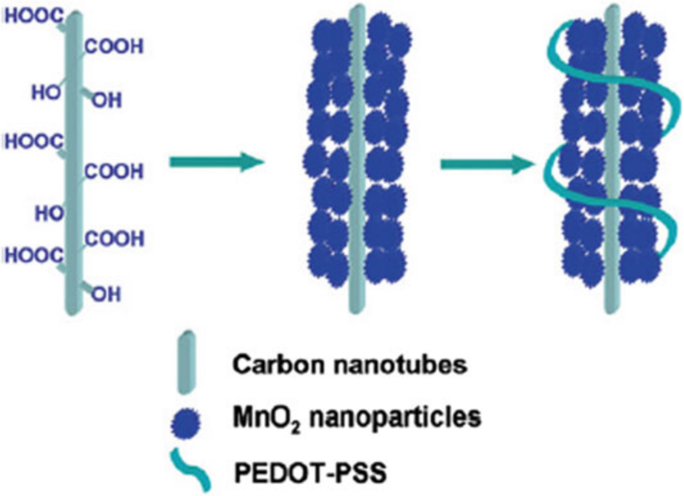

Fig. 12 MnO_2/CNTs/PEDTO-PSS ternary structure [14]

Despite initial promising results, the general opinion is that more research is needed to achieve the full potential of battery-type hybrids.

2 Applications and Future Prospects

The supercapacitor has proven to have a high potential for performance growth, and the market is reacting well to this type of new technology and is ready to invest heavily in research and finance plants with increasing production volumes. In fact, although the commercial value of the sector is still marginal when compared to that of secondary batteries, the market for SCs is projected to grow by 15% per year from 2018 to 2026 [15]. It is also interesting to note that the market, in the same time frame, will reach an eleven billion dollars revenue and that, maintaining the current employment, about a quarter of the production will be absorbed by Europe [16].

As aforementioned, in those cases in which the weight of the stored energy is not a problem, the SC offers an excellent performance when working at low temperatures, when it is subject to many cycles of charge and discharge or when upload and/or download speeds are crucial. Examples of applications in which SCs are already widely used are: emergency opening systems in buses, UPS systems, KERS and stop-start technology in cars (especially hybrids) and the partial replacement of batteries in trucks (to give them more starting torque, especially in cold climates) [17]. They are also used in energy intermittence protection systems in wind or solar power generation plants, in the energy recovery apparatus of overhead cranes and hoists and, recently, also in mobile devices (powerful flashes and Wi-fi) that require a higher power than that supplied by batteries.

The complete list would be too long and too difficult to upkeep because the market for SCs is so dynamic that it registers new applications with great frequency. Currently, however, the automotive sector appears to be the most suitable for their employment. Many companies are focusing on vehicles equipped with SCs, of which the wide spectrum of applications varies from limited uses, such as the aforementioned KERS systems and start-stop technology, to a wide range of uses, such as battery support systems to provide extra power torque or more uphill power to preserve the batteries in electric or hybrid vehicles.

To better understand which applications best fit the SCs characteristics, it would be useful to give some compared performance data.

From Table 1, we could state the following figures:

SC cost per kWh is 10–100 times the cost of electrochemical batteries.
SC charge time is 1000 times faster than batteries.
SC specific energy is 10–50 times lower than batteries.
SC specific power is over ten times the maximum allowed by the most powerful batteries.
SC life cycles are 1000 times those of batteries.

Table 1 Source: author's survey on commercially available items

	Lead acid	NiCd	NiMH	Li ion	Supercap
Specific energy (Wh/kg)	30–50	45–80	60–120	100–250	5
Number of cycles	200–1000	High	High	1000–3000	>1,000,000
Temperature performance	Low when cold	−50 to 70 °C	Reduced when cold	Low when cold	−40 °C +80 °C
Cost per cycle ($US)	$0.2	$0.3	$0.3	$0.2	<$0.001
Cost per kWh ($US)	$100–200	$300–600	$300–600	$300–1000	$10,000
Load levelling, powertrain					
Applications	UPS with infrequent discharges	Rugged, high/low temperature	HEV, UPS with frequent discharges	EV, UPS with frequent discharges	EV, UPS with frequent discharges, very high power charge/discharge
Regular maintenance	Yes	No	No	No	No
Specific power (W/kg)	10–50	20–100	20–100	500–1000	10,000

Given the higher cost of SC together with their higher lifetime, the ideal application must exceed from 10 to 100 times the life cycle of the electrochemical storage. Thus, at the current state of the art, the simple consideration about lifetime would not be enough to favour the SC in many applications unless some more features that the batteries cannot fulfil are required.

Some classes of feature that favour SCs are the power density, the charge and discharge speed, the low/null maintenance and the extended temperature range.

Let us consider some sample applications:

Energy storage for UPS or grids
SCs have been widely used as backup power supply for the data transmission units and actuator equipment, which requires long lifetime, high reliability, free of maintenance, and wide working temperature. Usually, those applications have small storages because they are intended to avoid micro-power shortages that may damage such devices or affect their service assurance.

Bigger storages use cases like a backup for home solar plant show clearly the current limits of the SCs application:

Lead–acid battery may cost around 100 $/kWh and last 500 cycles.
SC storage may cost around 10,000 $/kWh and last 1,000,000 cycles.

So lead acid storage would cost 100 times less but would last 2000 times less. Given one complete cycle per day, the lead storage would last about 1.5 years before replacing it but the solar panel would last about 15 years, so the total cost of the lead storage will be about 1000 $/kWh (tenfold the initial cost), while the SC storage would be 10 times higher anyway. We are supposing that the maintenance and the battery refurbishment are made by the householder as it is a very small infrastructure. Maybe for such small quantities, there would be some negligible disposal expenses.

A huge grid storage application would be different because those infrastructures may be designed to last 50+ years and have low maintenance; a feature that lead acid storage, despite the low initial cost, does not have. Replacement and disposal of exhaust batteries would be unmanageable and environmentally harmful because of the dimensions of such infrastructures (MWh or GWh). SC storage will be a main aid for grid infrastructure as it may run together with the electrochemical storages to provide extra power during demand peaks or to smooth the effect of intermittent power sources (wind or solar). The Chinese producer SPSCAP is providing KW to MW supercapacitor unit for complex energy storage system of micro-grid, which can provide instantaneous high power to stabilize the voltage [18]. The micro-grid issues are widely analysed among the proponents of the project ComESto, funded by the Italian Ministry of University financed and led by the major Italian electric company, ENEL. The project aims to model, design and test a micro-grid having many different distributed generators and storage nodes, among which there will be a SC rack of about 1 kWh. The role of the latter will be delivering high power for short time in order to stabilize the supply, whereas the grid conditions require it. In the future, the role of the SC storage in the grid management will grow as much as its market price reduces.

High power density demanding applications

SCs have been widely applied to blade pitch control of wind turbines. Their huge power density overwhelms the performance of electrochemical batteries for such application where the power is required for a short time and the maintenance is reduced. Both Maxwell and SPSCAP provide solutions for such market.

Even though not yet widely diffused, cranes and machine tools, for the same above-mentioned reason, are also good applications for SCs. Moreover, those tools have big potential for energy saving by exploiting at best SC high performance in regenerative braking. Maxwell (US company, recently acquired by Tesla, that calls “ultracapacitor” its device) supplies SC energy storage for cranes, straddle carriers, stackers, forklifts and other earth-moving and mining equipment to benefit of the most important features of ultracapacitors: their ability to increase the power density of an energy source. Ultracapacitor energy storage modules handle deep discharge cycling coupled with high duty cycle requirements.

Recently, the military research centres have been interested in SCs for application requiring huge pulsed power like laser or magnetic weapons.

Automotive/railways/public transportation

Full electric cars are, at the time of writing, far impossible target for a pure SC application, as the minimum allowed range of 300–500 km would require about 100 kWh. Such a SC-based battery electric vehicle (BEV) would have 20+ tons of storage having a cost of $100.000.

Commercial SC-based solutions for specific task are available for both internal combustion engine (ICE) and electric cars. They range from aids to jump start or start/stop in ICE models to regenerative braking in hybrid and BEVs. On plug-in hybrid bus, braking energy recovery system composed of supercapacitor modules can absorb and store the energy produced at braking and then release the energy during start-up or acceleration, so the vehicle could save fuel consumption and reduce emission more efficiently. If pure electric vehicles only use batteries as power supply, which has relatively short service life and limited number of charging and discharging cycles, the high power required by the vehicle at start-up will have great impact on the battery life. However, if a SC system is connected in parallel with the batteries on the vehicles, it will provide instantaneous high power on starting, quick accelerations and strong braking, letting batteries operate in more steady running situations. Summarizing, SCs can provide peak voltage for pure electric vehicles, stabilize the voltage and significantly extend the service life of batteries.

An interesting SC hybrid architecture that we may see in the near future is the serial hybrid, where a small size SC storage (<1 kWh, providing a range of 3–4 km for a medium utility car) is charged by a small ICE engine to considerably extend the range and allow both regenerative braking and power for fulfilling peak demand. This solution is also suitable to solve the air-conditioning problem that affects the BEVs considerably reducing their running range. Because the ICE engine is not intended to provide the peak power, it may be about 5 times smaller than the one of a traditional car of the same size/class. It would run at a constant and optimal rpm regime and, managed by a start/stop system, increase its efficiency and reduce its emissions, while providing a service comparable to ICE models, especially in the urban context. It also allows full electric motion for short trips. The SC serial hybrid solves or reduces substantially the safety issues that may arise during rescue operations after accidents involving BEVs. The potentially damaged batteries, having a huge quantity of energy stored, may create hazards of electric shocks. Small SC storages would be much safer as they may be quickly discharged by a brake resistor whenever a simple accelerometer system detects a crash.

A potential helper for such application may come from the design of structural SC storage, exploiting the same aluminium shell that protects the cells for the vehicle's structural purposes. In this way, the chassis or the bodywork may perform both the storage and structural functionalities, greatly reducing the vehicle weight and cost.

It is possible to quote several more examples. One of the greatest, in economic terms, is a $318 million tender, won by Meidensha/Sojitz, to provide 2 MW of SCs to the South Island Metro Line of Hong Kong. This installation should reduce by 10% the consumption along the 7.1 km, five-station route [19]. In Paris, BatScap provided tens of thousands of SCs to install on Bluecars (electric cars) as an aid to traditional batteries.

In 2014, China started the initial testing of trams and electric trains, in which a hybrid system of traction, equipped with SCs, will allow the employment of the vehicle even in an emergency situation and to furthermore eliminate, for aesthetic reasons, the aerial power lines in sites of particular value or at intersections. Bombardier, a well-known manufacturer of buses with low environmental impact, seems to be considering the use of SCs for energy recovery during braking, and Riversimple intends to use them in assisting the fuel cells that power its vehicles [17].

Even more radical solutions, in which energy is accumulated only by SCs, are for now used only on city buses. It should be emphasized how the transition from hybrid systems without SCs to other mixed battery/SCs systems, and then to systems with only SCs, has taken place at an amazing speed. The following is yet another proof of the unexpected technological opportunities that this type of batteries can offer. MAN and CSR Zhuzhou Electric Locomotive [20] supply examples of “fully electric” vehicles using only SCs. The latter is testing the prototype of a light metro—therefore on rails—in which a “plug”, located under the floor of the train, can connect SCs, fitted on the roof, to a “grip” on the ground. The refills take place during the stops, require only 30 s each and provide 2 km of autonomy, thanks to the recovery of braking energy.

Therefore, although the idea of powering an electric road vehicle just using SCs may seem extreme, the concept still attracts the attention of various manufacturers throughout the world.

A special feature that always creates a favourable situation for SCs versus batteries is the charging speed, allowing pure SC mobility applications. There are many situations, in which vehicles do repetitive tasks, like city bus trip, airport shuttle, school bus, waste management truck and forklift in a port or in a factory. In all these cases, vehicles run for a short route and repetitively stop at the same places, where there is the opportunity to perform a fast recharge during such stops, provided the vehicle has a SC storage on board. The storage may be small and cheap because the task is short-lasting, as said. Although SCs can manage a greater power compared to batteries, still an issue similar to BEVs remains: not always there is enough power availability at the point of charge. This issue can be resolved putting at each stop a stationary SC storage, responsible for the fast energy transfer to the vehicle, and then recharging it more slowly with the available grid power (and/or solar panels).

In deeper detail, the main problem of this type of accumulators—lower specific energy than batteries—has been overcome by the Italian inventor M. Ippolito, proponent of the International Patent WO2008020463A2. The patented technology was exploited by the Italian company Sequoia Automation in the frame of the EU project K-VEC [21]. A fast-charging conductive system recharges the on-vehicle SCs from a ground station SC storage in 30–50 s during the vehicle stops, practically unaffecting the regular operativity. Passenger transport and loading/unloading times remain almost unchanged. The system comprising the ground storage and the vehicle is called K-Bus.

During the recharging phase, contact between the ground SCs and those on-board the vehicle is assured by a system structured in two parts:

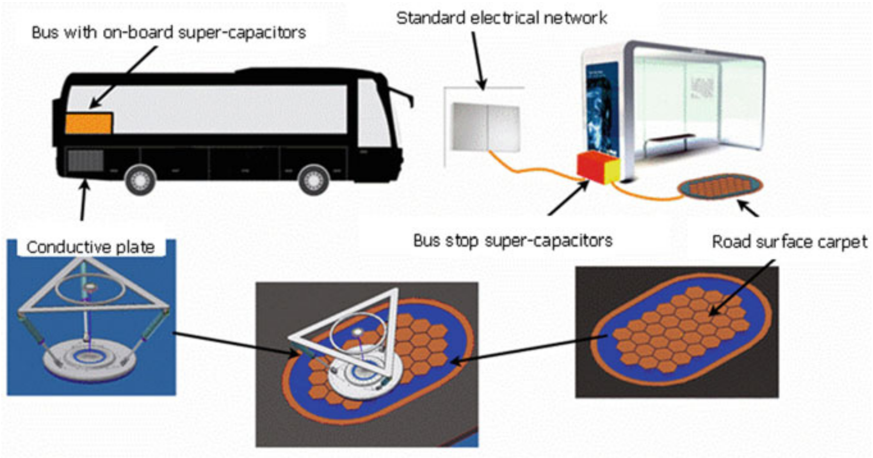

Fig. 13 K-Bus fast-charging system operating diagram [22]

(a) **under the chassis of the vehicle**, through an electromechanical arm that holds a conductive plate, equipped with a thick cluster of metal pins;

(b) **on the road surface**, through a "carpet" of metallic hexagons, each one electrically isolated from the others, but each one connected to the electrical and electronic charging system, and made from a material that ensures long-lasting resistance to deterioration, which do not pose limits, or constitute danger, to the mobility of vehicles or pedestrians. The arm can drop or rise in a few seconds and can adapt to any change in the vehicle balance, letting the plate to optimally descend and settle on the "carpet" and maintain stable electrical contact during the entire charging phase (Fig. 13).

Plate and carpet ensure the electrical connection between the SCs installed on the vehicle and those on the ground station, allowing to recharge the former in a very short time. The power flow is very high indeed—hence a recharge time similar to that required for normal passenger loading and unloading—but is risk free for people or things thanks to the architecture planned for the coupling of plate and carpet and to the electronic assistance. The dimensions of the carpet, in addition, facilitate the placement of the charging device, since they allow margins of error of tens of centimetres, which is much greater than those required, for example, by inductive charging systems.

The key point of the system is the set of SCs to the ground, an "energy reservoir" that can supply, within dozens of seconds, energy at a power rate unmanageable for the normal electrical network. Then, the latter recharges the ground-based SCs at a lower power, during the much longer time that elapses between the passage of one bus and the next. This technology avoids the need for expensive and complex cabling.

Another key feature is that, for safety purposes, the charging phase is compliant with the following procedure:

(a) A Wi-fi signal allows the vehicle's electronic system to perceive the approach to a charging point and starts the descent of the supply arm.
(b) The plate, which is also equipped with a brush to clean the carpet from any possible debris, is pressed against the carpet to ensure an optimal electrical contact.
(c) The pins on the plate are distributed on concentric circumferences: the inner ones are the positive pole, while the outer ones, "protective", are the ground.
(d) Contact between each pin and the hexagonal metal of the carpet is verified by an electronic device capable of identifying the socket and bus code number, the exact position of the vehicle with respect to the carpet, the number of pins in touch with every single hexagon and the absence of "bridges" or conductive contact interruptions due to external causes.
(e) Only after verifying that there are no obstacles to a safe energy transfer, the electronic system supplies power only to the hexagons in contact with the positive pole pins, and the charging phase takes place (Fig. 14).

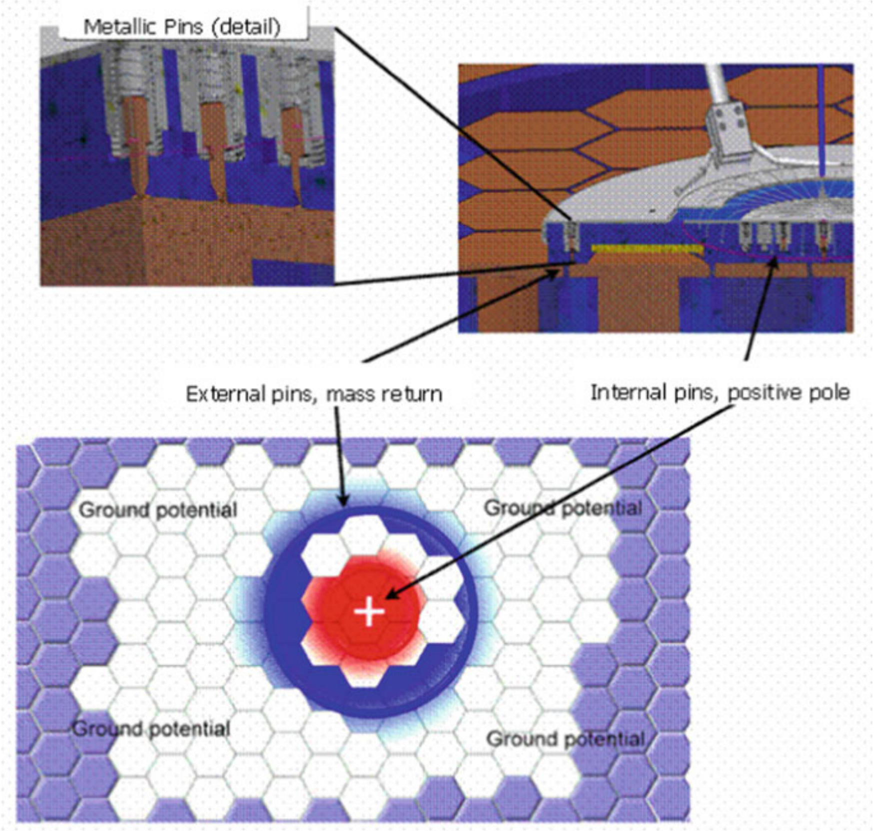

Fig. 14 Construction details of the conductive plate in the vehicle and its power supply [22]

In the case, an unforeseen event should hinder the recharge of the K-Bus at a certain station; each vehicle is equipped with a limited sized electrochemical battery, with enough autonomy to allow the vehicle to safely cover twice the maximum distance between two stations.

This zero-emission solution therefore allows to have a limited battery weight on board the vehicle, without limiting the range of action, thus decreasing the operating costs (see Fig. 15). Furthermore, it makes the vehicle perfectly functional in urban traffic, without having the restrictions other public transport means have, such as trolleybus or tramways, and with the flexibility of use offered by road vehicles.

The charging stations would also have limited initial investment and management costs, when compared, for example, to a system of overhead power lines, which also involves a remarkably unpleasing aesthetic impact.

In addition, to limit the overall energy use, the recovery of kinetic energy is fully exploited during braking and while proceeding downhill on routes with marked differences in altitude.

A cost analysis and economical evaluation of the K-Bus technology was made through a comparison of real data obtained by the GTT Star 1 urban electric bus line circulating in Turin (Italy) with the simulated ones of a hypothetical similar line, equipped with K-Bus vehicles. The real Star 1 line is served by electric battery-powered buses, which cover a distance of nearly 12 km and that undergo partial recharges at the terminal stations and a total recharge during night.

The resulting data showed that if the present system was replaced with the innovative K-Bus, the initial investment costs would be almost halved. Moreover, the

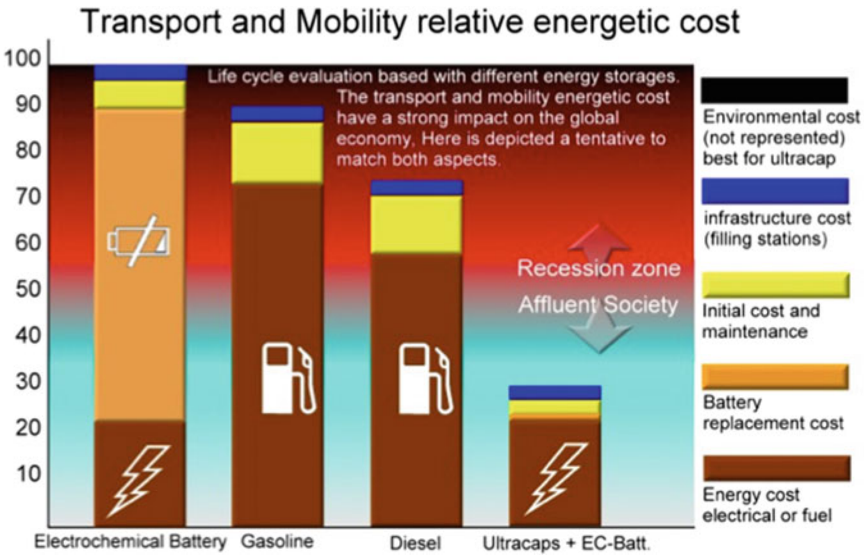

Fig. 15 Comparison of operating costs between various alternative power systems for urban buses [22]

overall operating costs after 12 years (including maintenance and material substitution costs) would amount to less than half of the costs required by the present system, where a major cost comes from the need of frequent battery replacement.

In a similar way, in the context of urban public transport, an electric K-Bus vehicle, even with an operational autonomy limited to a few kilometres, could replace an internal combustion engine vehicle thanks to the patented fast charge technology. This system, in fact, does not limit in any way the vehicle operation or the public comfort and safety, but rather would provide a big advantage in terms of environmental care and, in the medium term, even in economic terms.

The fast charge K-Bus technology could be extended to other areas of the same type, i.e. services for which a number of vehicles perform fixed routes with stop points at short distances, such as garbage collection, mail delivery, industrial or airport logistics. Nor can one rule out, at least in principle, the possibility that multiple services, independent of each other, recharge their SC-based electric vehicles through a single network of appropriately distributed K-Bus-type "carpets".

Feeding K-Bus through photovoltaic modules has also been theorized. These modules, installed on the roof of adequately exposed charging platforms at bus stop, could supply their "tanks". Given the amount of energy that needs to be produced and transferred, and the type of power involved, in most cases this type of recharge system would be just supplementary to the electric network. However, it would be the ideal solution for extra-urban stations with a limited daily vehicle passage (Fig. 16).

The K-Bus potentially solves one of the most vexing problems related to modern urban roads, it is in fact a zero-emissions system, with a competitive cost with respect to those powered directly from fossil fuels (even without considering possible incentives for electric vehicles), with technical solutions that ensure an efficient and versatile transport.

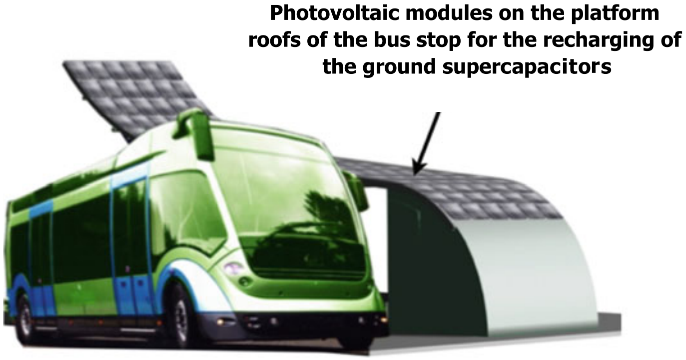

Fig. 16 Bus stop powered by solar panels (photovoltaic system) [22]

3 Main Lines of Research on Supercapacitors

3.1 New Electrodes

As previously said, the scientific literature on SCs is so vast that it is conveniently divided into subcategories, one of these being related to the search for an electrode alternative to the activated carbon for EDLC and to the other electrodes presently employed in pseudo-capacitors. The research about new electrodes includes composite materials and even significant optimization steps, both in terms of performance and cost reduction, of the activated carbon.

However, the main alternatives to activated carbon still belong to the family of carbon-based materials, which includes graphene, nanocarbons (nanotubes, nano-onions, etc.), carbon aerogels and some composite structures that combine these materials.

In the search for increasing the SC specific energy, generally a new electrode is sought to improve the specific capacity, while the working voltage remains determined by the electrolyte. However in Sect. 3.1.3, we will mention an interesting exception to this general rule.

Talking about electrode materials derived from carbon, we notice that they all have in common a cheap starting material, good conductivity and good thermal behaviour. Let us overview some of them.

3.1.1 Activated Carbon

There were many progresses in the preparation of new activated carbon, mainly in achieving higher specific area from a minimum of 1150 m^2/g [23] to a record of 3000 m^2/g, using new processes, like chemical activation with KOH [24], or starting from a new biological matter, namely a seaweed biopolymer [25]. In any case, specific area cannot be the only one important parameter, as demonstrated by the unsatisfactory capacity value of 10 mF/cm^2 obtained by the 3000 m^2/g activated carbon, against common values of 15–25 mF/cm^2 a exhibited by EDLC with standard activated carbon. Consequently, the second relevant parameter should be the presence of a suited mixture of pore sizes that best fit the employed electrolyte so that both good capacitance and good power performance can be simultaneously achieved. Moreover, an excessive specific area can be correlated with the presence of immobilized free radical that may cause degradation of the electrolyte, especially with organic solvents. Therefore, it is general opinion that a process to produce activated carbon from waste, such as sugar cane bagasse, cellulose, sawdust, cherry stone and corn grains would be preferable, also from an ecological point of view.

3.1.2 Carbon Nanotubes

Many research works refer to carbon nanotubes (CNTs). Generally, CNTs can be made in two ways: a single graphite sheet curled into cylindrical form having a single-walled CNT (SWCNT), or multiwalled CNTs (MWCNTs) that contain many concentric SWCNTs with different diameters.

CNTs attract researchers' interest due to their high specific capacity and because they are able to sustain high currents.

A CNT-based electrode has a mesoporous matrix which favours the ion diffusion to the active surfaces, and they can reach high values of surface area up to 1600 m^2/g, besides a good electrical conductivity (105 S/cm). Moreover, CNTs have low mass density and intrinsic flexibility. Some practical limits are determined by the evidence of micro-pore formation and increase of the internal resistance so that the actual performances can be less than the theoretical ones. Finally, their manipulation can give toxicity issues during processing.

In a recent work, CNTs were coupled with flexible carbon fibre (CF) to make a hybrid electrode (CF-CNT). A further improvement was to develop a 3D composite architecture with a combination of CF, CNT and graphene. This electrode was realized by Xiong et al. [26] working on reduced graphene oxide and CNTs grown on CF using electrophoretic deposition and chemical vapour deposition (see Fig. 17). The 3D electrode showed a specific capacity of 203 F/g, which is 4 times greater than that of pure CF.

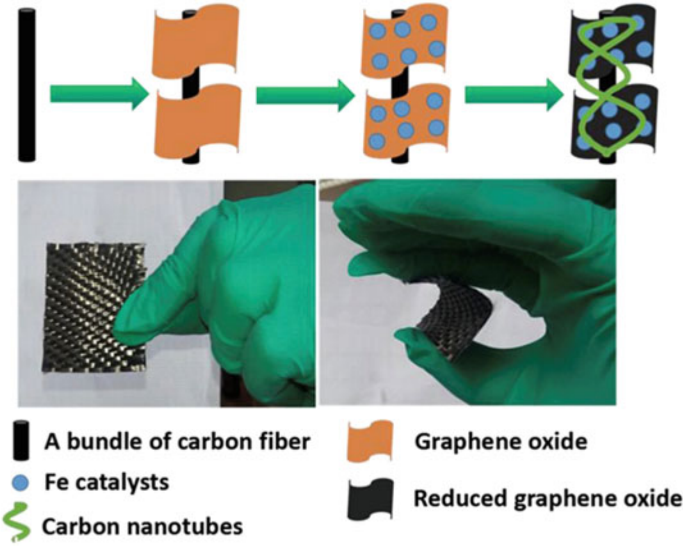

Fig. 17 Scheme of the synthesis of the 3D CF-rGO-CNT hybrid [26]

3.1.3 Graphene

The materials that presently attracting most research activity are graphene and its derivatives: graphene oxide (GO), reduced graphene oxide (rGO) and graphene combined with different materials. Graphene is a well-known two-dimensional material made of carbon atoms arranged in a honeycomb pattern. It has many extraordinary properties, the electric and geometric ones being the most relevant for SC realization: electrical conductivity (1.00×10^8 S/m), electrical mobility (15,000 $\mathrm{cm}^2\ \mathrm{V}^{-1}\ \mathrm{s}^{-1}$) and specific area (2675 m^2/g).

The maximum theoretically achievable specific capacity reaches 550 F/g. However, this very large value would be obtained only by a perfect configuration with graphene sheets perpendicular to the current collectors, and this is not an easy task to achieve. Graphene-based SCs with ionic liquid salts, aqueous electrolytes and organic electrolytes can reach specific capacity of 75 [27], 135 and 99 F/g [28], respectively. Reduced graphene oxide, when produced with low agglomeration, can reach a maximum specific capacity of 205 F/g in an aqueous electrolyte, yielding an energy density of 28.5 Wh/kg [29].

A great number of uses of graphene are possible in the SC production; here, we report just four significant strategies.

Graphene can be nanostructured; i.e., it can be coated on another material to obtain a special structure; for example, it can be put on textile fibre (adding MnO_2, see Fig. 18) [30] to gain more specific capacity (315 F/g), specific energy (12.5 Wh/kg) and mainly more life-cycle stability (100,000 cycles of charge/discharge, a quite high value compared with other sophisticated SCs).

In another work [31], researchers from the University of Salerno (Italy) covered nanoparticles of Fe_3O_4 (5–8 nm) with graphene sheets. After annealing, a SC with an aqueous electrolyte and this kind of electrode reached the outstanding specific capacity and energy of 787 F/g and 109 Wh/kg, respectively [31]. Its specific power

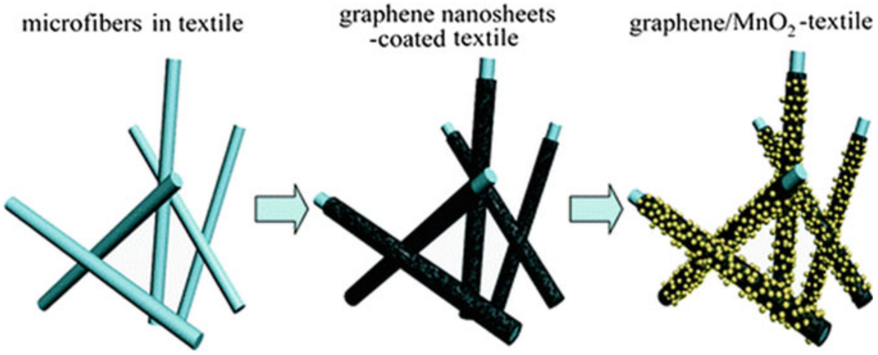

Fig. 18 Illustration of the steps to produce the hybrid structure: in blue, the micro-fibres which are covered with graphene sheets (in grey), and which finally receive the MnO_2 particles (in yellow) by controlled electrodeposition [30]

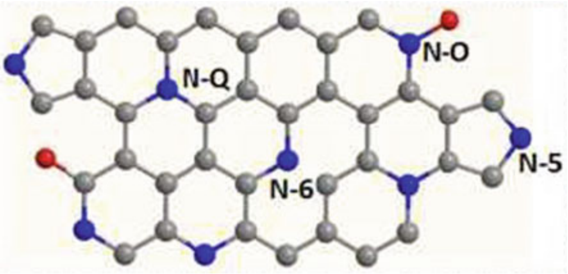

Fig. 19 Nitrogen-functionalized graphene model for the work described in the text [33]

range was between 250 and 9000 W/kg according to a specific current range of 0.5–18 A/g, and its life cycle was about 30,000 cycles.

Another very common strategy to improve graphene-based SCs, and in particular to prevent restacking of the sheets, is based on the use of functionalized graphene. A functionalized graphene is a graphene with another chemical element or group, functional group, linked to its surface with a controlled density, to obtain additional specific properties, without a significant decrease of the electrical conductivity. This technique is applied also for biotechnological applications [32]. In the SC field, we can mention a graphene electrode functionalized by nitrogen atoms [33] (see Fig. 19). A remarkable result shown in this work is that the nitrogen functionalization is obtained directly during the production process of the graphene-like material from shrimp shells, used as starting raw material.

A SC with this kind of electrodes and aqueous electrolyte showed a maximum specific energy of 11.2 Wh/kg that is reduced to 8.4 Wh/kg when tested at the maximum power of 25,400 W/kg.

A third strategy, which gained a relevant industrial impact, is the use of curved graphene. Although graphene is by definition a two-dimensional material, its perfect flatness does not help in SC applications, and it may even be useless when parallel to the collector sheet. A curved graphene has proven to be more effective. The curved graphene is in fact a graphene sheet made in a concave shape to better expose its area and to avoid the stacking of graphene planes. We can see an example of this graphene in Fig. 20 [34].

The structure shown in Fig. 20a has pores between 2 and 25 nm (mesopores). This curved graphene was employed in a SC with a 5 wt% carbon black and a ionic liquid salt (see Sect. 3.2) that can sustain a maximum voltage of 4.0 V. The obtained specific energy is in the range 21.4–42.8 Wh/kg, depending on the electrode mass fraction.

Finally, a very recent strategy deals with aerogel-like material based on graphene.

It is known that a SC cannot work outside the electrochemical stability window because solvent electrolysis reactions take place and the reaction products can obstruct the pores of the electrode, reducing both the capacitance and the life cycle of the device. Avoiding the occurrence of such phenomena actually determines the electrode stability to the applied voltage. In a recent work [35], a research group at the Tohoku University (Japan) showed a new electrode material made of seamless

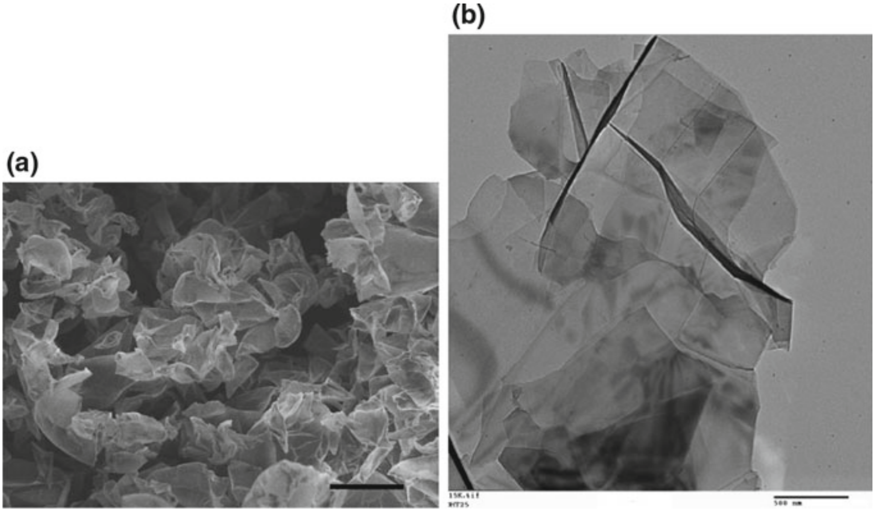

Fig. 20 **a** SEM image of the curved graphene layers (scale bar: 10 μm); **b** TEM image of planar layers of graphene prepared with the usual chemical procedure, which overlap so they have the relative space as in the graphite bulk, i.e. less than 1 nm (scale bar: 500 nm) [34]

mesoporous carbon sheet consisting of a continuous three-dimensional framework of graphene mesosponge (GMS). It can be seen as a mesoporous carbon made of edge-free graphene walls.

This material is very attractive for its high specific surface area (1500 m^2/g); however, its main feature is the possibility to use it to assemble symmetric SCs that can work up to 3.5 and 4.4 V, at 60 and 25 °C, respectively. It is worth noting that these results were obtained using a conventional electrolyte (1 M Et_3MeNBF_4/propylene carbonate TEMATFB/PC electrolyte) generally limited to 2.7 V.

GMS is prepared using Al_2O_3 nanoparticles as a hard template (Fig. 21d). A graphene-like material is deposited of an Al_2O_3 surface through chemical vapour deposition (CVD) of CH_4, followed by template removal by chemical etching. The resulting mesoporous carbon is then annealed at 1800 °C to convert discrete graphene into the continuous GMS. Then, GMS is obtained in powder form and eventually in a self-standing GMS sheet (Fig. 21e). Figure 21a–c shows the main carbon materials (CNTs, rGO and activated carbon, AC) employed in SCs.

In case of high-voltage operation, the GMS sheet exhibits a high energy density (60 Wh/kg, whole electrode mass basis) at 1 kW/kg. This energy value is 2.7 times higher than that of the conventional AC at the same operating power, which however is very low with respect to common applications. Moreover, the GMS sheet retained its capacitance over 100,000 cycles.

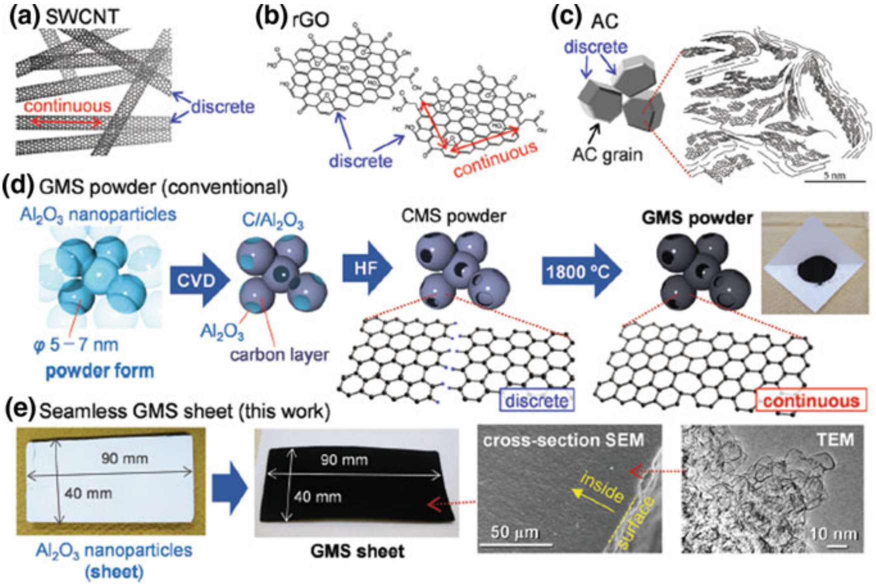

Fig. 21 A list of carbon materials examined in this work. **a** SWCNTs. **b** rGO. **c** AC. The inset depicts the molecular-level structure of AC [29]. **d** Preparation scheme of the GMS powder, together with its photograph. **e** Photographs of sheet-moulded Al_2O_3 nanoparticles (template) and a resulting seamless GMS sheet. Cross-sectional SEM and TEM images of the GMS sheet are also shown [35]

3.1.4 Conducting Polymers

Among conducting polymers (CPs), polyaniline (PANI), polypyrrole (PPy) and polythiophene derivatives got particular attention as SC electrode materials for their high conductivity and low cost [36–42]. Optimizing the morphology of CPs is an important factor for the electrochemical performance of the resulting SCs. In particular, nanostructured CPs can achieve better performances than their bulk variation.

PANI (polyaniline) is a conducting polymer that has found promising applications in energy storage devices due to its easy synthesis, low cost, good electrical activity and good stability. However, bulk PANI has low available surface area; thus, the nanostructured version is always preferred. Moreover, to make a SC electrode, the PANI nanostructure needs a binder that can distort the structure and introduce inert materials in it. This problem is usually afforded with electrospinning and addition of small quantities of a different polymer. Simotwo et al. [43] found a facile approach to the fabrication of PANI nanofibre electrodes, without any binder, by means of electrospinning and CNTs. The SEM image in Fig. 22a shows that electrospinning PANI at 93% solution produces a continuous and nonwoven nanofibre structure with controllable inter-fibre porosity. CNT addition (Fig. 22b) does not degrade in any way the nanostructure. In the following work, Li et al. [44] prepared a SC electrode by a PANI nanofibre coated with graphite, showing a capacitance of 2136 F/g at a

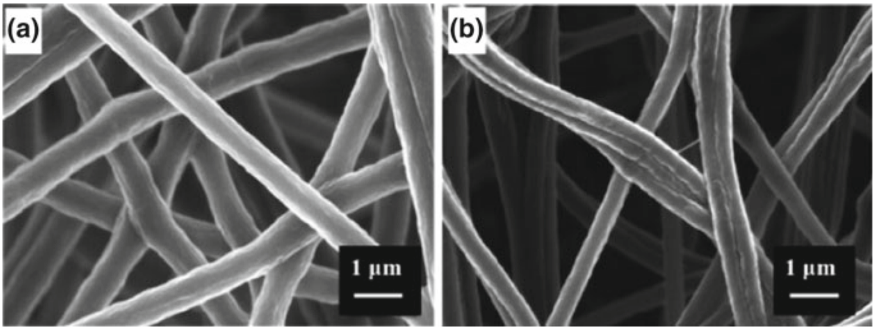

Fig. 22 SEM images of **a** PANI and **b** PANI-CNT [43]

current density of 1 A/g, in 6 M H_2SO_4 and 91% capacitive retention up to 1000 cycles.

The polypyrrole (PPy) has received a lot of interest because it is water-soluble and commercially available; it can store high specific energy and show reversible electrochemical doping/de-doping and easy electrochemical processability. One research group [45] recently prepared the rGO/PPy/Cu_2O–$Cu(OH)_2$ ternary nanocomposite as an electrode material for SCs. In three electrode systems, this nanocomposite showed a gravimetric specific capacity of 997 F/g at a current density of 10 A/g. The EDLC with the PC and this kind of electrode resulted in specific energy and power of 20 Wh/kg and 8 kW/kg, respectively, while at the maximum specific power of 20 kW/kg, the specific energy was reduced to 5.8 Wh/kg, with a capacitance retention of 90% after 2000 cycles.

3.1.5 Metal Oxides

The metal oxides used for SCs belong mainly to the transition metal family, such as nickel oxides (NiO), cobalt oxide (Co_3O_4), ruthenium oxide (RuO_2) and manganese dioxide (MnO_2). They raised interest due to their mesoporous structures, yielding high specific capacity. [46, 47] However, they are expensive materials, so many researchers considered also cheaper and earth-abundant alternatives. In particular, cobalt sulphide materials, such as Co_3S_4, CoS_2, Co_9S_8, $Co_{1-x}S$ and Co_xS_y, have gained attention for their wide stoichiometric composition and good stability. However, the development of these materials is still at an early stage. Other metals oxides for SCs with neutral solutions are iron oxide (Fe_2O_3), vanadium oxide (V_2O_5), indium oxide (In_2O_3) and tin oxide (SnO_2).

3.1.6 Composites

Composite materials are presently the best and most studied choice for SC electrodes. We already mentioned different examples of electrodes made by a combination of materials: carbon-based material with another carbon-based material (AC with rGO, graphene on CNTs, and so on); carbon-based materials and metals oxides; carbon-based materials and ad hoc chosen materials.

Recent research has shown that graphene is the most adaptable and promising material. Graphene composites are usually multiphase materials in which graphene is mixed into a ceramic, polymeric or metallic matrix by physical processing techniques, such as shear mixing or ball milling.

3.2 New Electrolytes

The most efficient way to increase the specific energy of SCs, at least from a simple mathematical point of view, could be finding a new electrolytic solution, able to withstand higher voltage. This is a simple consequence of (2) that states that the stored energy in a SC depends linearly on capacitance but quadratically on voltage. Moreover, it is possible to improve the electrolyte performances also choosing ion molecules with suitable geometry. In fact, smaller ions can better fit in smaller pores, thus better exploiting all the available pore surfaces. In this way, the effective capacitance of the same electrode will result greater than that obtained with the usual commercial organic salts (e.g. TEATFB or TEMATFB) and more energy can be stored in the SC.

As said before, the most common electrolyte solvent in a commercial SC is acetonitrile, which works with a maximum voltage of 2.7–2.85 V. However, in the scientific literature, there are many papers dealing with solid-state and quasi-solid-state electrolytes. Solid-state electrolytes mitigate the risk of leakage, a common problem for liquid electrolytes. Leakage is the phenomenon for which a SC, charged at maximum voltage, loses charges due to small currents (exchange of charge carriers among the electrolyte and the electrode), which should be absent in the ideal case (constant voltage at complete charging) but in practice unavoidable, because of electrode irregularities at the molecular scale. In SCs with liquid electrolyte, leakage is caused by the normal limits of the stability of the double layer formed near the electrodes. This problem is obviously much less severe in SCs with solid electrolytes. The latter, however, have lower conductivity than liquid ones.

Other aspects afforded by the research on electrolytes are the working temperature range (which then affects the operating temperature range of the SC), the specific heat and the thermal conductivity (i.e. the thermal stability, which is related to the maximum current that a SC can deliver and dissipate), and the environmental impact (i.e. how ecological the electrolyte preparation and its disposal are).

3.2.1 Aqueous Electrolytes

Aqueous electrolytes are grouped into alkaline, acid and neutral solutions, of which Na_2SO_4, H_2SO_4 and KOH are the most commonly used representatives. Generally, aqueous electrolytes show good conductivity (e.g. 0.8 S/cm for 1 M H_2SO_4 at 25 °C) but they must be coupled with suitable electrodes to compensate the relatively low ESW.

Qu et al. [48] studied the performances of MnO_2 nanorods using neutral aqueous electrolytes (e.g. Li_2SO_4, K_2SO_4 and Na_2SO_4). In Fig. 23a, a SEM image of the nanorods is shown. The newly fabricated AC SC showed good life-cycle stability (Fig. 23b) with large specific energy (17 Wh/kg) and power (2 kW/kg).

In another study [49], the combination of $NaMnO_2$ and activated carbon was tested using aqueous solution of Na_2SO_4 (see Fig. 24). This system delivers a maximum specific energy of 19.5 Wh/kg at a power of 130 W/kg. The measured capacitance loss is about 3% after 10,000 cycles, and the estimated remaining capacitance after 100,000 cycles is above 80%.

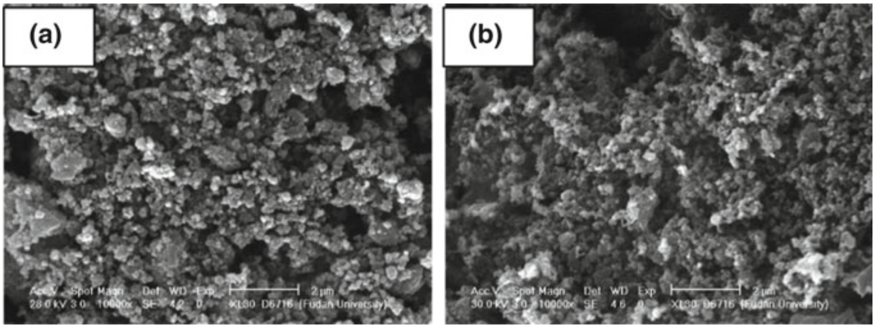

Fig. 23 SEM images of the MnO_2 electrodes, **a** native and **b** after 23,000 cycles [48]

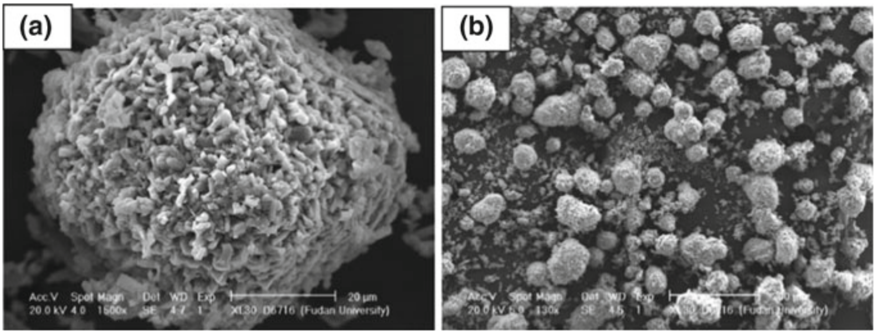

Fig. 24 SEM images of the as-prepared $NaMnO_2$ with different scales: **a** 20 µm and **b** 200 µm [49]

3.2.2 Organic Electrolytes

We already explained advantages (wide ESW) and disadvantages (lower conductivity, toxicity, flammability, volatility and hygroscopicity) of the organic electrolyte, in particular of the most common one, acetonitrile (ACN) with TEATFB. The second most common solvent is PC, because even if it has a lower ESW (2.5 V), it has a lower toxicity than ACN, wide liquid temperature range and resistance against hydrolysis.

A first example of an alternative electrolyte comes from a research published in 2010 [50], where NASA Tech Briefs reported of an organic electrolyte with a freezing temperature of −85.7 °C. It was formulated by the addition of $TEABF_4$ to mixed ACN and 1,3-dioxolane (DOL) at 1:1 volume ratio. The cell filled with this electrolyte showed highly linear discharge curves over a wide range of temperatures. Of course, it can be considered a good solution for special applications at low temperature working condition.

For what concern more substantial alternatives, a first strategy consists in the search for new organic salts. Some asymmetric tetraalkylammonium salts and cyclic quaternary ammonium salts were thus explored, including triethylmethylammonium (TEMATFB), 1-ethyl-1-methyl-pyrrolidinium (EMPYTFB) and tetramethylenepyrrolidinium (TMPYTFB). These salts show higher solubility in PC, thus can be used in higher concentrations and hence offer higher conductivity than commonly employed salts, e.g. TEATFB. However, many studies showed that it is highly challenging to increase the operating voltage beyond 3 V for EDLCs using any known commercial electrolyte.

Novel electrolytes including new solvents were published in the scientific literature with the aim of increasing significantly the operating voltage. Some of them are based on linear sulphones, like the ethyl isopropyl sulphone (EiPS, operating up to 3.7 V), alkylated cyclic carbonates, like the 2,3-butylene carbonate (2,3-BC, up to 3.5 V) and adiponitrile (AND, up to 3.75 V). Unfortunately, their relatively high viscosity and low ionic conductivity, especially at room temperature, reduce the power performance of such EDLCs.

3.2.3 Ionic Liquid Electrolytes

An alternative to electrolyte solutions is represented by ionic liquids (IL). IL are salts that as a result of a deprived crystalline packaging (when, for example, cations are particularly large compared to anions and have a low degree of symmetry) are in the liquid state at room temperature and often also at lower temperatures. The ionic nature of these materials and the weak coordination between the ions prevent their evaporation, so IL do not have a measurable vapour pressure and have a high chemical stability at high temperatures, even greater than 400 °C.

In an EDLC with ionic liquids, the formation process of the double layer is quite different from the general case because, due to the absence of the solvent, the ions have not a solvation sphere around them and therefore the distance from the charges

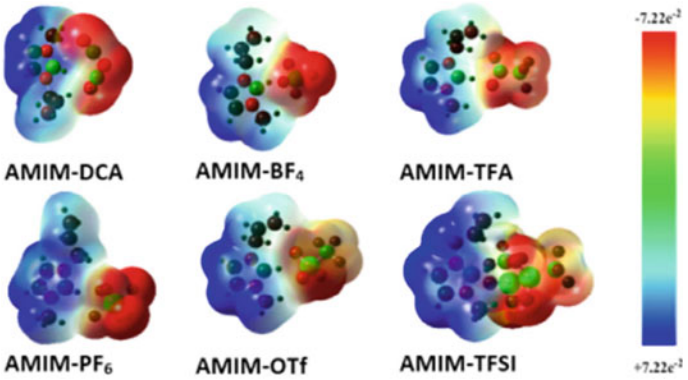

Fig. 25 Structures of the six ILs with the electrostatic potential map [52]

in the electrode is shorter. This peculiarity results in a large increase of the most important SC feature, the ESW, that can reach values over 5 V.

A good example of IL for SC technology is the $PYR_{14}TFSI$, pyrrolidinium trifluoromethanesulphonylimide. Its electrochemical properties, hydrophobic nature, high level of purity, are well suited for long life cycle and high-voltage SC. The downside of this IL is its ESR ten times greater than ACN-based electrolytes, because of the lower conductivity exhibited at 60 °C [51]. Even at room temperature, the electrical resistance is so high to prevent its standard use in commercial SCs. Moreover, the maximum applicable voltage depends crucially on the residual humidity (even a few ppm of water can break down the working voltage), which would entail considerable constructive problems for an industrial line.

In a recent research on IL, Zarrougui et al. [52] prepared six novel, low-viscosity IL to serve as electrolytes for SCs. All of them were formed with the cation $AMIM^+$ (1-allyl-3-methylimidazolium) and one with a planar anion (DCA^-), while the other five anions (PF_6, BF_4^-, $TFSI^-$, TFA^- and OTf^-) with non-polar architectures (see Fig. 25).

The electrochemical system based on those electrolytes showed good performance in terms of specific capacity (135–228 F/g), reasonable energy density (41–115 Wh/kg) and cycling stability up to 1000 cycles (a good value for a IL-based SC, even if it is very low for current commercial SCs).

3.3 General Optimization

In this paragraph, we will summarize the observations collected so far, adding some more details.

Currently produced SC may be based on acetonitrile or propylene carbonate if the amount of energy to be stored or the application temperature range is more important, respectively. If, for specific or legal reasons, the toxicity of acetonitrile is a problem, the PC is preferred.

Since a single SC works at a maximum voltage of 2.85 V, to apply the SCs in systems that require higher voltages it is necessary to package them and connect them in series, forming the so-called module. This procedure will be made more or less easy by the shape of the single device (cylindrical or parallelepipedal), but above all will depend heavily on the control and balancing system of the SCs.

Two elements that have a secondary impact on the performance of the SCs are the separator and the binder. However, studying their margins for improvement is still useful for improving the overall product.

The separator has a slight negative influence on the electrical capacitance if it exceeds a certain thickness, while it must be suitably porous to minimize the open circuit self-discharge.

The binder can be optimized looking for a polymer that could guarantee, with the same mass of a common binder, a stronger adhesion of the electrode to the current collector and a better conductivity. On the other hand, the choice of a water-based binder during the preparation of the electrode makes the manufacture more environmentally safe.

At present, the use of aluminium as current collector is not questioned, because of its excellent conductivity and low mass density. Furthermore, it is a cheap and abundant material. However, in the future the research could identify an electrode with a good capacitance but also so resistant from the mechanical point of view to coincide with the current collector or to request only a sheet of paper as a support. Graphene seems to be the best candidate in this regard.

On the side of SC applications, possible improvements regard the realization of SC systems to be included in a generic machine that take advantage of the great charge and discharge speed that characterizes this device. Even if this problem does not directly concern the SCs, the companies that produce SCs are also involved in the system-oriented researches to find a good compromise between the efficiency of the supply of high currents and the amount of storable energy.

The development of electric cars and heavy machinery seems to proceed in parallel with that of the SCs, which in turn is closely connected to what happens in the field of renewable sources, in an increasingly strong network, in which all the nodes become more and more important.

4 Concluding Remarks

Through the presentation of the state of the art, the most common and the near-future foreseen applications, and the possible evolutions in the research of new lines of SCs, we showed that such technologies, although not capable of substituting the electrochemical batteries in all applications, are gaining momentum. The scientific literatures about innovations and the industrial applications are growing quite exponentially, the market is following the growth trend, and the attention is growing also in the media that publish numerous popular articles. At the time of writing, expectations are high for incremental improvement of the energy density, which is the weakest feature of the supercapacitor. A possible breakthrough based on new materials and chemicals or on a better design of hybrid "supercabatteries" would be disruptive to many applications, especially in the automotive, automation and grid power sectors. In the meanwhile, there is enough space for new and better design of existing state-of-the-art supercapacitors and applications to boost the applied research investment. In our opinion, one of the most important drivers will be the commitment taken by an increasing number of politicians and organizations to reduce emissions of pollutants in the automotive sector. This is triggering huge investments, part of which will be necessarily dedicated to solving the safety, cost and life duration issues related to electrochemical batteries that would, ultimately, benefit the SC industry.

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Sustainable Services to Enhance Flexibility in the Upcoming Smart Grids

Pavlos Nikolaidis and Andreas Poullikkas

Abstract Global efforts are already focusing on future targets for even more increases in renewable energy sources contribution, greater efficiency improvements and further greenhouse gas emission reductions. With the fast-paced changing technologies in the context of sustainable development, new approaches and concepts are needed to cope with the variability and uncertainty affecting generation, transmission and load demand. The main challenge remains in developing technologies that can efficiently make use of the available renewable resources. Alternatives in the form of microgrids or virtual power plants along with electricity storage are potential candidates for enhancing flexibility. However, intelligence must be added at all levels in the grid and among all the equipment comprising each subsystem, in order to achieve two-way communications and bidirectional flow of power. Then, the concept of smart grid can be realized and, relying upon software systems, it can remotely and automatically dispatch and optimize generation or storage resources in a single, secure and Web-connected way. Deploying smart configurations and metering promises new possibilities for self-managed energy consumption, improved energy efficiency among final consumers and transition to more consumer-centric energy systems via demand response and demand-side management mechanisms.

Keywords Microgrid · Virtual power plant · Electricity storage · Smart grid · Demand response · Demand-side management

1 Introduction

Historically earlier, the production adjustment to consumption could be realized at the same time the electricity was demanded utilizing conventional power plants. This characterized thermal power generation as dispatchable and controllable, earning the

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advantages of tractable and predictable load profile, passive power transmission and distribution, simple control logics for balancing supply and demand, etc. In recent years, the increase in energy demand and reduction in resources for conventional energy generation, along with various environmental impacts, have promoted the use of renewable energy sources (RES) for electricity production. However, RES are by nature intermittent and unstable creating a lot of power integration and fluctuation issues which ultimately disturb the stability of the grid [1].

Over the last two decades, significant changes have been affecting the power system; the deregulation of the energy market, the expansion of intermittent renewable generation (RG), the increasing penetration of distributed generation (DG), the price-responsive demand participation and the plug-in electric vehicles (PEV) are only some of the most important examples. These representative changes irreversibly reshape the electric system scenario [2]. While they are opening new opportunities for a more sustainable and environmentally friendly operation of the electric grids, they also create remarkable challenges for the secure and reliable energy supply.

The introduction of EVs and weather-sensitive electric devices (e.g. heat pumps) imposes uneven load-profile fluctuations, difficult to predict. In addition, once RG possesses the priority in generation and is commonly interpreted as negative load, the residual, net load fluctuates even more stochastically. This is likely to cause frequent ramping and start-ups/shut-downs for thermal units [3]. At the same time, due to their large scale and increased DG, the distribution grids are becoming an active complex system with bidirectional flows. From the reliability perspective, at a relative low penetration level, the net load fluctuations are comparable to existing, and the conventional generators (thermal or hydro units) have sufficient load tracking capability without requiring additional operating reserves. As the RES penetration level increases, the response time of committed conventional units should be short enough during sudden deviations of generation and load due to random failures and thus more operating reserves are required [4].

From the stability perspective, the fast expansion of RES leads to increased levels of variability and uncertainty, degrading the frequency and grid voltage stability due to the surplus or shortage of power. The ability of a power system to cope with such adverse events in both generation and demand, while obeying system constraints at a reasonable cost over different time horizons is described as the power system flexibility [5]. A failure to meet the system flexibility requirements can manifest as power balance violations, high electricity-price volatility, frequency deviations, extensive use of regulation services and, in extreme cases, unavoidable RG curtailments, transmission congestion and unintentional customer demand interruptions [6, 7]. It is therefore important for more flexible resources to be involved in dealing with the increasing complexities of the electric systems and facilitate the transition from the currently passive to future active, fully operated smart grids.

According to US Department of Energy, the concept of smart grid involves an electricity grid that delivers electric energy using various approaches to communicate, compute and control in order to enable: (1) self-healing from power disturbance events; (2) active participation by consumers in demand response; (3) resilient operation against physical and cyberattack; (4) power quality provision for twenty-first-century needs; (5) accommodation of all generation and storage options; (6) new products, services and markets; and (7) assets optimization and efficient operation. The smart grid (also known as intergrid, future grid or intragrid) represents a perception of the future power system, composed of advanced communication, sensing and control technologies at the generation, transmission and distribution levels in a consumer-friendly environment [8].

Such approaches may include energy storage techniques, hybrid renewable energy systems, power-to-work alternatives, AC or DC microgrid formations, demand response and demand-side management, distributed energy resources, interconnections between adjacent power grids, virtual power plant schemes and smart grid configurations. In the context of smart grid, new services must be considered to sustain supply continuity and power quality, increase the operation efficiency, achieve fuel cost savings and reduce environmental impacts. While these alternatives may influence different stakeholders across the power chain, their impact is continuously being studied and compared. In recent times, all three aspects of the energy trilemma—affordability, reliability and sustainability—must be tested.

This work provides a broad overview of existing and emerging potential power services that enhance the flexibility in existing and future power systems. Developing a deep understanding of the individual requirements and preferences of various services in the power chain from central generation to end user, the state-of-the-art approaches capable of supporting these services in the upcoming smart grids are reviewed and analysed, along with their key components and operation principles. An updated summary and guide to the information extensively published in the literature is separately approached from the perspective of each stakeholder's objectives in the power system.

The rest of the chapter is organized as follows. In Sect. 2, emphasis is given on the potential power system services and the different categories identified across the power chain. In Sect. 3, a variety of sustainable approaches that can efficiently make use of the available RES is discussed, with special focus on their principle advantages. The importance of the state-of-the-art approaches for future smart grids along with their roles for different stakeholders is analysed in Sect. 4. Finally, the conclusions are drawn in Sect. 5.

2 Potential Power System Services

The potential services identified across the power system chain to incorporate RES can be categorized by the duration of their application into power quality regulation (short-term), bridging power (medium-term) and energy management (long-term) services, as summarized in Table 1.

Table 1 Classification of services by category and function performed

Category	Service	Function
Power quality and regulation	Fluctuation suppression (FS)	Absorb/inject energy to smooth generation from intermittent RES
	Frequency regulation (FR)	Increase/decrease the output to continuously maintain nominal frequency
	Voltage regulation (VR)	Absorb/inject energy to remain connected throughout a short voltage drop
Bridging power	Load following (LF)	Withdraw/inject energy to accurately adapt power output to changing demand
	Spinning reserve (SR)	Store/provide energy to replace production deficit of spinning reserves
	Congestion relief (CR)	Store excess generation and inject back when the delivery capability is available again
	Emergency backup (EB)	Operate as a complement or substitute to an emergency diesel generator
Energy management	Load levelling (LL)	Charge and discharge as needed to reduce the gap between peak and off-peak
	Peak shaving (PS)	Store/inject energy at off-peak/on-peak demand periods
	Energy arbitrage (EA)	Consume energy during low market prices and release when market prices are higher
	Demand shifting (DS)	Absorb energy during low time-of-use charges and return at high time-of-use charges
	Seasonal recovery (SR)	Long-term electricity storage to recover large seasonal variations at a later stage

2.1 Power Quality Regulation

Power quality regulation services include the fluctuation suppression, frequency regulation and voltage support, to ensure that the provision of power is reliable and maintains nominal voltage levels, unity power factor, nominal frequency levels (50 Hz or 60 Hz depending on the country's standard) and a purely sinusoidal waveform with zero harmonics and no transients. These services are the fastest acting, requiring rapid-response times and operation within milliseconds to minutes.

Fluctuation suppression is needed to mitigate fast output variations and smooth generation from intermittent RES. These fluctuations usually occur due to variations in weather conditions which in turn disturb the system stability. Voltage and frequency deviations from nominal values by means of short-term spikes or dips, and long-term surges or sags, as well as interruptions in service of any duration, can be fatal for some power electronic, information and communication systems in the grid. Up to a certain RES penetration rate, this can be managed by existing flexibility sources. As the penetration increases, it may compromise the whole system's stability, especially in weak or isolated grids [9].

Figure 1 demonstrates a representative example of such variations. Although daily forecasts exist, it is impossible for power output from RES to be predicted accurately, leading to generation–demand imbalances reflected as nominal frequency deviations. Assuming the RES output as negative load, these variations occur in system demand, allowing to define the importance of the second service in category. Frequency regulation involves flows interchanges between generation and demand to match the moment-to-moment deviations.

Besides, stable voltage must be guaranteed along the whole range of a power system. Voltage degradation often takes place due to the weakness of the power grid to withstand the dynamic changes in active and reactive power. This may be caused by undesired harmonics introduced to the grid by power electronics (converters) used to facilitate RES integration.

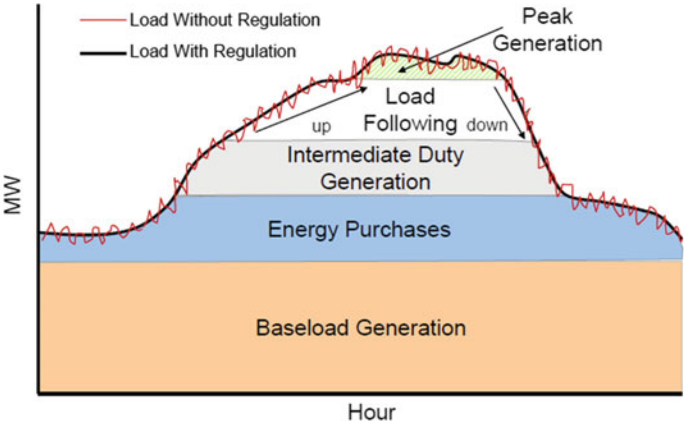


Fig. 1 System load without and with frequency regulation [12]

2.2 Bridging Power

The main objective of this category is to provide a bridge between the limited generation capability of RES and highly variable electricity demand. Bridging power services require medium-response times and operation within minutes to hours. They support load following, spinning reserve, congestion relief and emergency backup operations.

Increasing RG penetration seems likely to increase the need for load following resources for a more dispatchable electric supply mix. The alternative sources must be characterized by good ramping capabilities to efficiently meet the mismatches between production and consumption, shaping the energy profile and mitigating the variability [10]. On the other side, spinning reserves are required to deal with uncertainty and thus scale according to RES participation levels. Their role is to replace production deficit because of unexpected failures or forecast errors. Spinning reserve constitutes a key constraint in modern power systems and is planned ahead considering the predicted RG and power demand. Its maximum value is estimated by taking into account the ramping capacity of each committed thermal generating unit [11].

At any given point in time, the transmission system may not have enough capacity to transfer the energy generated by all RG systems, causing "congestion" on the grid (i.e. too much energy to be transferred through the available transmission capacity). Instead of being curtailed, flexibility resources (located either upstream or downstream) could be used in lieu of upgrading transmission or distribution to accommodate wind or PV generation during times when congestion occurs [12]. This way, both transmission and distribution curtailment are reduced, and investment upgrades are deferred for years, while improving the utilization factor of the existing network.

Bridging power services can also provide a source of backup power that allows ride-through unexpected RG shortfalls and continue normal operation. The principle of system control that classifies loads by priority and employs load shedding is not suitable for achieving high reliability in modern systems [13, 14]. Hence, emergency reserves could be deployed when wind velocity is considerably lower than predicted or during a cloud occurrence, until conventional generation can ramp-up (or even start-up). The ability of a power system to sustain the generation connected to the grid throughout a short voltage drop or a total failure of the system is crucial, in order to avoid a possible chain event, where the voltage may be forced to drop further and down far enough to force another generator to trip and so on [9].

2.3 Energy Management

Energy management services call for long-term applications in a range between hours to days or even months. They definitely decouple the timing of electricity generation and consumption through time-shifting operations and are typically distinguished in the literature into load levelling, peak shaving, energy arbitrage, demand shifting and seasonal recovery.

Electricity prices tend to a daily pattern of low prices during nighttime off-peak hours and high prices during day-time on-peak hours. On the contrary, RG cannot strictly follow such rules, adding variability to the residual load and subsequent volatility to electricity prices. This calls for load levelling services to leverage the gap between peak and off-peak. Regardless of season, weekday or weekend, the maximum peak demand may approximate twice the average value, leading to oversized both conventional and RG. Peak shaving is based on providing the power surplus, thus effectively “shaving” the total exchanged power in order to avoid surpassing the programmed set-point. This is translated as de-activation of expensive peak generation plants and improved operational efficiency [15]. Hence, fuel consumption and associated emissions can be reduced to a minimum.

Energy arbitrage is another paradigm of time-decoupling services able to facilitate a transition towards de-carbonization. In the presence of variable RES, energy arbitrage consumes energy during low market prices and releases energy when market prices are higher. Functioning in such a manner, it prevents consumers from being exposed to highly unstable electricity prices [16]. In a similar manner, customers may benefit from shifting their demand, exploiting time-varying demand charges through absorbing or returning energy during low or high time-of-use charges, respectively.

Finally, seasonal recovery may constitute the only way to allow bulk energy from RES to be absorbed by the grid. Such a long-term service can meet the yearly averaged demand with much lighter designs and consequent improved economics, especially for power systems exposed to large seasonal variations [10].

3 Sustainable Approaches

Global efforts are already shifting towards the 2030s targets, which are generally focused on even more increases in RES contribution, greater efficiency improvements and further greenhouse gas (GHG) emission reductions. This involves the electrification of both the heating/cooling and transportation sectors, adding considerable variability and uncertainty to the grid.

However, as a secondary energy source, electricity can be generated from the conversion of other sources of energy; the commonly used conventional sources are coal, natural gas, oil and nuclear, while renewable sources include solar, wind, hydro, biomass, geothermal, tidal and ocean waves. Since electricity cannot be stored as its demand rises and falls by season or during day portions, either additional generating amounts in reserve or controllable loads may be immediately brought on-line, in order to be dispatched and serve the variations in demand [17].

With the fast-paced changing technologies in the context of sustainable development, new approaches and concepts are coming to light. The main challenge remains in developing technologies that can efficiently make use of the available RES.

3.1 Electricity Storage Techniques

The only way to store the electrical energy is by converting it to other forms of energy, such as mechanical energy, chemical energy, electrochemical energy and electromagnetic. Electricity storage can be realized through different methods and several technologies to capture the energy when it is available and use it at a later time [18]. Through time-shifting, the power generation can be regulated to match the loads. Figure 2 shows a classification of various electricity storage systems (ESSs) by the form of stored energy.

Mechanical technologies accommodate flywheels, pumped hydro energy storage (PHES) and compressed-air energy storage (CAES) systems. Secondary batteries and flow batteries fall into the electrochemical category, whereas regenerative hydrogen (H_2) and synthetic natural gas (SNG) fuel cells (FCs) belong to chemical storage. The last category involves capacitive and inductive technologies, namely electrochemical double-layer capacitor (EDLC) and superconducting magnetic energy storage (SMES).

Each ESS has its unique characteristics, and hence, any single ESS cannot be suited to all the applications in the field of the power system. These characteristics refer to power rating, response time, storage duration, autonomy of operation, round-trip efficiency, lifetime, investment and overall lifetime costs. The necessary information found in the literature is listed in Table 2.

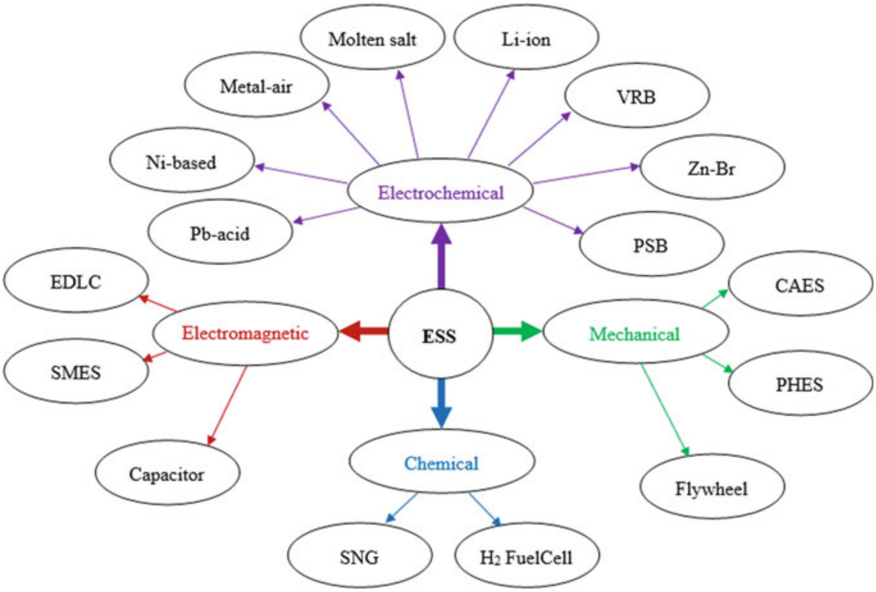


Fig. 2 Classification of ESS by the form of stored energy

Table 2 Comparisons of ESSs [10, 21]

ESS	Power capital cost ($/kW)	Energy capital cost ($/kWh)	Energy capacity (MWh)	Power rating (MW)	Daily self-discharge (%)	Round-trip efficiency (%)	DoD (%)	Response time	Suitable storage duration	Autonomy at power rating	Lifetime (years)
PHES	600–2000	5–100	500–8000	100–5000	Almost 0	70–85	95	min	hours–months	1–24 h	30–50
CAES	400–800	2–50	<1000	5–300	Almost 0	42–54	100	min	hours–months	1–24 h	30
Flywheel	250–350	1000–5000	0.75	0–0.25	55–100	90–95	100	ms	seconds–minutes	15 s–15 min	20
Pb-acid	300–600	200–400	0.001–40	0–20	0.1–0.2	85–90	80	ms	minutes–days	seconds–hours	5–15
Ni-based	500–1500	800–1500	6.75	0–40	0.1–0.2	60–90	100	ms	minutes–days	seconds–hours	10–20
Zn-air	100–250	10–60	–	0–0.01	Almost 0	50	100	min	hours–months	seconds–24 h	0.17–30
Na-based	>1000	300–500	0.4	0.05–8	Almost 0	89–92	100	ms	seconds–hours	seconds–hours	10–15
Li-ion	1200–4000	600–2500	0.004–10	0–0.1	0.03	~100	80	ms	minutes–days	minutes–hours	5–15
VRB	600–1500	150–1000	2	0.03–3	Almost 0	85	100	ms	hours–months	seconds–10 h	5–10
ZnBr	700–2500	150–1000	4	0.05–2	Almost 0	75	100	ms	hours–months	seconds–10 h	5–10
PSB	700–2500	150–1000	0.06	1–15	Almost 0	75	100	ms	hours–months	seconds–10 h	10–15
H_2-FC	500	15	0.312	0–50	0.06–3	20–50	90	s	hours–months	seconds–24 h	5–15
EDLC	100–300	300–2000	0.0005	0–0.3	20–40	85–98	100	ms	seconds–hours	seconds–hours	10–12
SMES	200–300	1000–10000	0.015	0.1–10	10–15	95	100	ms	≤30 min	minutes–hours	20+

While energy capacity is the maximum energy a storage device can hold, power rating is defined as "the maximum rate at which energy can be transferred into and out of the device" [19]. Broadly, ESS is divided into three types according to their power rating. PHES and CAES are suitable for large-scale applications (>100 MW). Lead-acid (Pb-acid), nickel-based (Ni-based), polysulfide bromide (PSB) flow battery, SMES and regenerative FCs are suitable for medium-scale (10–100 MW), while flywheels, EDLC, vanadium-redox (VRB), zinc-bromine (ZnBr), molten salt (sodium- or Na-based), Zn-air and lithium-ion (Li-ion) correspond to small-scale applications of lower than 1–3 MW.

As per power system requirements, some services like power quality regulation require very fast response from the ESS (in milliseconds), and therefore, ESS must respond in time accordingly. According to the timescale of response, various EES are distinguished as fast, relatively fast and not rapid. With response times within milliseconds to seconds, flywheels, EDLC, SMES, all kind of batteries and flow batteries are falling into fast-response systems. Regenerative FCs provide relatively fast response in the range of seconds, whereas PHES and CAES offer slower response times of a few minutes.

Storage duration of the ESSs depends on the self-discharge of the system. It is a key element which helps distinguish ESS technologies into short-term (seconds–minutes), medium-term (seconds–hours) and long-term (minutes–days). Short-term storage is provided by flywheels due to their very high daily energy dissipation. Medium-term storage is offered by electromagnetic systems (EDLC and SMES) and Na-based batteries, due to increased parasitic losses and because self-heating needs to maintain the operating temperature, respectively. PHES, CAES, regenerative FCs along with the rest of secondary and flow batteries are capable of providing long-term storage duration. However, Pb-acid, Ni-based, and Li-ion batteries have a moderate self-discharge rate and consequently they become inappropriate for storage durations longer than the tens of days.

Another important attribute related to storage capability regards autonomy, which is extremely important for isolated systems and microgrids relying on intermittent renewable sources. It determines the duration that an ESS system is able to continuously supply energy. Therefore, storage technologies can be classified in terms of their energy capacity (amount of stored energy) against the power they can deliver (power rating). Typically, less autonomy is expected from electromagnetic devices and flywheels. Higher autonomy can be provided by Pb-acid, Ni-based, Na-based and Li-ion batteries while PHES, CAES, flow batteries, Zn-air and regenerative FCs are considered capable of supplying power autonomously for several hours [20].

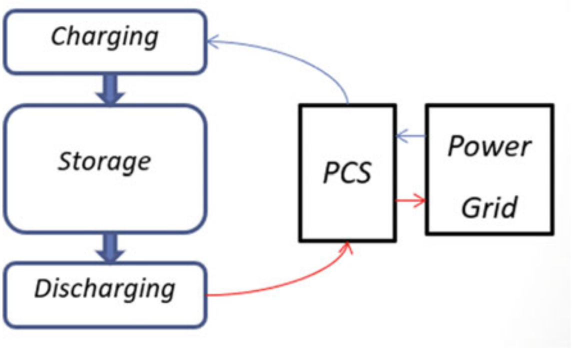
The ratio of output-to-input electrical energy for a storage device throughout the charge and discharge of the device can be defined as its cycle or round-trip efficiency. Very high efficiencies (>90%) appear in electromagnetic storage systems, flywheels and Li-ion batteries. Other batteries and flow batteries display high efficiencies of over 60%. CAES, Zn-air and regenerative FC are more energy-intensive conversion processes and thus exhibit low efficiencies, which in the case of regenerative FCs may fall by up to 20%. It must be noted that efficiency becomes a crucial factor in some applications and even the cheapest technologies may be considered unsuitable.

Additional factors affecting the overall investment cost are lifespan and cycle times. Electromagnetic devices provide extremely high cycling capability due to the absence of moving parts and chemical reactions. Mechanical components normally determine the lifetime of PHES, CAES and flywheel systems, whereas all kinds of chemical EES systems are deteriorated by time due to the degradation of chemical elements and electrolytes [9]. Apart from significant improvements in efficiency and extended lifetimes, capital and O&M costs tend to decrease by increasing R&D efforts. In this sense, mature and commercialized PHES and CAES offer the lowest energy capital cost, becoming appropriate in large-scale/long-term applications, followed by Zn-air and regenerative FCs which need further development to be proved as efficient.

Capital cost is among the most influential factors governing the commercial deployment of the ESS. While specific power and energy can be quite different, the power and energy capital costs are largely decoupled from each other. Generally, the capital cost is expressed in power cost ($/kW) and energy cost ($/kWh) to determine the costs related to the power conversion systems (PCS) and energy storage medium (ESM), respectively (Fig. 3). In terms of power capital cost, flywheel, EDLC and SMES systems are suitable for high-power/short-term needs along with developing Zn-air and regenerative FCs. Flow batteries and Li-ion are still far too expensive, while the rest of batteries are in between. However, overall expenditures of an EES facility consider both the investment and operation (purchased energy, fixed and variable O&M costs). Regarding O&M costs, electrochemical technologies that require chemical handling are disadvantageous relative to the others, followed by technologies that need additional equipment to maintain the energy stored [21]. In this regard, various ESSs are considered favourable or unfavourable in terms of functions they perform for different stakeholders and their exact placement location in the power grid.

Electricity storage has more complex operational requirements than conventional network assets due to their limited energy capacity. Within the literature on ESS sizing, a variety of techniques are proposed, including linear search optimisation

Fig. 3 Demonstration of ESS operation



algorithms, gradient-based algorithms, stochastic optimisation algorithms or heuristic techniques. Moreover, as the number of technologies available to ESS developers has increased, there has been an increased interest in algorithms to inform the selection of the most appropriate technology for a given application. However, it is shown that combinations of ESS technologies that integrate supplementary operating characteristics can be more economically viable solutions. On the other hand, the provision of multiple services by making use of a single electricity storage asset consists of an alternative approach that can increase its profitability [22].

3.2 Power-to-Work Alternatives

While energy storage consists of preserving a quantity of energy for later use, power-to-work alternatives mean the storage of the material containing the energy. Because of the intermittence or fluctuation of renewable energy, this operation ensures a longer-term continuity of the availability of energy. This concept stems from the nature of fossil fuels which are already available as reservoirs of stocks in their natural state. Even when they are extracted, they can easily be isolated, transported and stored [23].

The most common approaches regard hydrogen (H_2) and synthetic natural gas (SNG) production via electrolysis and storage for later use in other activities. Power-to-gas appears a promising pathway to decarbonize power production and store energy indirectly. Gas storage systems enable the process of carbon capture and storage (CCS) to be integrated and based on electrolysis, to increase both the flexibility of the power system and the share of bioenergy. This comprises power conversion to hydrogen through electrolysis with the possibility of further combining it with CO_2 from different sources (e.g. carbon capture, biogas, air) to produce methane [24].

Power-to-liquid includes co-electrolysis of CO_2 and H_2O, hydrogenation of CO_2 and reverse water gas shift (RWGS) to produce syngas (synthetic gas) and then fuel through Fischer–Tropsch or methanol. Another possible route is direct electroreduction of CO_2 to methanol. Power-to-chemicals is another option of power-to-work approaches. Once CO_2 and H_2O are converted to syngas, a multitude of compounds can be produced including solvents, formic acid, alcohols, waxes, among others [25].

Alternatively, green methods can be applied for their production, providing them as chemical substance rather than fuels. Although these methods are not presently available with reasonable efficiency and cost, implementations for RES integration purposes can be considered feasible [26, 27]. It is expected that to achieve 100% RES scenarios (with a large contribution from variable RG) they will be needed. Water desalination, water heating for district heating purposes, timing, the use of municipal water pumping and irrigation systems are some further examples which could be also considered viable alternatives [9].

3.3 Distributed Energy Resources

Over the last few years, the reserve capacity in transmission has been falling due to increase both in electricity demand and generation capacity. An obvious solution may lie on building more transmission lines and improve reliability protocols. The not so obvious alternative is to integrate generation within the distribution system. This can result in line loss reduction, reduced environmental impacts, transmission and distribution congestion relief and deferred investment to upgrade existing generation, transmission and distribution [28]. A cooperation scheme is presented in Fig. 4.

The term distributed energy resources (DERs) comprises distributed generation (DG), electricity storage systems (ESSs) and even vehicle-to-grid (V2G) mechanisms. Many drives lie behind the evolution of DERs, mainly, enhancing the capability of producing energy locally (within distribution networks), and consequently reducing energy losses due to distant transmission. Also, the awareness of customers of their individual consumption may help reduce energy consumption and moving

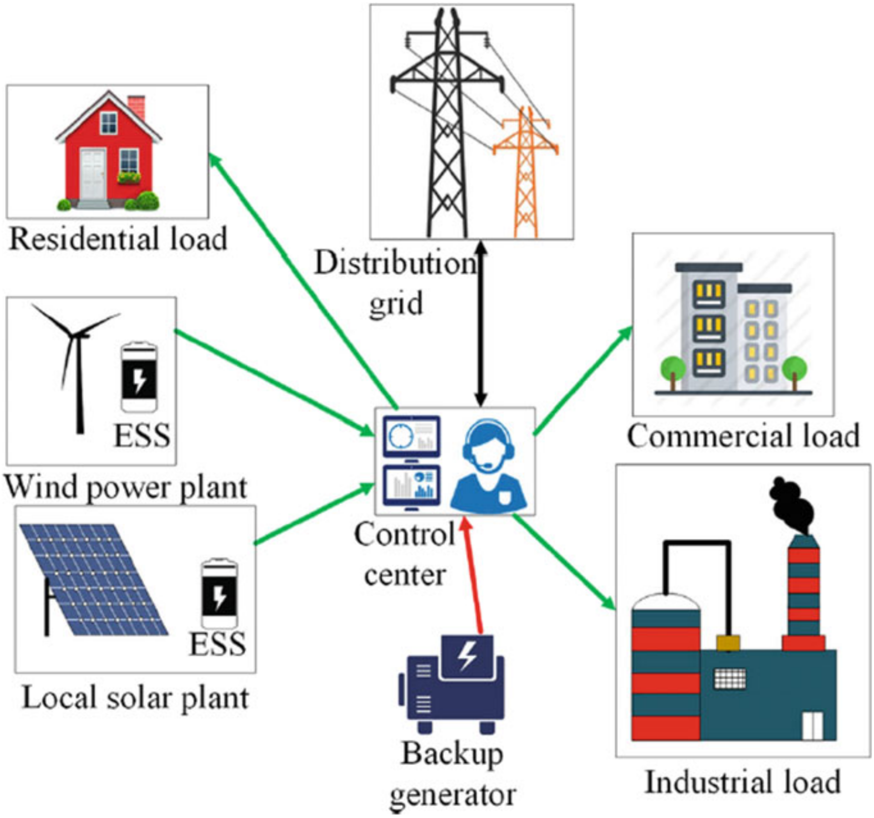


Fig. 4 Distributed energy resources cooperation scheme [20]

them from consumers to producers of power by installing power generation in their resident areas [29].

Since 2010, there has been transformational growth in the installation of distributed rooftop PV, primarily across residential customers, driven in part by government incentives and the avoidance of high retail electricity rates. This pattern is expected to become more extreme, based on projections for additional solar PV installations over time driven by commercial and industrial deployment [30].

DG is generally defined as the generation of electricity by facilities that are sufficiently smaller than central generating plants so as to allow interconnection at nearly any point in the power system. DG units are the emerging micro-generating technologies such as microturbines, fuel cells, and internal combustion engines (ICE). It also makes use of renewable energy sources such as PV arrays and wind turbines. Applying to the distribution (MV or LV) level, the DG units have low emission rates and are environmentally friendly and economical [31]. In comparison, DG is seen as less investment-intensive and would bring savings across the field in the form of lower electricity prices [32].

3.4 Demand Response Versus Demand-Side Management

Most developed countries to support renewable energy production and distribution promote grid-tie systems with "net metering" type concepts that do not require storage medium. The energy transformed is directly injected in the grid via a controller [33]. This turns the small-scale consumers into "prosumers" (consumers who become involved with generating, storage, using and providing electricity for their own needs) connected to the power system through LV grids [34, 35].

Such policies had created the conditions for the boost in PV installations which are being continuously upgraded to cover the increasing needs of electric vehicles (EVs), hybrid electric vehicles (HEVs) and plug-in hybrid vehicles (PHEV). A boost is also given to ESS (especially to batteries) to extend their power ratings, energy density and storage duration performance. Although currently the HEV uses mostly batteries to save fuel in acceleration phases and charges it while braking, it is expected that a more price-responsive behaviour will occur through the so-called grid-to-vehicle (G2V) and vehicle-to-grid (V2G) techniques [36].

Demand response (DR) is defined as changes in electricity usage by end-use consumers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized. From the sustainability point of view, this reduces the overall cost of the system, keeping energy prices lower, and avoids the production of electricity with the most polluting technologies (e.g. coal or oil) [32].

DR programs can be divided into two basic categories, namely time-based programs and incentive-based programs. In time-based programs such as time of use

(TOU), real-time pricing (RTP), and critical peak pricing (CPP), the price of electricity varies according to the supply cost of electricity for different time periods. Incentive-based programs are included in direct load control (DLC), interruptible/curtailable (I/C), emergency demand response program (EDRP), capacity market program (CAP), demand bidding (DB) and ancillary service (A/S) programs. In DLC and EDRP programs, there are voluntary options and if customers do not interrupt their consumption, they are not penalized. I/C and CAP are mandatory programs and the participating customers must pay penalties if they do not curtail when directed. DB program persuades customers to provide load reductions at a price at which they are willing to be curtailed or to identify how much load they would be willing to curtail at posted prices. A/S programs allow customers to bid load interruptions in electricity markets as operational reserves [37].

Demand-side management involved utility control of interruptible loads to improve the efficiency of buildings or industrial sites starts by preheating or precooling buildings, water heating and other kinds of interruptible loads. It deals with the temporal component and can be in direct competition with storage. It enables shifting the peaks in the load aiming to make it more stable and match the generation curve. Costs are usually low, related to automated switches and IT equipment O&M [25]. The proposed control strategy consists of predicting the generation and consumption pattern for all appliances, exploiting the potential to reach a global objective and deciding at what times appliances are switched on/off, when and how much energy flows from or to the buffers, as well as when and which generators are switched on.

The set of demand-side management choices can also include power-to-work alternatives (mentioned in Sect. 3.2), power-to-heat and power-to-mobility. Power-to-heat (electric boilers, heat pumps) links the surplus directly to a need, eliminating the inefficiency due to intermediate energy carriers (e.g. gas). Thermal storage uses electricity as an input to either cool or heat water or another storage medium where the energy is stored to serve subsequent cooling or heating needs. Primary options for thermal energy storage available for deployment today are direct load control of resistive electric water heaters or electric heat pump water heaters, chilled water storage, ice storage, chilled energy storage for inlet air cooling, heat pump/borehole, ceramic bricks, molten salt, high-temperature phase-change materials and space heating [38].

Power-to-mobility makes the direct match between power surplus and demand in the mobility sector through electric cars specifically. This is more efficient, since it substitutes the internal combustion engine (ICE) (efficiency of ~20%) or fuel cell (FC) (~50%) with an electric motor (~90%) [25].

3.5 Microgrids

Microgrids may be a hot topic among those forecasting key future trends shaping the world's energy infrastructure. A microgrid (MG) is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. MG can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode. Hence, rather than having to track and coordinate thousands or millions of individual distributed energy resources, each microgrid appears to the distribution utility as a small source or consumer of electricity with the ability to modify the net load profile in ways that benefit the main grid [39].

Inverters can play an important role in frequency and voltage control in islanded MGs as well as facilitating participation in black start strategies. Perhaps the most compelling feature of MGs is the ability to separate and isolate themselves (islanding) from the utility's distribution system during brownouts or blackouts. Additionally, all distributed generation, whether renewable or fossil-fuelled, must shut down during times of power outages, unless it can control voltage and not feed power back to the larger utility grid [40].

The interface with the main grid can be a synchronous AC connection or an asynchronous connection using a DC-coupled electronic power converter. Since most distributed energy resources (including fuel cells, solar PV and batteries) provide or accept DC electricity and many end loads use DC internally, full-DC microgrids have been proposed. The first advantage of making use of DC formations derived from the avoided losses from converting between DC and AC (and often again back to DC) power. These losses can range from 5 to 15% of power generation depending on the number of back-and-forth conversions. Additionally, faults in DC systems can be simply isolated with blocking diodes. This way the issues of synchronization, harmonic distortion and problematic circulating reactive currents are also alleviated. Lastly, a grid-tied DC-based, non-synchronous architecture simplifies interconnection with the AC grid and permits straightforward plug-and-play capabilities in the microgrid, allowing addition of components without substantial re-engineering [39, 41].

Deploying intermittent renewables with co-located flexible loads and storage technologies in microgrids allows for local supply/demand balancing and makes widespread distributed renewable contribution more manageable.

3.6 Interconnections

Network expansion via interconnecting of adjacent power grids deals with the spatial component in both generation (areas with different variable RG patterns) and demand, besides enabling RES installation where they have the largest potential. Power system isolation and weakness is typically observed in islands. However, for most islands the sunlight is sufficient for generating abundant electricity from PV in summer, while in winter the main contributor to electricity supply is wind power. In addition, the islands may give priority to utilizing the hydropower during rain seasons [42]. It is evident that interconnections open the pathway for hybridization in terms of renewable energy systems cooperation.

3.7 Virtual Power Plant

The main concept of virtual power plants (VPPs) is based on a centralized control structure which connects, controls, and visualizes a work of distributed generators. VPP relies upon software systems to remotely and automatically dispatch and optimize generation or demand-side or storage resources in a single, secure Web-connected system [40].

Combined heat and power generators (CHP), FCs, RG systems, heat pumps (HP), ESS devices and any other source of power (renewable or non-renewable) and end consumers (both interruptible and non-interruptible loads) might be aggregated and cooperate in the local area [43]. Figure 5 depicts a conceptual demonstration of a VPP scheme. VPP is a flexible representation of a DER portfolio that can be used to make contracts in the wholesale market and offer services to the system operator. Aggregating the capacity of many diverse DER, it creates a single operating profile from a composite of the parameters characterizing each DER and incorporates the impact of network on aggregated DER output [44].

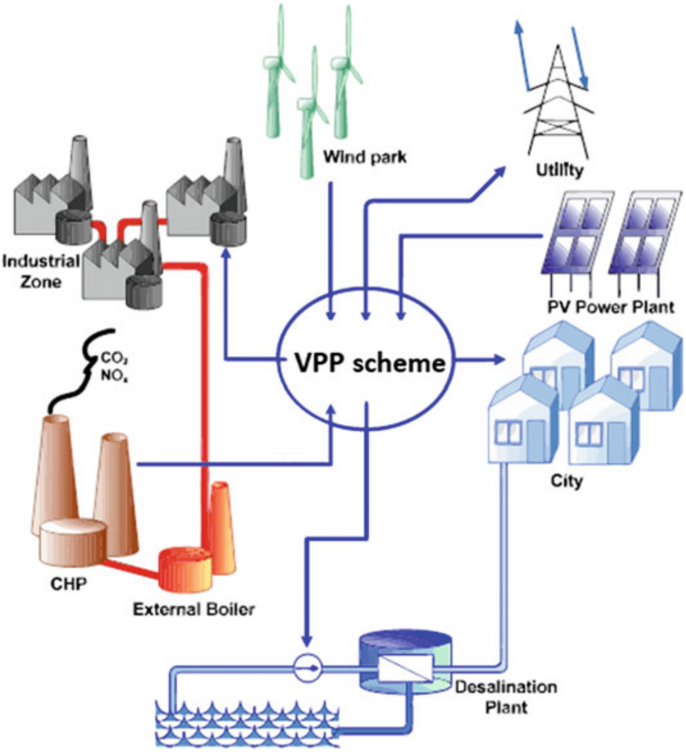


Fig. 5 Conceptual structure of the VPP [43]

VPP provides an opportunity to lower the load in the power network by minimizing or even eliminating a portion of energy losses by a factor. More power is generated locally and is shared by participants without the need to transmit it over long distances at high tension. Heading the VPP is a computer system controlled by the distribution system operator (DSO). Irrespective of how much generation capacity is installed in a single building, the most important feature is connecting all the sources together and running them so as to obtain a state of self-balance in the most effective way. VPP places more attention on local generation, meaning that central generation can operate in more stable conditions.

VPP could be defined the same as an autonomous microgrid able to be used in three different topologies: (1) the centralized controlled VPP (CCVPP) constitutes a design in which all control logic lies with the VPP and all knowledge about the market and the planning of production is separated from the DER; (2) the distributed controlled VPP (DCVPP) where a local VPP supervises and coordinates a limited number of DERs while delegating certain decisions upwards to a higher level VPP; and (3) the fully distributed controlled VPP (FDCVPP) where each DER acts as an independent and intelligent agent which participates in and reacts to the state of the power system and market [45].

The biggest advantage of VPP is its modular structure. It can be connected to power systems and comprises a number of DER units. Depending on requirements, extra modules can be added, in order to optimize the system, secure transmission and/or report results. VPP has the flexibility of building blocks and thus can optimize the entire system and deliver much greater value, without the need for large capital investments in infrastructure and corresponding long lead times for implementation.

3.8 Smart Grid Configurations

The evolution towards the smart grid paradigm is strictly dependent on the modernization of power grids. To achieve this target, new infrastructures, technologies and solutions are increasingly required. Any proposed solution needs to be highly scalable, distributed and possibly low cost.

One important feature of future power grids is the ability to predict the energy consumption over a wide range of time horizons. It is important to forecast not only aggregated demand but also to go deep into the individual building so that distributed generation resources can be deployed based on the local consumption, especially due to large appliances. Both information and communications technology (ICTs) and Internet of things (IoT) are fundamental to add intelligence at all levels in the grid, acting over various time horizons [46, 47]. Recent development of IoT technologies can help in managing the status of the power network. In this scenario, a key challenge is developing a cloud-based software platform for such IoT devices to cooperate and foster novel services. This should be supported by the deployment of a suitable measurement infrastructure, which is the basis for enabling complex management and control schemes [48].

Smart metering architectures enable access of new multiple actors (e.g. energy aggregators, virtual power plants and energy supply companies) to both control technologies and relevant data. Predicting the behaviour of the energy system is crucial to mitigate potential uncertainties. An accurate energy prediction at the customer level will reflect directly in efficiency improvements in the whole system. Hardware-independent interoperability among heterogeneous devices across a power system is a key requirement. This fosters competition in a fast-evolving sparse marketplace by providing new services for electrical energy management that will increase its security and reliability. Representative services may include user awareness, state estimations, demand response and demand-side management, fast fault detection, fault tolerance definitions, power quality monitoring, detection of unauthorized power usage, non-intrusive load monitoring, and so on [49].

In contrast to radial low-voltage portion, the medium-voltage part of distribution networks usually has a weakly meshed network structure, though it is radially operated. This type of operation provides possibilities for network reconfiguration and consists in modifying the network topology by operating remotely controlled sectionalizing switches to close normally open and/or open normally closed lines, while retaining the radial operation of the network. Such reconfigurations can be done for different purposes, like to redirect the power flows or to improve other performance indices [50].

A further smart grid configuration is provided with the help of energy management system (EMS). This system exploits the data collected from weather and occupancy sensors and, using them as inputs, performs output actions to manage energy and improve efficiency. It is applicable both in residential, commercial and industrial scales and is considered crucial for future digitized, smart grids where most electricity supply components will be strictly active. By making use of EMS, all functional requirements are supported and thus various approaches such as demand response, demand-side management as well as microgrid and VPP schemes could be realized [29].

The smart grid vision promises an extensively monitored and operated power network that organizes generation, transmission and distribution of electricity by facilitating two-way communications and flow of power other than one way, in comparison with current power grid. In this vision, consumers can provide their excess power to the utility grid in an interactive manner. The grid on the other hand provides the pricing and usage information over advanced metering infrastructure [51]. EMS on the customer side of the meter can then communicate through appropriate protocols with a supervisory control and data acquisition (SCADA) system. The SCADA integrates the breakers and all measurements and alarms from the core system components, (i.e. the PCS and the additional components). Time synchronization of measurements and events can be achieved by a global positioning system (GPS) clock, distributed via the network time protocol (NTP). The integrated process control (OPC) interface of the SCADA system allows to connect additional controllers and devices with a limited time resolution [52]. SCADA in turn monitors and controls the transmission and distribution equipment by means of reliability, availability and

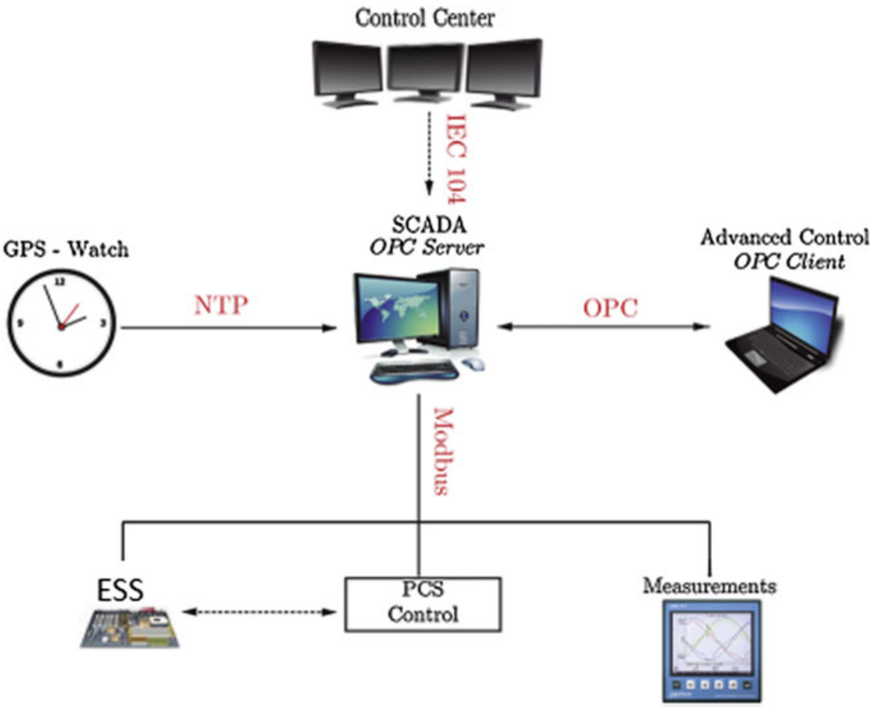


Fig. 6 Conceptual model of a smart grid [51]

efficiency, enhancing flexibility, manageability and overall system stability. Such a conceptual model is illustrated in Fig. 6.

The grid integration of EVs represents a unique and complex problem for the distribution power system. This is due to the fact that EVs act as loads while charging, ESSs during the idle state, and DG while discharging. This generates the need for a new market model that enables energy trading between consumers and prosumers in the electric distribution system. Smart parking lots are smart places that are capable of supporting both parking and charging services for electric vehicles during their parking time for a price [53]. A smart parking architecture of a typical cyber and physical system is depicted in Fig. 7.

Flexible AC transmission system (FACTS) devices constitute the equipment that can be used in the transmission system to provide dynamic voltage control and oscillation damping, improve transient stability, control active and reactive power and regulate frequency [54]. They relate to advanced technologies including: (1) power electronics to control the power flow, optimize power delivery and enhance resilience; (2) adaptive networks that provide complex interactive capabilities in order to allow the system respond to changes; (3) intelligent communications and control systems; and (4) new measurements, data analytics and models that leverage the latest scientific advancements in mathematics and computation [55]. There are three categories of

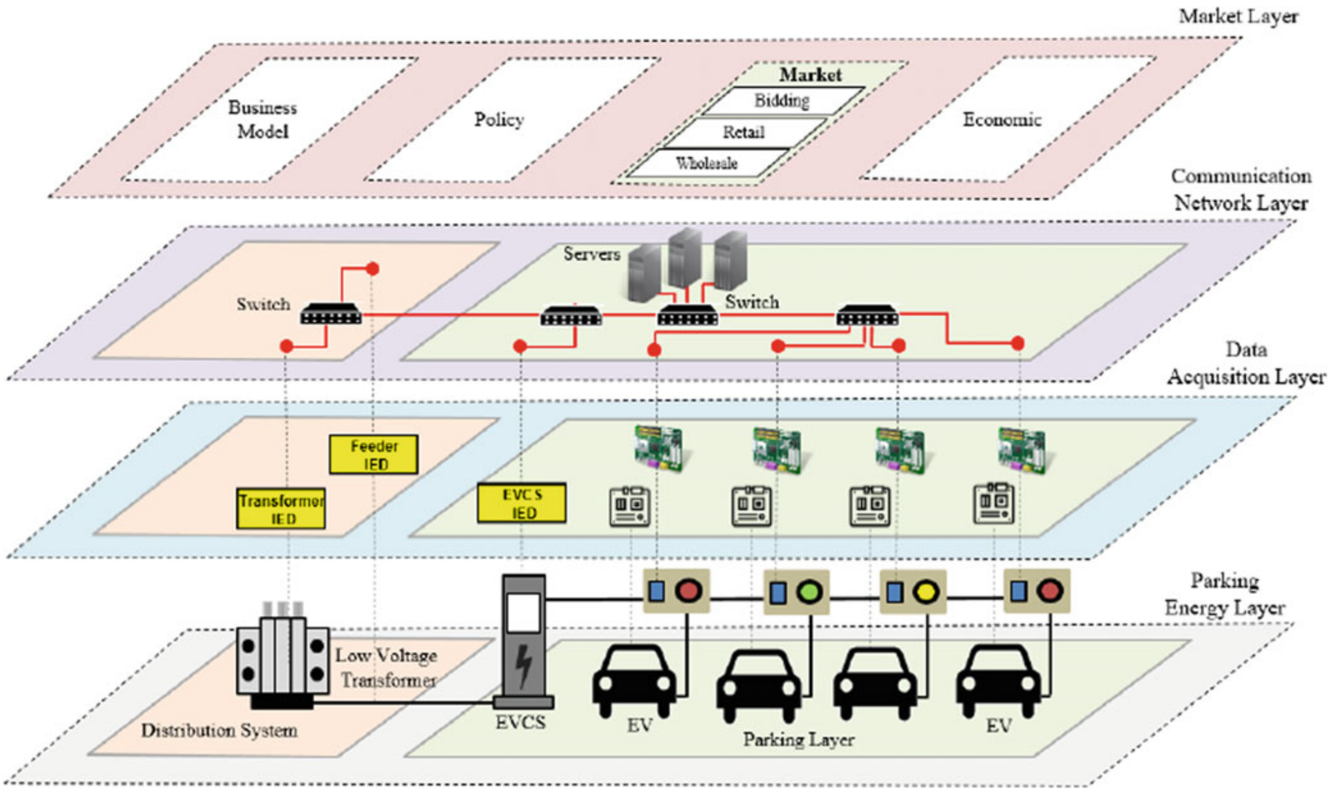


Fig. 7 Smart parking architecture example [53]

FACTS devices distinguishable by their connection to the grid, namely the series controllers, the shunt controllers and the combined series-shunt controllers. Both devices are commonly used in operations that require both rapid dynamic response and frequent variations in output, with the aim to increase utilization of transmission lines. They are extremely useful in areas where bottlenecks and less utilized power lines appear simultaneously and occur more economically viable options than ESS [56].

Smart inverters are also being conceived that could allow MGs to access smart meters and tap peak power pricing programs to help deliver ancillary services to the distribution grid, too. Furthermore, by making use of smart power electronic devices in addition with DERs, the integration of DG into the utility grid may become possible [31].

Finally, concerns exist about the power needed to run and cool high-demand data centres. Green computing comes to solve the problem not just about ecology but also for saving money and resources. The goals of green computing are to reduce the use of hazardous materials, maximize energy efficiency during the product's lifetime and promote the recyclability or biodegradability of non-operational products and factory waste. In this context, cloud computing can be seen as a smart grid component and seems to be the fastest and cheapest solution since such infrastructures address the critical elements of energy and resource efficiency simultaneously [57].

4 Main Concepts for Different Stakeholders

With the aim of enhancing system flexibility in the forthcoming smart grids, various services described in Sect. 2 can be conducted by several approaches as extensively discussed in Sect. 3. The optimal planning of such approaches includes four basic steps: (1) the appropriate type selection; (2) the optimal sizing; (3) the optimal siting; and (4) the operational strategy. These steps are distinguished by their roles for different stakeholders.

In this section, the roles of sustainable approaches involving different stakeholders (governments, regulators, balancing authorities, aggregators, retailers, RES plant owners, utility companies, transmission and distribution system operators, transmission and distribution network owners, all sorts of suppliers and end users) are summarized and categorized.

Regarding the smart grid configurations, different optimization objectives have been proposed and pursued in literature, like reducing network losses, improving the voltage profiles, load balancing, reducing service interruptions, minimizing fault currents, maximizing local consumption of renewable energy, etc. [58, 59]. The directly involved stakeholders into such reconfigurations are transmission and distribution system operators and owners since they make it easier and cheaper to design and operate the network protections. At a national level, the main focus of governmental and regulatory related efforts is the integration of DG into the current grid. Power electronics technologies offer advances which add potential functions that are not available in traditional power plants, such as plug-and-play capability for AC and DC buses [29].

Electricity price forecasting and pattern recognition are very useful for all sort of suppliers, utility companies, retailers and consumers when determining their offering and bidding strategies. Electricity demand is highly dependent on many factors including multiple seasonality (corresponding to daily and weekly periodicity, respectively), calendar effect (weekends, holidays), high volatility and high percentage of unusual prices (mainly in periods of high demand) due to unexpected or uncontrolled events in the electricity markets, weather conditions, intensity of business and daily activities, and more special characteristics such as randomness, nonstationarity and nonlinearity, which all make electricity prices fluctuate frequently [60]. According to individual smart data, smart metering will have a great impact on the efficiency of smart energy solutions. In addition, artificial intelligence techniques and smart grid approaches can set up sophisticated services for the optimization of energy consumption [61].

Through the VPP concept individual DERs can gain access and visibility across all energy markets and benefit from VPP market intelligence to optimize their position and maximize revenue opportunities. Specifically, DER owners can increase the assets value from markets and reduce the financial risk through aggregation. The DR providers (DRPs) can be defined to aggregate offers for load reduction made by determined consumers. In particular, for each hour, a DRP submits its price-quantity offer as a package. Each package offered by a DRP is bounded between a minimum and a maximum quantity for load reduction presented in several steps [37]. The main benefits for transmission and distribution system operators are the increased visibility of DER units from network, the improved use of grid investments and co-ordination between DSO and TSO. Policymakers gain a cost-effective large-scale RES integration and associated overall emissions reduction, improve consumer choices and open the markets to small-scale participants, whereas the main benefits for suppliers and aggregators are the mitigation of commercial risk and new business opportunities [44].

Microgrid represents an alternative business model for boosting the quality of grid services, particularly for end users. Similar to VPP, both of these aggregation platforms are emerging as viable options to boost reliability, shrink capital costs related to peaking generation plants, and tapping demand response (DR) resources that can help mitigate impacts of an increasing reliance upon variable renewable resources such as solar and wind power [40]. The key merits of VPP over MG are that the former can mix and match among a diversity of resources over large geographic regions and create a bridge to wholesale markets, whereas the latter can only tap DER at the retail distribution level and encompass a static set of resources in a confined geography.

The role of MG and the associated benefits depend on the control strategy. More specifically, MGs that operate without any central command and control system with generators and loads harmonizing autonomously based on local information will favour a single owner and whose top priority is reliability and sustainability during emergencies. On the contrary, for MGs that are much more focused on optimization of services outside the MG, the benefits of reliability may come second to generating new revenue streams from excess generation or even demand reductions. In this case, the aggregator is a buyer from the MG point of view and a seller from the main grid point of view [62].

MGs usually provide different advantages for consumers and power system operators such as transmission losses reduction, power quality enhancement and system efficiency increment. Small generators can participate in the energy market and consumers can profit from reliable energy. On the other hand, investments for the construction of new transmission lines, substations and bulk power generation can be postponed. The outland areas can use local power generations and independently be controlled as MG [63].

Storage systems may be either distributed or aggregated. In distributed arrangements, the ESSs are connected via individual power electronic interfaces to each RES. This way, each storage system has the responsibility for the control and optimization of the power output of the source to which it is connected. The aggregated model operates so that the whole system (e.g. a microgrid) is supported through a central ESS. Depending on the arrangement, such a system may be connected to the DC bus either directly or through a power electronic interface [13]. The revenues of such arrangements are defined as the revenues gained by ESSs in participating in load shifting of power distribution networks, mainly including direct revenues, revenues on delaying equipment investment, environmental benefits, government subsidies and revenues on reducing line loss [64].

A hybrid ESS (HESS) composed of two or more heterogeneous ESS technologies with matching characteristics can combine the power outputs and take advantages of each individual technology, hiding at the same time their drawbacks [65]. In HESS formations typically one storage technology is prescribed to cover “high power” demand, transients and fast load fluctuations and therefore is characterized by a fast response time, high efficiency and high cycle lifetime. A second storage device is typically the “high-energy” storage with a low self-discharge rate and lower energy-specific installation costs [66]. ESS owners can benefit from a total reduction in investment costs compared to a single storage system, total system efficiency improvement and strengthened system lifetimes. In this manner, energy trading with electric vehicles could provide opportunities to eliminate the high peak demand for EV charging while providing cost saving and profits for all participants.

With respect to the electric vehicle owner, the main objective is to charge an electric vehicle as quickly as possible considering a low charging cost without considering the status of neither electric vehicles nor the electricity price or grid condition. On the contrary, the main objective of retailers and the parking lot operator is to maximize the net profit. Finally, there are many operational benefits for utilities such as reduced dependence on the power grid, decreased transmission losses, improved system efficiency and balance between energy demand and supply [53]. Thus, market mechanisms are different based on actors (parking lot operator, retailers, customers, etc.) and the scale of the electric vehicle system (home, parking lots, fast charging stations, etc.).

Energy suppliers and distributors are expected to enjoy major benefits from smart grids and meters through improved energy peak-load shifting, emissions reduction, smaller meter-reading costs and reduced operational expenses. Deploying smart grids and metering promises new possibilities for self-managing energy consumption, improved energy efficiency among final consumers and transition to more consumer-centric energy systems [47]. Figure 8 presents such a cloud-based service-oriented system that assists smart city development and municipal service provision.

5 Conclusions

With the development of active power networks due to the intermittency of renewable energy and the randomness of the demand-side load, the operating uncertainty is becoming serious. At the same time, the means of controlling such networks are becoming more necessary to set the distributed generation as a decision variable, incentivise price-responsive prosumers and optimize the objectives of renewable generation utilization and user satisfaction. A wide variety of sustainable services and concepts are available to support the cooperation of flexible power sources and flexible loads, improving the predictability and manageability of various intermittent renewable energy sources.

In this work, a broad overview of the existing and emerging potential power services able to enhance the flexibility needed for the existing and future power systems has been carried out. The requirements and preferences of various services across the power chain from central generation to end users were presented and discussed in detail. The state-of-the-art approaches capable of supporting these services in the upcoming smart grids were reviewed along with their key components and principles. Also, their importance for future smart grids was analysed from the perspective of each stakeholder's objectives in the power system, providing an updated summary and guide to the vast information extensively published in the literature.

Transmission and distribution operators and owners can exploit smart grid configurations to optimally design and operate their networks with the aim to uninterruptedly supply electricity for the welfare of customers and their equipment. Through the virtual power plant and microgrid formation concepts, individual owners of distributed energy resources can gain access, visibility and benefit from intelligence to optimize their position and maximize revenue opportunities. In addition, policymakers can gain a cost-effective large-scale integration of renewable energy and associated overall emission reduction, improving consumer choices and opening the markets to small-scale participants. Finally, the mitigation of commercial risk and new business opportunities are some of the main benefits for suppliers and aggregators.

The future smart grid is expected to be a well-organized plug-and-play integration of microgrids and virtual power plants connected via dedicated high ways for

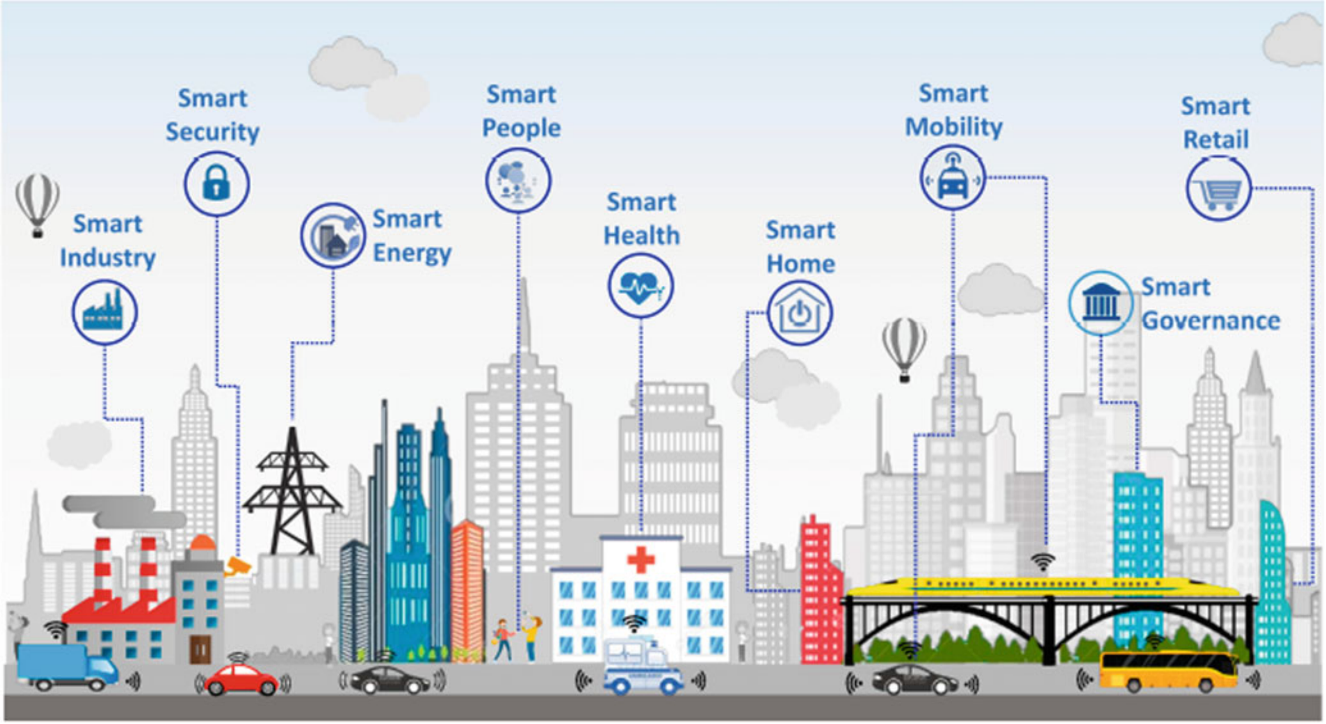


Fig. 8 Smart city overview [46]

exchange of commands, data and power. Advanced measurement devices, communication equipment and automation and control systems will make up the backbone of smart grid operations. A combination of different and multilevel approaches is expected to take place considering the technical, operational and environmental aspects to balance the benefits and cost within future power systems. All sorts of smart appliances and systems at a variety of scales are expected to synergize in the modern society of future.

From the sustainability point of view, sufficient tools and algorithms are still needed, capturing the whole range of the benefits derived from the interactions between electricity storage systems, distributed energy resources, microgrids, virtual power plants and the utility grid. This way, decision-makers will be facilitated in selecting the best-fit combination of approaches to participate and encourage them to do so in a user-friendly and market-healthy environment.

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Carbon Storage and Utilization as a Local Response to Use Fossil Fuels in a Sustainable Manner

Bernardo Llamas, Marcelo F. Ortega, María J. García and Pedro Mora

Abstract The reduction of CO_2 emissions requires the combination of measures that prevent the emission of this compound in the electrical and industrial sector. Each region will have different characteristics that should be accentuated to apply the most viable technologies. In this case, a study is carried out in the North of Spain, where a potential CO_2 store is located and, in this work, the development of a cluster CCS is studied, which is defined as the region with minimum CO_2 emissions. In this case, the connection of different industrial nodes with the storage is studied, and a cluster CCS definition methodology is proposed. Those nodes that are economically and/or environmentally unviable in connection with the geological storage may apply other technologies for direct or indirect use of CO_2.

1 Introduction

Global warming is one of the biggest challenges that humanity must solve: the use of fossil fuels since the industrial era has led to a greater presence of greenhouse gases in the composition of the Earth's atmosphere. The greatest evidence, recorded in the observatory of Mauna Loa (USA), where the milestone of exceeding 410 ppm of CO_2 in the atmosphere was reached, was exceeded last February 2019. And what is worse, the rate of growth is between 2 and 3 ppm CO_2 per year.

In this way, and if no measures are taken to stop this increase, the 450 ppm CO_2 equivalent limit established after the Paris Protocol (COPS21, 2015) for the entire twenty-first century to keep the temperature rise to less than 2 °C will be clearly exceeded. The energy transition is emerging as the main vector to reduce CO_2 emissions—considering not only the electricity sector, but also transport. The promotion of renewable sources will be the main development in the OECD countries. However, the forecasts of the International Energy Agency predict a continuous use of fossil fuels as the main primary energy in the coming decades.

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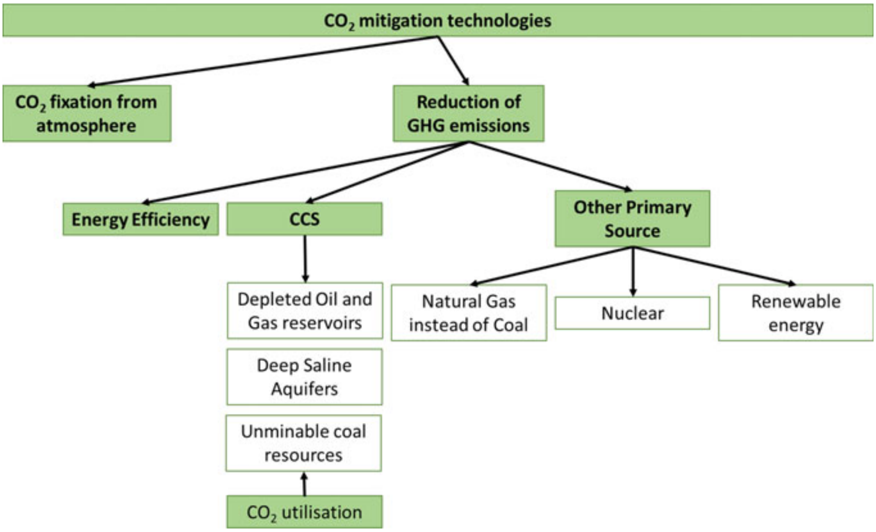

Fig. 1 Technologies considered to reduce greenhouse gas emissions

According to Fig. 1, the different strategies for the mitigation of CO_2 emissions in large stationary sources are described. Carbon dioxide capture and storage (CCS) or carbon capture and use (CCU) is recognized as one of the most promising options to mitigate the increase of atmospheric carbon dioxide concentration [1].

The study of a particular region and CO_2 sources should include the consideration of a wide range of technologies. In this case, the study and development of a cluster in the North of Spain, where there are different emission sources distributed by the region—with different characteristics and emission volumes—and a potential CO_2 storage has been defined (structure defined by the Geological and Mining Institute of Spain, and named Villameriel).

2 Carbon Capture and Storage, CCS

The CCS technology is considered for the significant reduction of CO_2 emissions in large emission sources [2]. The European Union regulated the emissions of six industrial sectors [3] in order to promote the decarbonization of these sectors.

The CCS technology is composed of three clearly differentiated phases: (i) capture, (ii) transport and (iii) storage of CO_2. Among the three phases, the last one requires a local solution to the emitting focus—considering that the competitive CO_2 capture technology can be developed anywhere in the world—which requires a country or region strategy.

2.1 CO_2 Capture

Current CO_2 capture technology (first generation) is adapted from gas separation processes already in industrial use [4, 5]. Technologies may be classified according to: pre-combustion, oxy-fuel and post-combustion. Various processes can be envisaged for separation of the CO_2 contained in a gas mixture. They are based on chemical, physical or hybrid absorption, adsorption, membranes separation or cryogenic separation [6].

2.1.1 Pre-combustion

The pre-combustion capture systems are characterized by eliminating CO_2 before the synthesis gas enters the turbine. The capture process is initiated by processing the fuel in the gasifier with water vapour and air or oxygen to produce the synthesis gas, which is composed mostly of carbon monoxide and hydrogen. This is then further converted to more hydrogen through the water-gas shift (WGS) reaction, resulting in high pressure CO_2 and H_2. Separation of these two components allows for the storage of CO_2, while H_2 can be used for a number of processes, such as power generation [7]. Finally, CO_2 is captured by a physical sorbent-based system.

The processes for CO_2 capture prior to combustion have a greater complexity than those after combustion. However, the products generated in pre-combustion have more favourable conditions for separation, high pressure and CO_2 concentration, as well as a higher efficiency.

2.1.2 Oxy-combustion

This capture process consists of carrying out the combustion in the presence of an oxidizer, pure oxygen or CO_2–O_2 mixture, instead of air to carry out the reaction.

The flue gas obtained from this system consists mainly of CO_2 and H_2O and is accompanied by minor quantities of N_2, SO_X, NO_X, Ar and Hg. The CO_2 content varies from 70 to 95%v/v in the oxy-fuel combustion, which is beneficial for the CO_2 capture and reduction of flue gas emission. Besides enriching the flue gas with CO_2, oxy-fuel combustion also has some other inherent advantages, like high combustion efficiency, low volume of flue gas, low fuel consumption and less NO_x formation [8]. This is being dependent on the process configuration, air in-leakages, fuel characteristics and the purity of O_2.

2.1.3 Post-combustion

Post-combustion capture systems separate CO_2 from combustion gases (mainly nitrogen), after the reaction of the primary fuel with air. Therefore, flue gas condition is defined by a low concentration in CO_2 and a large flow:

- Thermal power station (MW), coal: 12–14% CO_2 and volumes above 5 Mt CO_2/year.
- Combined cycle power plant (MW), natural gas: 5–7% and volumes above 3 Mt CO_2/year.

This technology can be used for existing installations based mainly on chemical absorption processes and based on amines that have an affinity for acidic compounds [9].

2.2 CO_2 Transport

To a greater or lesser extent, CO_2 must be transported from the emitting source to the geological CO_2 store, thus being necessary to deploy a CO_2 transport network [10]. For the correct sizing of the CO_2 pipeline, it will be necessary to consider:

- CO_2 should be transported in supercritical conditions (31.1 °C and 7.38 MPa) since in these conditions, the CO_2 shows optimal characteristics for transport: viscosity of a gas and a density of a liquid. In the operation of CO_2 ducts, the most common is a lower temperature and a higher pressure than stipulated in the supercritical behaviour parameters of CO_2, obtaining a very similar behaviour [11].
- Acidic character of CO_2, which can degrade some components of the transport system: elastomers, valves and others could be affected. The presence of other compounds such as water will aggravate the acid character of the fluid transported [12].

2.3 CO_2 Storage (CCS)

The geological storage of carbon dioxide is a technology directly applicable through experience in exploration and production of oil, gas, coal, waste injection and protection of groundwater. The retention time of CO_2 is hundreds to millions of years in stable structures, although the biggest drawback is the lack of knowledge of the potential and geographical location of these structures [2].

The objective is the permanent confinement of CO_2 in geological formations in safe, health and environmental conditions, in order to reduce anthropogenic CO_2 emissions into the atmosphere.

There are two fundamental requirements:

- The existence of pairs of geological storage/seals formations, with sufficient thickness and extension, and under structural conditions, guarantees the confinement of the storage.
- Injection of CO_2 must be carried out at more than 800 m depth to ensure that CO_2 is in supercritical state due to hydrostatic pressure. In addition, this fact optimizes the storage capacity of CO_2 since in supercritical conditions it behaves like a gas but much denser and occupies much less volume. The most common types of geological storage are usually: depleted oil and gas reservoirs, deep saline aquifers and non-exploitable coal reservoirs.

The way in which CO_2 moves is very conditioned by the characteristics and the heterogeneity of the storage. There is migration due to mobility difference, because supercritical CO_2 is less viscous than water, which generates greater mobility and displacement of water. A vertical flow is also generated by the density difference between saline water and CO_2 in the supercritical state which is quite significant, since the density of CO_2 at 35 °C and 100 bar is 0.71281 g/ml.

Depending on the geological and migratory characteristics of the store, the following trapping mechanisms can be classified [13, 14]:

- Structural and stratigraphic trapping. Physical confinement of CO_2, considering different layout of the storage and seal formations.
- Hydrodynamic trapping which is produced by CO_2 and water displacement throughout the storage formation.
- Residual trapping which occurs in the intergranular space due to capillarity forces.
- Dissolution trapping which is produced by dissolving the CO_2 in the water of the formation.
- Mineral trapping which is produced by the chemical fixation by reactions of the CO_2 with the storage rock and the water formation.

2.4 CO_2 Utilization (CCU)

Nowadays, many industrial applications demand CO_2 as a fluid for different uses. It demonstrates that CO_2 is a useful, versatile and safe product.

Life cycle assessment is the only normalized methodology to quantify the environmental impact of a product or a process. Although the CO_2 utilization technologies have the potential to reduce CO_2 emissions by at least 3.7 gigatonnes per year (Gt/y) [15], which are the environmental impacts of the different uses of CO_2? Life cycle assessment is the methodology proposed to evaluate those impacts.

The Carbon Sequestration Leadership Forum [16] classified the technologies into three main categories: resource recovery (e.g. enhanced gas and oil recovery), non-consumptive (reuse) applications and consumptive applications. In the following, reuse and consumptive applications are going to be taken into account.

2.4.1 Reuse (Non-consumptive) Applications

Technologies may be classified according to the CO_2-use:

- Use of CO_2 for desalination (5 kg of supercritical CO_2 would produce 50 kg of potable water),
- Use of CO_2 as a working fluid (i.e. coal cleaning; heat transfer fluid in power systems; transport media in freight pipelines; recovery or rare earth elements, treating hazardous waste via solvent extraction and others),
- Production of fuels and chemicals (i.e. gasoline, distillate fuel (diesel), methanol, acrylic acid, polyethylene carbonate (plastics), urea production, formic acid, algal fuels).

Non-consumptive CO_2-use applications have an indirect CO_2 reduction benefit in the form of production of freshwater or valuable minerals, higher efficiency or the displacement of fossil fuels.

2.4.2 Consumptive Applications

These applications involve the formation of minerals, or long-lived compounds from CO_2 leading to net-carbon sequestration by "locking-up" carbon. The primary benefits from the consumptive uses are comprised of avoided CO_2 emissions (use of mineral carbonates, and various by-products such as hydrogen, chlorine and aggregate) and the sale of the mineral carbonates and by-products.

Cuéllar-Franca and Azapagic [17] reviewed the life cycle environmental impacts of different carbon capture, storage and utilization technologies. Their conclusion is that the option that has lower Global Warming Potential (GWP) is CCS, estimated in 276 kg $CO_{2\text{-eq}}$/t $CO_{2\text{-removed}}$.

The worst CCU option was the production of dimethyl carbonate, DMC (GWP is 216 times higher than CCS), followed by biodiesel production (with a GWP four times higher). Carbon mineralization has a GWP 2.9 times higher, and enhanced oil recovery has a GWP 1.8 times higher than CCS. Although the CCS studies suggest that the GWP from power plants can be reduced by 63–82%, other environmental impacts as acidification and human toxicity are higher with than without CCS.

They conclude that the GWP of CCS is significantly lower than of the CCU options, but its other environmental impacts are higher compared to CCU except from DMC production. However, they propose to develop guidelines for the application of the LCA methodology to CCS and CCU technologies due to the inconsistencies in the system boundaries and functional units.

3 Case of Study: North of Spain

3.1 Cluster Description

According to Directive 2009/31/CE [18], a geological storage of CO_2 must guarantee access to third parties. In this way, the operation model should be based on the search for a suitable geological structure [19]. For this reason, the strategy to define a cluster must consider all the industries in a determined region. Economic and environmental conditions will limit the capacity to store totally the CO_2 emissions, but the aim of the cluster is to minimize these emissions; for this reason, not only CCS technology will be considered: some other technologies would be considered such as direct or indirect utilization of CO_2.

3.2 Villameriel Area

The structure object of the modelling is located in the Duero basin, being described in the ALGECO2 project of the Geological and Mining Institute of Spain [20]. The available preliminary information is based on: analysis of surface geology, seismic sections and stratigraphic column of the well Villameriel-1 (Fig. 2).

After the study of the geological formations, the storage formation in the Utrillas formation can be described [21]: alternation of sands and clays with conglomerates

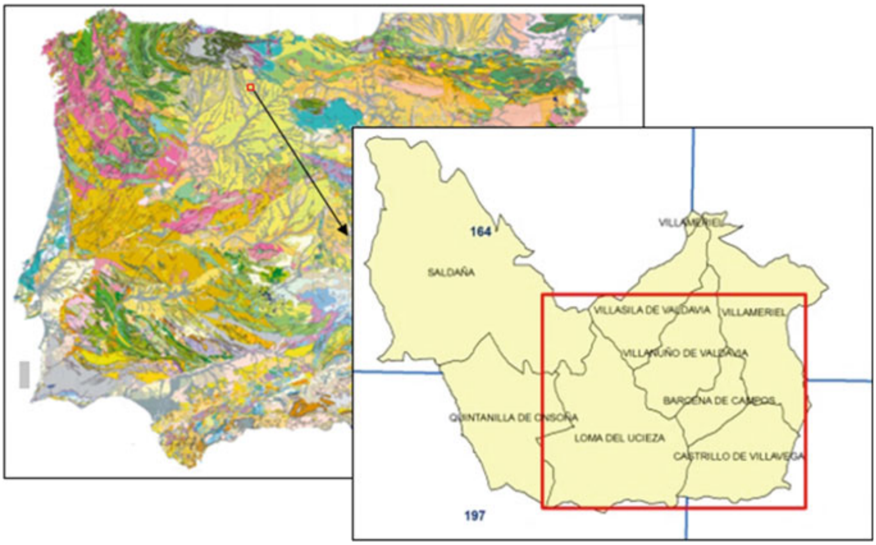

Fig. 2 North of Spain as a case of study: potential development of a zero-emission cluster

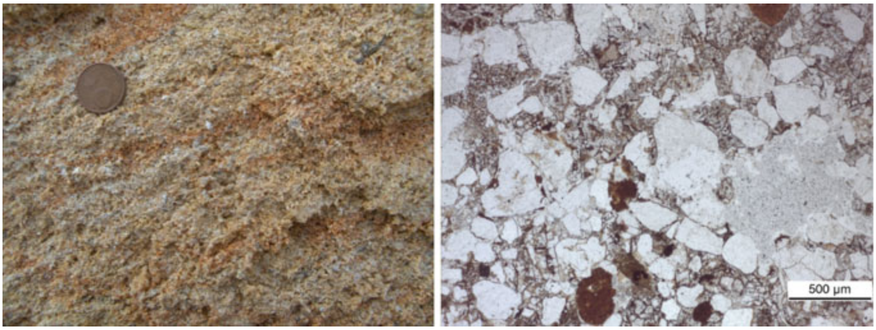

Fig. 3 Left: Utrillas sample, outcrop and right: optical microscopy of the sample (petrography analysis)

in the base with an average porosity of 14% with a thickness of 150 m and with a salinity of 60,000 ppm of $NaCl_{eq}$. The seal of the formation described above is formed by a formation consists of clays and marls of texture and varied constitution and an average thickness of 100 m (Fig. 3).

The structure is defined as a sequence of sub-horizontal layers, with an extension of 105 km^2 and whose theoretical storage volume is set at 118.5 million tons of CO_2 (Eq. 1).

Theoretical capacity of CO_2 geological storage formations (IEA GHG)

$$\text{Volume}(\text{Mt CO}_2) = \text{RV} \cdot \text{Storage}_{\text{net}} \cdot \rho_{\text{CO}_2} \cdot S_{\text{eff}} \tag{1}$$

Since RV is the total volume of rock (in this case: 7074×10^6 m^3), considering also a net storage ($\text{Storage}_{\text{net}}$) of 60% and porosity of 14%. The CO_2 density (ρ_{CO_2}) value is set at 650 kg/m^3 and, the storage efficiency coefficient (S_{eff}) of 0.3 (dimensionless).

With the density considered and knowing the geothermal gradient of the basin (25.5 °C/km), the proposed training can be considered as feasible storage.

3.3 CO_2 Transport: Storage Connection with Emission Sources. Cluster Definition

To carry out this study, the CO_2 sources regulated by Directive 2003/87/EC [22] and Directive 2009/29/EC have been taken into account. The region under study has several CO_2 emission sources, which could be representative for the case of Spain and Europe (Table 1).

According to the transport criteria [10], aspects such as environmentally protected spaces, populations and infrastructures that could be affected by the development of CO_2 transport should be considered.

Table 1 Industries and CO_2 sources considered in this study

Source	Location	CO_2 emissions (t/y) 2017
Power Thermal plant, Compostilla	León-Ponferrada	2,800,000
Power Thermal plant, La Robla	León-La Robla	1,620,000
Cement plant, La Robla	León-La Robla	721,000
Cement plant, Lemona	Vitoria	484,800
Cement plant, Cosmos(Toral de los Vados)	Leon-Ponferrada	440,000
Cement plant, Rezola - HeidelbergCement Group	Vitoria	364,566
Cement plant, Portland	Navara estación	363,555
Cement plant, Portland Valderrivas	Palencia	248,000
Energy Works	Vitoria	150,267
Energy Works Aranda	Burgos	117,000
Enercrisa	Burgos	116,000
Montefibre Hispania	Burgos	96,200
Minera Santa Marta	Burgos	33,000
Biodiesel Olmedo	Palencia	32,000
Adisseo España	Burgos	27,100
Bridgestone Hispania	Burgos	20,400
Kronospan Chemicals	Burgos	11,500
SMP Automotive Technology	Palencia	4110
Maxam Europe	Burgos	4100

3.3.1 Cluster CCS: Zero Emissions in the Industry

The potential storage of CO_2 is considered in the present study where according to the data (storage capacity and emitters), it can be established that the Villameriel warehouse would allow establishing a region with zero industrial CO_2 emissions during the next 15 years.

The transport of CO_2 and its viability are the stages that will allow to reach this zero-emission objective. To this end, the formulas indicated by the International Energy Agency will be established where it is possible to determine the cost of this stage and, in this way, determine the optimal CCS cluster.

The calculated cost includes those related to the existence of possible pumping stations, whose costs are added to the costs per km of pipeline. The installation of these pumping stations is justified by comparing the costs of their installation against the existence of longer pipes and consequently larger in diameter and greater thickness.

CO_2-pipeline investment

$$\begin{aligned}\mathrm{Inv}_{\mathrm{pipe}} = (C1 \cdot L + C2 + (C3 \cdot L - C4) \cdot D \\ +(C5 \cdot L - C6) \cdot D2) \times 10^{6} \cdot \mathrm{TF}\end{aligned} \tag{2}$$

Diameter of the CO_2-pipeline

$$D = \frac{\left(\frac{F}{v \times \pi \times 0.25 \times \rho}\right)^{0.5}}{0.0254} \tag{3}$$

The investment costs related to pumping stations, to recompress CO_2 during long-distance transport, is independent of its flow. The costs of these pumping stations are, therefore, considered constant and estimated at 7 M€/200 km for onshore compress station.

Compression Station Investment

$$\mathrm{Inv}_{\mathrm{BS}} = \mathrm{Inv}_{\mathrm{BS\text{-}norm}} \cdot L \tag{4}$$

The energy consumption for the intermediate compression station is calculated considering an average pressure difference for each station of $\Delta P = 4$ MPa, a density of carbon dioxide of 800 kg/m^3 and a pump efficiency of 75%. The energy consumed by the station is 6.7 kJ/kg (1.9 kWh/t CO_2) for every 200 km of pipeline.

Energy Consumption

$$P_p = \frac{\frac{1}{\rho} \times \frac{\Delta p}{\eta_p}}{\mathrm{Dist}_{\mathrm{BS}}} \tag{5}$$

The annual costs will be the sum of the annualized investment costs and the operating expenses, and others can be determined by the Eq. 6.

Annual Cost, CO_2-pipeline

$$\begin{aligned}\mathrm{AC}_{\mathrm{Invest+O\&M}} = -\mathrm{PMT}\big(\mathrm{DC}, \mathrm{LT}, \mathrm{Inv}_{\mathrm{Pipe}} + \mathrm{Inv}_{\mathrm{BS}}\big) \\ + \mathrm{FOMPipe} \cdot \mathrm{Inv}_{\mathrm{Pipe}} + \mathrm{FOMBS} \cdot \mathrm{Inv}_{\mathrm{BS}}\end{aligned} \tag{6}$$

In this last step, transport costs (expressed in €/t CO_2) are calculated by dividing the annual costs by the total volume of carbon dioxide transported, according to the following equation:

Cost of CO_2 transport

$$\mathrm{SC} = \frac{\mathrm{AC}}{F \cdot S_{\mathrm{per\ Y}} \cdot \mathrm{LF}} + \mathrm{CP} + P_p \cdot L \tag{7}$$

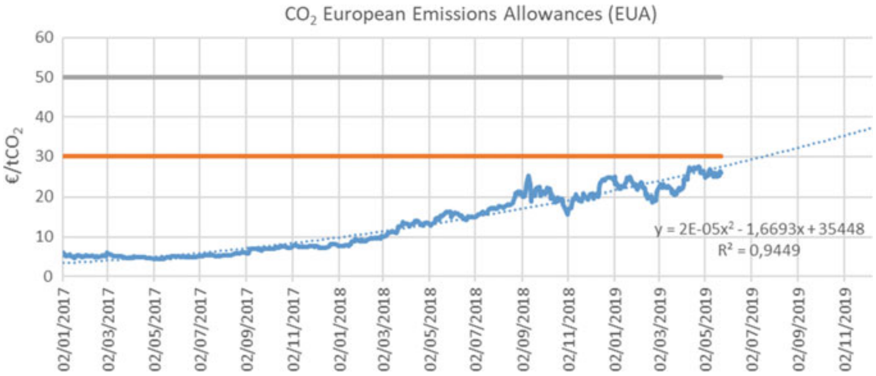

Fig. 4 Evolution of the CO_2 European Emission Allowances prize

3.4 EU Emissions Market

The European Union Emissions Trading Scheme creates an incentive or economic disincentive that pursues an environmental benefit that several industrial sectors, defined by Directive 2003/87/EC [22] collectively, reduce CO_2 emissions. The price of emission rights is closely linked to the environmental and economic policies that produce changes in energy consumption. At present, the quotation of the emission right is in clear growth (Fig. 4) after 5 years of stability (2012–2017). It seems clear that the reform agreed by the European Union in the framework of reducing emissions, which seeks to reduce the emission rights existing in this market as of 2019, has caused the cost of the tonne of CO_2 to have increased [22].

The forecasts made here indicate that during the year 2019, the reference price of €30/t CO_2 will be reached. However, in the present study, and in order to develop the cluster zero emissions, quote scenarios of 30, 50 and 100 €/t CO_2 will be considered.

4 Results: Cluster Definition

4.1 Economic Analysis

For this study, two variables are considered: volume of emissions and distance source emitter-warehouse. In this case, the differentiation between sectors—all those considered by Directive 2003/87/EC [22]—is not considered, since according to the European Directive 2009/31/EC [18] access to third parties must be guaranteed. Together with the first study in Llamas et al. [4, 10], it is considered the most favourable centralized transport compared to point-to-point transportation.

In this case, four scenarios are considered:

1. Transportation and conduction of CO_2 produced by all the industries considered in the project.
2. Transportation and conduction of CO_2 produced by the industries belonging to the centralized networks that carry the greatest volume.
3. Transportation of the CO_2 generated by the most relevant facilities in the region (more than 400,000 t CO_2/year).
4. Transport of the CO_2 produced by the power generation plants and the cement plants of the same centralized network.

A geographical information system (GIS) has been built that allows analysing and defining up to five different nodes within the cluster under study, defined by the compression points, which are defined by Table 2.

The cost associated to CO_2 transport phase is shown in Table 3. It is possible to differentiate each emitter in a specific node.

4.2 Environmental Analysis

CCS activities have the potential to affect the environment. Although each project must be analysed in detail to identify the potential environmental impacts, a brief description of this potential impacts associated with transport will be done. Transport of CO_2 through pipelines would probably be the main way of transport [23].

Leakages could occur through pipeline corrosion, physical external impacts (i.e. through agricultural practices) or through inadequate sealant materials. Small leakages could be unnoticed and could pose environmental problems to soil, water and flora through acidification.

Surficial water quality could be affected in the preoperational phase due to discharges during the pipelines testing, causing the surficial water acidification. The groundwater hydrogeology could be affected through the construction of the pipelines if groundwater is shallow. Moreover, the groundwater could get acidified due to an uncontrolled emission of CO_2 during transport, which could let to the lixiviation of metals of the surroundings. The abnormal liberation could also reduce the pH of soils, resulting in oxygen-depleted soils and in the mobilization of heavy metals. This would reduce the soil quality and could result in toxic conditions for flora.

CO_2 emissions during the operation of the pipeline could let to the deposition of impurities of the CO_2 stream in the surrounding environment and could cause a reduction in the quality of the air, being worse in calm weather conditions. Local air quality changes may have implications for human beings, flora and fauna. Any significant release of CO_2 has the potential of accumulate in the surface, posing a risk for humans in the affected area.

Due to these potential impacts, a careful selection of the place, design and route of CO_2 transport must be done. The construction phase is important to detect the

Table 2 Different pipeline routes considering different nodes in a cluster

				Flow (kg/s)	Distance: source centralized point (km)	Diameter (inch)
NET 1	42° 47′ 50.10″N	5° 37′ 14.29″O	Fábrica de Cementos de la Robla	22.86	10.00	5.31
			Central Térmica de La Robla	51.37	10.00	7.96
NET 2	42° 1′ 36.77″N	4° 23′ 52.49″O	Producción Biodiesel Olmedo	1.01	81.98	1.12
			Energy Works Aranda	3.71	71.77	2.14
			SMP Automotive Technology	0.13	10.07	0.40
			Cementos Portland Valderrivas	7.86	10.95	3.11
NET 3	42° 59′ 26.15″N	2° 40′ 58.84″O	Montefibre Hispania	3.05	39.48	1.94
			Cementos Portland	11.53	42.13	3.77
			Cementos Rezola - HeidelbergCement Group	11.56	29.50	3.78
			Energy Works	4.76	14.07	2.42
			Cementos Lemona	15.37	25.01	4.35
NET 4	42° 24′ 33.30″N	3° 37′ 37.77″O	Maxam Europe	0.13	20.91	0.40
			Kronospan Chemicals	0.36	7.41	0.67
			Bridgestone Hispania	0.65	6.37	0.89
			Adisseo Espana	0.86	9.97	1.03

(continued)

Table 2 (continued)

				Flow (kg/s)	Distance: source centralized point (km)	Diameter (inch)
			Minera Santa Marta	1.05	36.00	1.14
			Enercrisa	3.68	40.20	2.13
NET 5	42° 36′ 41.53″N	6° 34′ 6.35″O	Cementos Cosmos (Toral de los Vados)	13.95	16.40	4.15
			Central de Compostilla	88.79	4.30	11.26

Table 3 Cost of the CO_2 pipeline, considering different nodes in a cluster

CO_2 Source	Length (km)	Diameter (inch)	Inv_{Pipe} (€)
Maxam Europe	20.91	0.40	3,684,720 €
Kronospan Chemicals	7.41	0.67	2,756,037 €
Bridgestone Hispania	6.37	0.89	2,687,034 €
Adisseo España	9.97	1.03	2,943,552 €
Minera Santa Marta	36.00	1.14	4,792,360 €
Enercrisa	40.20	2.13	5,228,123 €
Producción Biodiesel Olmedo	81.98	1.12	8,048,796 €
Energy Works Aranda	71.77	2.14	7,577,796 €
SMP Automotive Technology	10.07	0.40	2,935,541 €
Cementos Portland Valderrivas	10.95	3.11	3,103,195 €
Montefibre Hispania	39.48	1.94	5,145,142 €
Cementos Portland	42.13	3.77	5,716,437 €
Cementos Rezola - HeidelbergCement Group	29.50	3.78	4,675,000 €
Energy Works	14.07	2.42	3,302,929 €
Cementos Lemona	25.01	4.35	4,395,245 €
Fabrica de Cementos de la Robla	10.00	5.31	3,169,991 €
Central Térmica de La Robla	10.00	7.96	3,415,778 €
Cementos Cosmos (Toral de los Vados)	16.40	4.15	3,631,093 €
Central de Compostilla	4.30	11.26	2,925,343 €

possible ways of leakage. The pipeline route selection has to avoid high population densities and sensible places.

To reduce the risks associated with CO_2 pipelines leakages, a management/security plan must be implemented to set out the operational requirements, and the inspection, supervision, and emergency protocols. Pipelines should be monitored by internal inspection, external corrosion checks and leak detection (where possible) and regular foot and air patrols. The early detection of a leakage should initiate a planned reparation to stop the leakage and repair the damage.

5 Conclusions

According to the work presented here, progress is being made in defining a local development model to address the reduction of CO_2 emissions in the industrial sector.

In this case, the existence of a potential geological storage of CO_2 offers the possibility of studying the possible development of the cluster, understood as a region with low industrial CO_2 emissions. The different nodes that make up the cluster are defined as that group of industries located in a local area.

In this case, the viability of addressing the development of nodes with large emissions in the region is studied, discarding those nodes that have little representation in the volume of CO_2 emissions (below 10% of the total emissions of the emission sources). Considering those emissions and industries, it might be possible to apply other technologies for CO_2 use, thus avoiding the transport of CO_2 to the emitting source.

The feasibility of studying each cluster in a particular way has been demonstrated, proposing solutions based on its characteristics. Again, CO_2 transport and storage technology are considered as the most attractive solution in the reduction of CO_2 emissions in large stationary sources.

According to the present work, the geological structure (with a theoretical capacity of 100 Mt CO_2) which could be considered in the north of Spain, might generated a business case of up to 3000×10^6 € (considering 30 €/t CO_2 of the cost of the CO_2 European Emission Allowance). This economic model should attract new industries and emitters, considering a free CO_2 emissions area, thanks to the CO_2 geological storage considered in the present work.

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