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Muhammad Asif *Editor*

# Energy and Environmental Security in Developing Countries

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# Energy and Environmental Security in Developing Countries

Springer

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*to my late parents*

# Foreword

The book ‘Energy and Environmental Security in Developing Countries’ is an important and timely reflection of the energy and environmental challenges facing the developing world. The distinguished editor, Dr. Asif, and other competent chapter authors have provided a detailed coverage of the issues facing developing countries from around the world. The book has done an excellent job in integrally addressing the increasingly interwoven areas of energy security and environmental security. The design and structure of the book, also incorporating regional and country-specific case studies from all of the four main clusters of developing countries, make it a unique and valuable contribution on the subject.

Balanced treatment of the three key dimensions of the sustainable development triangle (environment, economy and society) is important for the whole world. Energy is intimately connected to environment via society and economy. Examining this nexus, the book shows how energy, socioeconomic and ecological systems have co-evolved to a critical point in the developing world. Unless future human activities are better oriented towards sustainability, especially Sustainable Energy Development (SED), the living conditions of billions (especially the poor) will be at risk. The authors provide valuable guidance regarding the way forward.

SED seeks to harness energy resources to make human development more sustainable, while harmonizing economic, social and environmental dimensions. First, the growth of modern economies depends on energy services such as heating, refrigeration, cooking, lighting, communications, and motive power. Over two billion people cannot access affordable energy services, impeding opportunities for economic development and improved living standards. Second, energy is a basic social need affecting human well-being. Wide disparities in access to affordable commercial energy and energy services in both urban and rural areas undermine social progress. Access to decentralized, small-scale energy technologies is important for poverty alleviation. Women and children, who are relatively more dependent on traditional fuels, suffer disproportionately.

Third, there are many environmental links (mainly negative), since energy production and use continue to be a primary source of local, transnational and global pollution. Specific impacts include, water contamination; land degradation;

marine and coastal pollution; ecosystems destruction and loss of biodiversity; damage to health, structures and natural systems from $SO_x$, $NO_x$, and particulates that degrade air quality; and finally, climate change driven by Greenhouse Gas (GHG) emissions that will worsen all other problems. The socio-economic impacts of climate change will be severe especially on billions of poor people in developing countries. Adaptation to reduce climate change vulnerability must have high priority.

The Balanced Inclusive Green Growth (BIGG) path offers an overall framework to address all sustainable development issues in an integrated manner, and the 17 sustainable development goals (SDG) provide a practical implementation mechanism, after appropriately localizing to specific developing countries. Energy for SD will play a key role, requiring: (a) more efficient use of energy, especially in end use —buildings, transportation and production processes; (b) increased reliance on renewable energy sources; and (c) accelerated development and deployment of new energy technologies.

Strategies and policies for globally achieving SED include better governance; encouraging greater international cooperation in areas like technology, harmonization of environmental taxes and emissions trading, and energy efficiency standards for equipment and products; adopting mechanisms to increase access to energy services through modern fuels and electricity; enabling all stakeholders to participate in energy decisions; advancing innovation throughout the innovation chain; encouraging competitiveness in energy markets to reduce energy services costs; cost-based prices, especially ending subsidies for fossil fuels and nuclear power; internalizing external environmental and health impacts; encouraging greater energy efficiency; and developing and diffusing new technologies widely. Innovation, agility and sustainability in providing energy services will be even more important to face many uncertainties, as stressed socioeconomic systems undergo transformation after COVID-19.

'Energy and Environmental Security in Developing Countries' is a clearly written book that explores a full range of such options and will help to build a better future for everyone on the planet.

Mohan Munasinghe
Vice Chair, Intergovernmental Panel
on Climate Change (IPCC-AR4) that
shared the 2007 Nobel Peace Prize.

# Preface and Acknowledgements

Despite the growing realization about the importance of energy in the socio-economic well-being and advancement of societies, the global energy landscape continues to face numerous challenges, above all, energy security issues. The nature of energy insecurity in countries at different socio-economic and technological strata varies significantly. While fuel poverty is a concern across the world, the situation with regards to energy affordability is acutely critical in developing countries. The spectrum of energy security challenges facing developing countries is quite broad. Notwithstanding the situation has improved in recent years, access to refined energy fuels remains to be a serious issue as nearly one billion people in developing countries lack access to electricity and over 2.6 billion rely on crude biomass fuels to meet cooking requirements. Issues like poor grid quality, power outages and breakdowns, and planned load-shedding are almost a regular phenomenon especially in South Asia and Sub-Saharan Africa. The global environmental scenario is also facing mounting challenges. Although climate change is a threat to the whole planet, its intensity is not uniformly distributed. The majority of the affected are from developing countries with limited resources to mitigate the challenges and to rebuild their lives after extreme environmental events.

Energy security and environmental security, integral dimensions of sustainable development in the twenty-first century, are becoming increasingly interwoven areas given their commonalities in terms of dimensions, challenges, implications, and potential solutions. The energy- and environmental security challenges not only affect the socio-economic well-being of masses but also have implications for societies at large including their economic and political systems. The profound challenge world faces is therefore to meet the rapidly growing energy requirements without inflicting damage to the environment as is manifested by the United Nations Sustainable Development Goals (SDGs). The COVID-19 pandemic has underpinned the importance of energy and environmental security. The world needs to adopt the build back better strategy to sustainably recover from the impacts of the pandemic. The UN Secretary-General acknowledges "The recovery must also respect the rights of future generations, enhancing climate action aiming at carbon neutrality by 2050 and protecting biodiversity."

This book presents a holistic account of the energy- and environmental security perspectives of the developing countries. In terms of scope, it covers the broader developing world, particularly focusing on the four main developing regions: South East Asia (SEA), South Asia (SA), Sub-Saharan Africa (SSA), and Latin America (LA). These four regions have over 99% and 95% of the global population respectively without access to electricity and clean cooking fuels. The world's 10 most affected countries from extreme weather-related natural disasters are also in these regions. To cover the subject comprehensively the book not only addresses the concerned wide-ranging energy and environmental issues and their solutions but also incorporates regional and country-specific case studies.

It is over a decade now that I initially realized the need for a holistic book on the energy and environmental security of the developing countries. I am grateful to the chapter contributors in helping me materialize this book. They deserve credit for demonstrating due proficiency and focus in their respective chapters. I would like to thank reviewers for their time and efforts in reviewing chapter abstracts and manuscripts. Given the COVID-related challenges, all these efforts deserve even more appreciation. I would also acknowledge the King Fahd University of Petroleum and Minerals (KFUPM) for the appreciative support.

Dharan, KSA Muhammad Asif

The original version of the book was revised: Dedication, Foreword, Preface, and Acknowledgement pages have been included in the book front-matter and the country name has been updated from UK to Kingdom of Saudi Arabia. The correction to the book is available at https://doi.org/10.1007/978-3-030-63654-8_28

# Contents

# Introduction

**Muhammad Asif**

## 1 Age of Sustainable Development

Human civilization has evolved throughout the course of history. The advancements societies have experienced since the industrial revolution are unprecedented in human history. This progression is manifested by indicators like technological advancements, economic prosperity, improved social services, increased mobility, comfortable lifestyle, communication and information revolution, and broader resourcefulness. These accomplishments have largely been achieved through the increasingly efficient and extensive harnessing of various forms of energy to extend human capabilities and ingenuity. Energy has become an integral part of human activities. It is fair to regard energy as the key driving force behind all important aspects of modern societies including household, industry, mobility and transport, agriculture, health, education, and trade, and commerce.

The human use of energy has evolved to match with contemporary development and requirements. It has been estimated that the global population in 1800 was approximately 1 billion, an uncertain estimate given that the first population census had just been introduced around that time in Sweden and England. Estimates of past energy use based on historic statistics and current energy use in rural areas of developing countries suggest that energy use per capita typically did not exceed some 20 GJ as a global average [1, 2]. 220 years later, the global population has risen by a factor of less than 8 while the per capita energy consumption is estimated to have risen by a factor of almost 30. A 30-fold increase, far in excess of world population growth, constitutes a major energy transition, a transition from penury to abundance. Rapid growth in energy demand is set to continue in the foreseeable future as Energy Information Administration (EIA) predicts a 50% increase in energy

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demand over the 2020–2050 period. The growth in energy demand is projected to be led by developing countries in Asia [3]. The rapid growth in energy demand in developing countries is driven by factors like burgeoning population, urbanization, modernization, and economic and infrastructure development [4, 5].

The post-industrial revolution developments in general and the increased use of energy, in particular, has come at a price. The environmental landscape of the planet has dramatically changed over this period, most notably manifested by global warming. The energy sector has played a key role in global warming. Energy, during its production, distribution, and consumption, is responsible for producing environmentally harmful substances [6–8]. Particularly, fossil fuels have been considered to be the prime source of greenhouse gas (GHG) emissions. Energy systems vary in terms of their potential to generate greenhouse gases as is shown in Table 1 [9].

A healthy and safe environment is important for human well-being and the socio-economic prosperity of a society, and biodiversity at large. Global warming is arguably the biggest challenge facing mankind [10, 7, 8]. Climate change as a result of global warming is resulting in wide-ranging problems such as seasonal disorder, a pattern of intense and more frequent weather-related events such as floods, droughts, storms, heatwaves, wildfires, health problems, and financial loss [11, 12]. The United Nations (UN) warns that climate change can also lead to a global food crisis [13]. It has been reported that since the advent of the twentieth century, natural disasters such as floods, storms, earthquakes, and bushfires have resulted in an estimated loss of nearly 8 million lives and over $7 trillion of economic loss [14]. In a survey 50 Nobel Laureates described climate change as the biggest threat facing mankind ahead of issues like disease, nuclear war, and terrorism [15]. Future projections suggest that by the year 2060 more than one billion people around the world might be living

**Table 1** Comparison of different power generation systems in terms of $CO_2$ emission [9]

| Type of power plant | Fuel/type of energy | $CO_2$/(kg/kWh) |
|---|---|---|
| Steam power plant | Lignite | 1.04–1.16 |
| Steam power plant | Hard coal | 0.83 |
| Gas power plant | Pit coal | 0.79 |
| Thermal power plant | Fuel oil (heavy) | 0.76 |
| Gas turbine power plant | Natural gas | 0.58 |
| Nuclear power plant (pressurised water) | Uranium | 0.025 |
| Thermal power plant | Natural gas | 0.45 |
| Solar thermal power plant | Solar energy | 0.1–0.15 |
| Photovoltaic power plant | Solar energy | 0.1–0.2 |
| Wind power plant | Solar/wind energy | 0.02 |
| Hydro-electric power plant | Hydropower | 0.004 |

in areas at risk of devastating flooding due to climate change [16]. The majority of the affected will be from developing countries with limited resources to mitigate the challenges and to rebuild their lives after extreme environmental events.

With the growing world population and people's innate aspirations for an improved life, a central and collective global issue in the twenty-first century is to sustain socio-economic growth within the constraints of the Earth's limited natural resources while at the same time preserving the environment [17]. The goal of sustainable development can be met by ensuring energy and environmental sustainability. The Sustainable Development Goals (SDGs) adopted by the UN in 2015 as part of its 2030 Agenda for Sustainable Development have also placed a strong emphasis on energy and environmental sustainability. The SDGs focusing on energy and environmental sustainability are highlighted in Table 2 (UN 2020).

As of the pre-COVID-19 statistics, countries around the world were largely lagging in meeting the SDG targets. The latest data shows that although the world continues to make progress towards addressing energy and environmental challenges, the efforts fall well short of the scale required to reach the concerned SDGs by 2030. COVID-19 has turned out to be a pandemic with unprecedented socio-economic impacts at all levels. Besides the health implications, the pandemic has almost halted the global economic wheel, pushing nations across the world including the major economies into recessions. In the wake of developments like severe health emergencies, immense pressure on national economies, disrupted supply chains, socio-political unrest, and almost half of the global workforce facing joblessness and loss of earning, the progress on SDGs is certain to be adversely affected. The situation demands global cohesive efforts to mitigate the impacts of the pandemic and to find a recovery path. Nations need to find ways for economic stimulus not only to tackle

**Table 2** Overview of the key SDGs focusing on energy and environmental security

| Sustainable development goal | Description |
|---|---|
| SDG 6: clean water and sanitation | Ensure availability and sustainable management of water and sanitation for all |
| SDG 7: affordable and clean energy | Ensure access to affordable, reliable, sustainable and modern energy for all |
| SDG 11: sustainable cities and communities | Make cities and human settlements inclusive, safe, resilient and sustainable |
| SDG 12: responsible consumption and production | Ensure sustainable consumption and production patterns |
| SDG 13: climate action | Take urgent action to combat climate change and its impacts |
| SDG 14: life below water | Conserve and sustainably use the oceans, seas and marine resources for sustainable development |
| SDG 15: life on land | Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss |

the pandemic but also to ensure longer-term socio-economic and environmental sustainability [18].

## 2 Energy- and Environmental Security

Energy security is widely being perceived as an important parameter to promote sustainable development. Energy security is becoming one of the foundational blocks of energy policies and frameworks around the world, especially in developed countries. Energy security is an evolving concept and does not have a universal definition. The concept has significantly transformed over time and has become an umbrella term encapsulating multiple factors about energy prosperity in a society. The concept of energy security can be remotely traced back to the First World War (WWI) era in the form of access to refined and efficient fuels. In 1918, Lord Curzon, who also served as a member of the British War Cabinet and later Foreign Secretary, proclaimed that the 'Allied cause had floated to victory upon a wave of oil'. Energy security became a vital issue during the Second World War (WWII) in the form of access to oil reserves and interruption-free supplies. During the War, the oil embargo was used as a weapon by the Allied Forces against Japan and Germany. Energy played a decisive role in the outcomes of many battles in particular and the WWII in general as the British Prime Minister Winston Churchill stated: 'Above all, petrol governed every movement', and the Soviet leader Joseph Stalin expressed the importance of oil as: 'The War was decided by engines and octane.' After WWII the role of oil as a vital commodity became more prominent in geopolitical planning across the world. The concept of energy security resurfaced in the political and policy debate in the wake of the 1973 oil embargo [9].

During the 1970s and 1980s, the concept of energy security primarily dealt with a stable supply of cheap oil. Attention was also being paid towards better management of energy enterprises and new energy technologies. With the debate around sustainable development in the 1990s, 'affordability' became an important part of the concept of energy security. Subsequently, the growing concerns over global warming and climate change also started to influence the definitions of energy security. Over the years the concept of energy security has varied spatially. It has been transformed in meaning and scope to match the emerging challenges. The modern definitions of energy security encompass indicators such as reliability, adequacy, consistency, affordability, sustainability, and environmental acceptability of energy supplies. The International Energy Agency (IEA) defines energy security as "the uninterrupted availability of energy sources at an affordable price" [19]. The United Nations Development Program regards energy security as "continuous availability of energy in varied forms, in sufficient quantities, and at reasonable prices". The European Union's perspective on energy security is viewed as "the uninterrupted physical availability of energy products on the market, at a price which is affordable for all consumers (private and industrial), while respecting environmental concerns and looking towards sustainable development." The concept of energy security has also been discussed under the four ‘As’ approach. The four ‘As’ dimensions of energy security include availability, affordability, accessibility, and acceptability [20]. Energy security can be improved through indigenous, adequate, and diverse supplies. Energy insecurity undermines the socio-economic well-being of societies and can be defined as “the loss of welfare that may occur as a result of a change in the price or availability of energy” [21].

Environmental security is the state of protection of vital interests of the individual, society, and natural environment from threats resulting from anthropogenic and natural impacts on the environment [22]. Environmental security simply implies striking a balance between the dynamic human–environment interactions. The environment is one of the most transnational issues, and its security is an important dimension of sustainable development. Environmental security is also regarded to be closely linked to national security, owing to the dynamics and interconnections among humans and natural resources. Because of its broader scope and dimensions, environmental security is a normative concept. Environmental insecurity is an all affecting phenomenon—it poses threats not only to humans but also to natural resources and the ecosystem. Ensuring environmental security, therefore, means guarding against environmental degradation to preserve or protect human, material, and natural resources at scales ranging from global to local [23]. Global warming is regarded as the biggest threat to the environmental security. Climate change and other implications of global warming are affecting nations around the world on multiple fronts.

Energy security and environmental security are becoming increasingly interwoven areas especially in the wake of the global drive for sustainable development. They have commonalities both in terms of the challenges faced and potential solutions. Fossil fuels, for example, besides their crucial contribution in terms of supplying almost 80% of the energy needs of the world, are also a cause of concern when it comes to energy security due to their highly localized nature, depleting reserves and fluctuating prices. Fossil fuels are also regarded to be a threat to environmental security due to their associated greenhouse gas emissions. Similarly, renewable energy for its comparative advantages like diverse, replenishing, abundant, and widely available resources, declining price trends, and environmental friendliness are regarded to be helpful both towards improving energy- and environmental security. Compared to energy security, environmental security is a significantly more dynamic and complex phenomenon. Environmental security is highly dynamic in nature primarily due to three factors: vibrant human–environment partnership; versatile impacts of environment; and a vast number of parameters constituting and influencing the environment. The critical nature of environmental security is also reflected from the fact that seven of the 17 SDGs are focused on environment.

## 3 Developing Countries' Outlook

Adequate and affordable energy, a healthy natural environment, and biodiversity are vital for addressing the socio-economic challenges including poverty, hunger, disease, and illiteracy. Poor and inadequate access to secure and affordable energy is hindering the progress of developing countries. Electricity, for example, is vital for providing basic social services such as education and health, water supply and purification, sanitation, and refrigeration of essential medicines. Electricity can also help support a wide range of income-generating opportunities. Over the last couple of decades, significant progress has been made in developing countries in terms of electricity access. According to the World Economic Forum around 1.1 billion people still don't have access to it [24]. A large proportion of the population in developing countries especially in Sub-Saharan Africa and South Asia still lack access to electricity as shown in Fig. 1 [25]. Biomass meets around 14% of the world's total energy supplies and is one of the main sources of energy in developing countries as over 2.6 billion people rely on it to meet their cooking and heating needs. Biomass typically used in the developing world comes through forestry and agricultural residues, wood, and animal dung. Ironically, the use of biomass in these countries is quite inefficient as traditional cooking stoves have an efficiency of up to 10%. Although biomass is the backbone of the energy supplies to a large number of developing countries as shown in Table 3, it has several disadvantages too. Some of the main problems associated with crude use of biomass include health problems due to smoke inhalation, environmental pollution, and emission of greenhouse gases, deforestation, and lack of agricultural and animal waste to serve as manure for agriculture. According to the World Health Organization, annually around 4 million people die prematurely from illnesses attributable to household air pollution from inefficient biomass-based

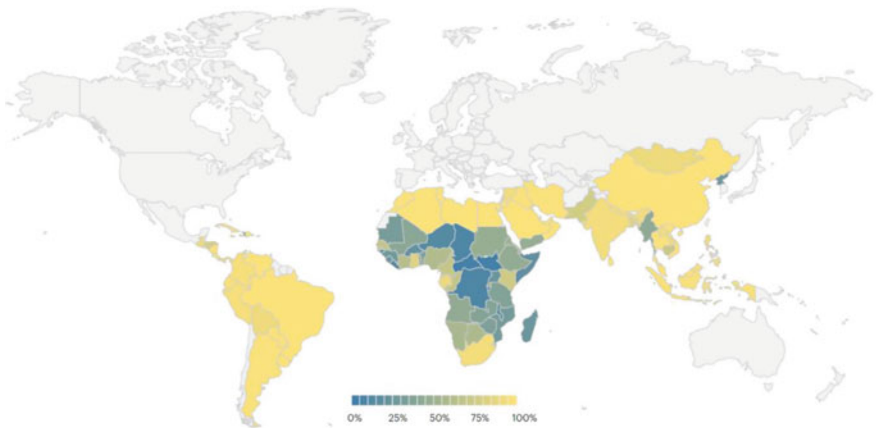


**Fig. 1** Population in developing countries with access to electricity [25]

**Table 3** Top 20 Countries with a share of biomass and combustible waste in energy supplies [27]

| Country | Share in (%) |
|---|---|
| Ethiopia | 92.9 |
| DR Congo | 92.2 |
| Tanzania | 85.0 |
| Nigeria | 81.5 |
| Haiti | 81.0 |
| Nepal | 80.6 |
| Togo | 79.9 |
| Mozambique | 79.8 |
| Eritrea | 78.2 |
| Zambia | 76.9 |
| Ivory Coast | 73.6 |
| Niger | 73.2 |
| Kenya | 72.2 |
| Cambodia | 66.9 |
| Myanmar | 65.3 |
| Cameroon | 65.0 |
| Sudan | 62.9 |
| Guatemala | 62.8 |
| Zimbabwe | 61.8 |
| Republic of Congo | 59.2 |

cooking [26]. The greatest use of traditional biomass is in Africa as the continent has 15 of the world's 20 countries most dependent on this energy resource.

Climate change in terms of implications is also a concern mainly for developing countries. Though climate change is a global issue in its very nature and will affect all countries, the poorest will suffer the earliest and the most [28]. Ironically, the poor and developing countries, despite having a marginal contribution towards the greenhouse gas emissions, are mainly at the suffering end when it comes to the implications of climate change. Low-lying island nations are particularly facing serious challenges form the rising sea level.

Climate change is projected to have serious economic implications for the developing world. Almost all of the world's population categorized as 'absolutely poor' live in developing countries, half of them in South Asia alone. The livelihood of many of this segment of the population depends on climate-sensitive sectors such as agriculture, forestry, and fishing. Owing to its impacts on agriculture and water cycle, climate change is affecting food and water security. There is an inevitable knock-on effect on poverty alleviation and economic development efforts in the region [29]. Overall, the impact of natural disasters, health problems, food and water shortages, and loss of biodiversity is quite heavy for the economies of these countries. The economic cost of climate change is projected to rise in the future. The South Asian countries like Maldives, Nepal, India, and Bangladesh are expected to annually experience a respective economic loss of 12.6, 9.9, 9.4, and 8.7% by the end of this century [30].

## 4 Regions in Focus

The book presents the case for the energy and environmental security in the developing countries in terms of the faced challenges and the potential solutions. Although the scope of the book covers the broader developing world, it has particularly focused on four regions: South East Asia (SEA), South Asia (SA), Sub-Saharan Africa (SSA), and Latin America (LA). These regions account for almost 55% of the global population. Several countries from within these regions have also been discussed as case studies. Figure 2 highlights the regions and the countries the book has focused on.

Although the Europe and Central Asia (ECA) and the Middle East and North Africa (MENA) regions also have some developing countries, their situation in terms of energy and environmental challenges is not as critical as in the four regions selected in this book. Over 99% of the world population without access to electricity, for example, lives in these four regions as shown in Fig. 3 [31] and Fig. 4 [3]. The selected four regions are also at the lower end when it comes to per capita electricity consumption and the quality of electricity services.

Lack of access to clean cooking fuel is another important indicator in terms of energy security in a society. The four regions the book has focused on are home to over 95% of the global population relying on inefficient biomass fuels to meet their cooking and heating needs. Figure 4 shows the developing countries in terms of access to clean cooking fuels.


**Fig. 2** Regions and countries discussed in the book

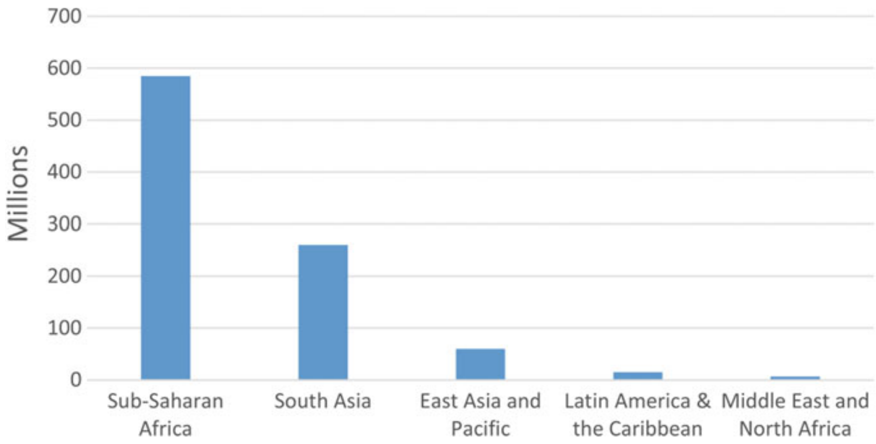


**Fig. 3** Population without access to electricity

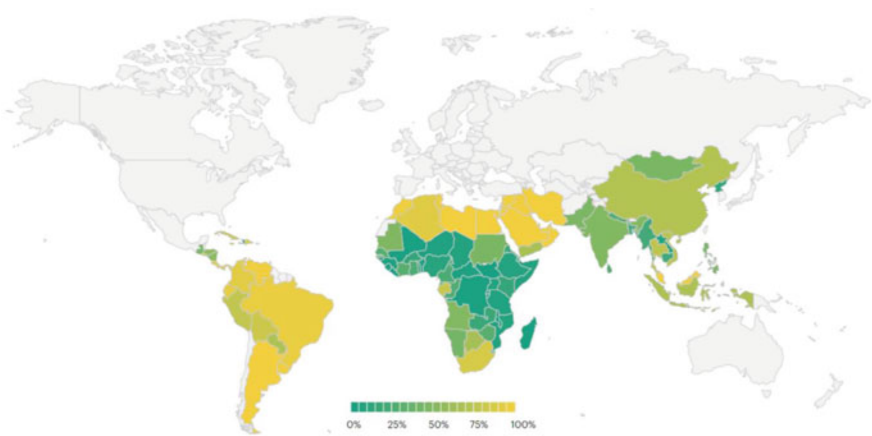


**Fig. 4** Population with access to clean cooking fuels

The four regions the book is focusing on are experiencing severe environmental challenges and include most of the world's highly vulnerable countries in terms of climate change. The world's 10 most affected countries from the extreme weather-related natural disasters over the period 1999–2018 are also in these regions [32].

## 4.1 *Southeast Asia*

Southeast Asia is part of the Asian continent geographically located east of the Indian subcontinent, south of China, and north-west of Australia. It consists of

11 countries: Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Timor-Leste, Thailand, and Vietnam. Except for Timor-Leste, the remaining 10 nations in the region are part of the Association of Southeast Asian Nations (ASEAN). Over the last two decades, ASEAN countries have made significant progress in terms of electrification. Of its total population 655 million, around 65 million people in ASEAN still lack access to electricity and 250 million depend on biomass to meet their cooking needs [33]. It is estimated that reliance on biomass and fuelwood is taking a toll on the land use in Southeast Asia as deforestation in the region is estimated to be at 5 times the global average and 10 times the average for the rest of Asia. Indonesia alone is reported to be experiencing deforestation at a rate of 1.4 million hectares (3.5 million acres) per year with only 53 million hectares (131 million acres) of total forest area left. ASEAN is regarded as one of the most vulnerable regions to climate change. The Global Climate Risk Index 2019 classifies half of ASEAN countries in the top 20 of the worlds' most affected countries by extreme weather. If climate change is left unaddressed, ASEAN is expected to lose 6.7% of combined gross domestic product (GDP) by 2100 [34].

### *4.2 South Asia*

South Asia is one of the most important developing regions of the world. The region has noteworthy statistics not only from the perspective of struggling socio-economics but also from the faced energy and environmental challenges. With a population of over 1.85 billion, it is home to almost a quarter of mankind, more than 600 million of which are regarded as 'absolute poor' accounting for half of the world's total poor. Over 260 million people in the region lack access to electricity and those relying on crude biomass to meet the cooking needs are more than 1 billion. South Asia has only 5% of the global electricity generation capacity to fulfill the needs of almost a quarter of the world population with a per capita consumption of less than a quarter of the world average. Even those connected to the grid—with the majority—face issues in quality of electricity supplies like prolonged power outages, load shedding, and low voltages. The region is thus rated the lowest in the world in terms of reliability of electricity services as indicated in Fig. 5. Rising sea level, melting glaciers, and other extreme weather-related calamities such as frequent flooding and droughts add greatly to the serious challenges to the region; low-lying areas of Maldives and Bangladesh are now facing existential threats [4]. During 1999–2018, Pakistan, Bangladesh, and Nepal were the 5th, 7th, and 9th most affected countries in the world from extreme weather-related natural disasters. Climate change further aggravates the food and water security crisis in the region. In 2019, four out of five countries in the world with the worst levels of the particulate matter 2.5 (PM2.5) were noted in south Asia, while 27 of the most polluted cities were located in the region, with India alone having 21 of them [35]. The livelihood of a large proportion of the population in South Asia is also bound to be affected by climate change especially of those

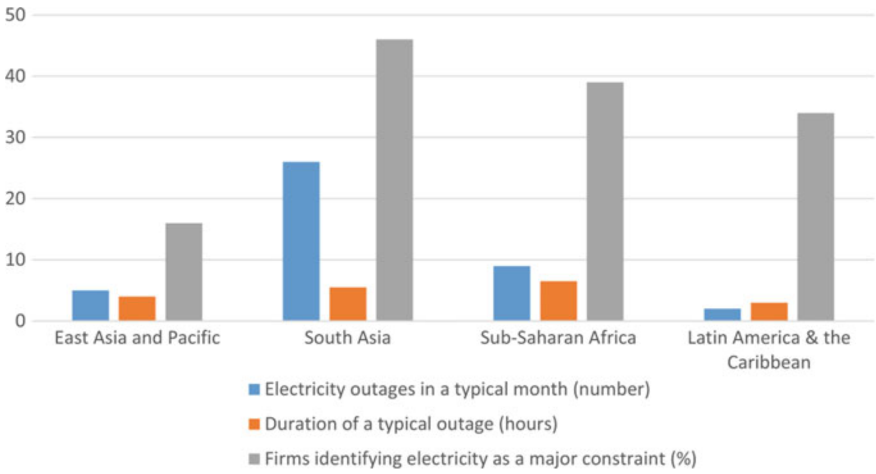


**Fig. 5** Overview of the reliability of electricity supply in the four discussed regions

relying on agriculture, forestry, and fishing. The situation in terms of food and water security will also be seriously undermined.

### *4.3 Sub-Saharan Africa*

Sub Saharan Africa (SSA) is the part of the African continent that lies south of the Sahara desert. With a population of over 1 billion, and consisting of 46 countries, SSA is notably the most deprived region in the world when it comes to access to electricity and per capita electricity consumption as shown in Fig. 5. The annual per capita electricity consumption at the regional level is less than 500 kWh while individual countries like South Sudan, Niger, and Ethiopia have figures of 44, 51, and 69 kWh equivalent to 1.4, 1.7 and 2.3% of the world average figure. The region has nearly 600 million people lacking access to electricity. It is estimated that by 2030 around 620 million people will still be without access to electricity worldwide, 85 percent of which will be in Sub-Saharan Africa [36, 37]. Around 83% of the population lives on biomass for meeting cooking and heating needs [38].

In terms of global warming and climate change, Sub Saharan Africa is regarded as one of the most vulnerable regions in the world. According to the United Nations, no continent will be struck as severely by the impacts of climate change as Africa [39]. The region is expected to be the worst hit by the changing weather patterns as a large proportion of the population depends on rainfall to grow their food. Apart from sea level rise and melting ice caps, SSA is experiencing a pattern of more frequent and intense weather-driven disasters with implications like flooding, drought, sand storms, and impact on agriculture, food, water, health, shelter, national security, and the larger ecosystem. The region's response to the challenge is seriously compromised by the lack of financial resources [40]. UN also acknowledges Africa to be particularly vulnerable to climate change due to the considerably limited adaptive capacity and exacerbated by widespread poverty.

### *4.4 Latin America*

Latin America is a group of countries spanning across the American continents. According to Encyclopaedia Britannica "Latin America is generally understood to consist of the entire continent of South America in addition to Mexico, Central America, and the islands of the Caribbean whose inhabitants speak a Romance language." [41]. Over 95 and 90% of the population in the region have access to electricity and clean cooking fuels respectively [25]. Compared to other regions in the world, Latin America has the highest share of renewables in the electricity generation mix with a figure of around 30%, most of which comes from hydropower. Latin America is not a large emitter of greenhouse gases as the region has a large share of hydropower in the power generation mix and does not have a huge industrial base. Rapid deforestation is however a major environmental concern. Latin America is a region crucial for the environmental sustainability and biodiversity of the planet. It houses Amazon, the largest and the most diverse tropical rain forest on Earth, spanning over an area of 5.5 million $km^2$. For its importance in the global ecosystem, Amazon is also termed as 'lungs of the planet'. Latin America also has large freshwater reserves. Climate change poses serious threats to the region. Major droughts in Amazon, more frequent Atlantic hurricanes, and the 90% loss of tropical glaciers are regarded as some of the evidence of climate change [42].

## 5 Structure of the Book

This book has 27 chapters. Except for the two introductory and concluding chapters, the remaining 25 have been divided into two parts: Part 1—Regional and Country Analysis and Part 2-Broader Dimensions of Energy and Environmental Security.

Part 1 has 12 chapters around the four regions: South East Asia, South Asia, Sub-Saharan Africa, and Latin America. Each of these regions, organized in the book in terms of their geographic positioning from East to West, has been covered with the help of a chapter providing regional perspective followed by country-specific chapter(s) as below.

- A chapter on Southeast Asia followed by a case study chapter on Indonesia
- A chapter on South Asia followed by three case-study chapters on India, Pakistan and Bangladesh

- A chapter on Sub-Saharan Africa followed by three case-study chapters on Nigeria, South Africa and Mozambique
- A chapter on Latin America followed by a case-study chapter on Argentina.

Chapters under Part 1 have maintained focus within the scope of the book in providing comprehensive energy and environmental perspectives of the respective regions/countries taking into account key challenges and the prospective solutions.

Part 2 of the book incorporates 13 chapters mainly on the wider dimensions of energy and environmental security in the context of developing countries. The range of topics covered under these chapters includes: concepts and dynamics of energy security; energy and environment in perspective of Sustainable Development Goals and global policy landscape; energy and sustainable development from the perspective of energy poverty; energy security in the perspective of national security and environmental protection; energy-water nexus; social discount rate as a tool to indicate sustainable development dynamics; effect of climate change on women-adaptation and mitigation; carbon capture; renewable energy; bioenergy for sustainable development; energy conservation; and floating PV systems.

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# Regional and Country Analysis

# Energy and Environmental Security in Developing Countries Case Studies of Countries in Southeast Asia

**Azni Zain Ahmed, Abdul Rahim Ridzuan, Azlin Mohd Azmi, Baljit Singh A/L Bathal Singh, and Ramlan Zailani**

**Abstract** Southeast Asia (SEA) is composed of Brunei, Myanmar, Cambodia, Timor-Leste, Indonesia, Laos, Malaysia, the Philippines, Singapore, Thailand and Vietnam. The population is forecasted to expand by 20% with the urban population alone growing by over 150 million people which is the driving force behind the region's growing energy demand. The Association of Southeast Asian Nations (ASEAN) and six other countries in the Asia–Pacific region comprising of: Australia, the People's Republic of China, India, Japan, Korea and New Zealand forming the ASEAN + 6 group, whose share of global energy demand is expected to reach 40% by 2040 making this region the world's most dynamic economically. Southeast Asia's supply of energy comes from more than 50% of fossil fuels (led by oil, coal and natural gas) and 17% from renewables but the supply is now depleting fast as these countries have become net importers of oil rather than exporters since 2018. The region is also relatively well endowed with renewable energy sources particularly in hydro and solar and other types of renewable energy (such as geothermal found mainly in the Philippines and Indonesia). Although this region has set out a target to contribute 23% of its primary energy supply from renewables by 2025, conventional fossil energy still dominates the regional energy mix. Energy security has now become an issue as it affects Southeast Asia's efforts to secure their energy requirements in a sustainable manner environmentally and economically. Continuous reliance on energy imports, especially of oil and gas, to sustain economic growth serves as an example of Asia's energy insecurity. Natural gas security has also become a concern in the region, as it is expected to account for 85% of the growth in global gas trade between now and 2040. The energy impacts on environmental systems and climate change have strong links to energy security. More than 60% of global carbon dioxide emissions are produced from energy supply and transport. Continuing to subsidise the cost of energy to citizens over the course of the next ten years will not be sustainable. It becomes necessary to reform some present policies and formulate new policies to ensure the energy security of these countries. Governments in the

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region also need to employ alternative energy sources and collaborate to maintain energy security not only for their own countries, but for the rest of the region as well. Recent reports by the World Economic Forum (WEF) have favorably focused on ASEAN countries based on their current energy systems and readiness to adapt to future needs. This chapter therefore, discusses on the current scenario of energy in the light of climate change, sustainability in environment, energy security issues and economy in ASEAN + 6, barriers, possible solutions, and case studies of mitigation efforts as well as policies laid out and implemented with specific examples from Malaysia, Thailand, Indonesia, Singapore, Vietnam and the Philippines.

# 1 Introduction

## *1.1 Current Scenario and Trends*

Southeast Asia (SEA) is composed of 11 countries which are Brunei, Myanmar, Cambodia, Timor-Leste, Indonesia, Lao People's Democratic Republic (Lao PDR), Malaysia, the Philippines, Singapore, Thailand and Vietnam Fig. 1. The Association


**Fig. 1** ASEAN member countries. (*Source* https://www.lanariassociates.com/map-asean-2/?lang=en) [3]

of Southeast Asian Nations (ASEAN) is comprised of all the SEA countries with the exception of Timor-Leste. ASEAN was established in August 1967 with the purpose of accelerating the economic growth, social progress, and cultural development in the region, and promoting regional peace and stability [1]. The population of SEA is forecasted to expand by 20% with the urban population alone growing by over 150 million people which is the driving force behind the region's growing energy demand [2].

Southeast Asia is part of Asia which includes India, China, Japan and Korea. The population of Asia was expected to increase to over 5.4 billion people by 2015 which is more than 30% of the population in 2018 [4]. Southeast Asia is a very diverse and dynamically developing region and ASEAN has the world's third largest population, with more than half under the age of 30 [5]. As a result, the whole of Asia would be emitting 35% of the world's energy related carbon dioxide ($CO_2$). Seventeen percent of the $CO_2$ emitted from forest and land-use change of which one third is from Asia and Asia Pacific (comprising of Australia and New Zealand) [6]. The same authors went on to report that Asia would be responsible for the emissions from energy use of 45% by 2030 if greater use renewable energy is not implemented. With this percentage Asia is therefore an important region to be in position to tackle climate change. ASEAN and 6 other countries in the Asia–Pacific region comprising of: Australia, the People's Republic of China, India, Japan, Korea and New Zealand form the ASEAN + 6 group, whose share of global energy demand is expected to reach 40% by 2040 making this region the world's most dynamic economically [4, 2]. All the 10 ASEAN countries signed the Paris Agreement which aims to limit the average global temperature gain to 2 °C above pre-industrial levels [7]. With the increase of energy consumption from fossil fuels there will be a risk of not achieving the goals set out in the agreement.

## *1.2 Energy Security Issues*

Southeast Asia's supply of energy comes from more than 50% of fossil fuels (led by oil, coal and natural gas) and 17% from renewables [8] but the supply is now depleting fast as these countries have become net importers of oil rather than exporters since 2018 [9]. The region is endowed with renewable energy sources particularly in hydro and solar and other types of renewable energy (such as geothermal found mainly in the Philippines and Indonesia). Although this region has set out a target to contribute 23% of its primary energy supply from renewables by 2025, conventional fossil energy still dominates the regional energy mix [10, 11].

Energy security has now become an issue as it affects Southeast Asia's efforts to secure their energy requirements in a sustainable manner environmentally and economically. Continuous reliance on energy imports, especially of oil and gas, to sustain economic growth serves as an example of Asia's energy insecurity. Natural gas security has also become a concern in the region, as it is expected to account for 85% of the growth in global gas trade between now and 2040 [12]. The energy impacts on environmental systems and climate change have strong links to energy security. More than 60% of global carbon dioxide emissions are produced from energy supply and transport [12]. Continuing to subsidise the cost of energy to citizens over the course of the next ten years will not be sustainable. It becomes necessary to reform some present policies and formulate new policies to ensure the energy security of these countries. Governments in the region also need to employ alternative energy sources and collaborate to maintain energy security not only for their own countries, but for the rest of the region as well.

The Asian Development Bank [13] describes the environmental dimensions of energy security as mainly concerning climate change, air pollution, water availability and quality, and land-use change which can have devastating multiplier effect. For example flooding and natural disasters disrupt energy supply and destroy crops, therefore affecting food security and health. Another aspect of energy security is economics. Such disasters will reduce the income of those affected. Disasters due to the impacts of climate change can destabilise government efforts to control national debt and the implementation of economic policies. A report by the Intergovernmental Panel on Climate Change (IPCC) that due to changing patterns of urbanisation and temperature change, Indonesia, the Philippines, Thailand and Vietnam are predicted to lose 6.7% of combined gross domestic product (GDP) by 2100 [14].

## *1.3 Impact of Climate Change*

The rapid economic growth and the process of urbanisation in Southeast Asia are also contributing while magnifying its impact on climate change [7]. In turn, climate change causes impacts on the environment and human systems across continents and oceans which are distinguishable from other influences and therefore can be observed easily at local levels [14]. Scientific studies have shown that extreme climate change effects are increasing all over the world and is continuing to increase in tandem with the increase of heat and rising sea levels [15]. Indicators or indices have been created to monitor climate change. Countries can be even ranked for climate change impacts. For instance, a report by Kreft et al. [16], published by a non-governmental organisation, Germanwatch, from 1996 till 2015, six Asian countries, namely Myanmar, Philippines, Bangladesh, Pakistan, Vietnam and Thailand were ranked the world's top 10 countries which were badly affected by extreme weather events. Between the period 1997 to 2016, Vietnam and India were the top 10 hardest hit [17] while Myanmar recorded one of the worst country to be affected between the period 1998 to 2017 [18] and for the period between 1999 and 2018, Japan, the Philippines and Myanmar were the most affected by climate change events [19]. In addition, Myanmar, the Philippines, Vietnam, Cambodia and Thailand ranked in the world's top 20 countries between the period 1998–2017 [15].

A major source of greenhouse gas (GHG) emissions is deforestation [7]. The growing population of Southeast Asia is forcing some countries, like Indonesia and Malaysia to cut down trees from their forests to support pulp, paper industries and palm oil for export. Prakash [7] reports that deforestation produces GHGs more than the use of fossil fuels. To make the situation worse, since 1997, Malaysia and Indonesia have bee suffering from forest fires caused by dry peat swamps and open burning which add to the emissions of GHGs. Another source of heat build-up is the migration of people form rural to urban areas. Changes in land use for biofuel collection and production in Southeast Asia have also resulted in deforestation at 5 times the global average and 10 times the average for the rest of Asia and therefore policymakers should incorporate the cost of this negativity into energy prices [20].

To sustain the increase in urban population, there are new constructions to provide fresh water supplies to communities. The construction of new reservoirs usually involve changes in river flows and coupled with increased rainfall cause floods such as in Hoi An and Da Nang in Vietnam. In addition, constructions involving the tourism industry along the coastlines have also increased and indirectly causing coastal erosion. For example the Cua Dai Beach along Hoi An receded by 150 m from 2004 to 2012 [7]. Seventy percent of Vietnam's population reside along its coastline and in the low-lying Mekong Delta. Other Southeast Asia countries are similarly vulnerable as they are exposed to the open seas such as Indonesia, Thailand and the Philippines. Cambodia, Lao PDR and Thailand have been experiencing excessive rain, storms and extreme heat. The Philippines experience an average of 20 typhoons a year and all these events damage the environment and cause health issues [7]. The region has already been warned that if the increasing energy demands are met by the traditional mix of energy supply with current technologies, then the implications for the environment in terms of GHG emissions, green growth, anthropogenic climate change and prices of fossil fuels would not be sustainable. Although renewables are cleaner than fossil fuels there are still negative impacts on human health, ecosystem, biodiversity and the environment [20].

## 2 Energy Security and Macroeconomics

Energy is the primary input to economic systems that powers the flow of goods, services, and factors of production between companies and households. As such, there exists a strong link between economic activity and energy use regardless of the level of technological know-how or relative prices [21]. Studies in Southeast Asia (Mat Sahid & Tan [22] have also found that that there is a high correlation between energy, the economy and population (i.e. GDP). Anthropogenic climate change and energy security coupled with the uncertainties in macroeconomic stability and energy justice have created a call for a change in energy demand. The rising energy demand from the least and developing countries around the world is connected to the issue of environmental degradation as most of these countries still use coal as their main source of energy. The rise of carbon emission, the main culprit of air pollution in these countries could hinder their sustainable development agenda as set under ASEAN Vision 2025. This section highlights the trend of non-renewable and renewable energy for the main four original member of ASEAN namely, Malaysia, Indonesia, Thailand

and the Philippines. These countries were selected as they have progressed rapidly in terms of their economic development as a result of various economic policies introduced by their policymakers. The rising demand for non-renewable energy such as coal are understandable as it is considered as the cheapest source of energy to generate electricity especially for developing countries of ASEAN-4.

In order to address the challenges of meeting such high energy demand, as well as ensuring sustainable energy growth and mitigating climate change, the ASEAN states have been following a deliberate policy of diversifying and using indigenous energy sources efficiently at the national level. Policy makers have been intensifying their efforts to ensure a secure, affordable and more sustainable pathway for the energy sector [12]. Renewable energy is expected to play a key role in delivering a sustainable energy future. It enhances energy security, decreases dependence on imported fuels and contribute to the carbon reduction goals.

## *2.1 Trends in Non-Renewable Energy*

Coal and natural gas will both play a key role in the ASEAN's energy mixes for the next few decades. There are three common reasons for this: abundance, affordability and availability of these resources [23]. These advantages help ASEAN states to achieve both energy security and environmental goals. However, coal is always considered as the dirtiest fuel, since coal combustion has the highest $CO_2$ energy index. It is therefore, important for ASEAN states to take into account the benefits of natural gas in planning their long-term energy strategy [23].

One of the key findings of the *IEA Southeast Asia Energy Outlook 2019* [12] was, due to the rising fuel demand, especially for oil, has far outpaced production from within the region. Southeast Asia as a whole is now on the verge of becoming a net importer of fossil fuels for the first time. Malaysia for example, one of the major oil exporters in the region for the past four decades, was officially declared as a net importer of crude oil in 2014 [23, 24].

The Asia Development Bank [25] predicted that the Southeast Asia economies are expected to rise annually by 5.8% from 2012 to 2030. However, the Southeast Asia Energy Outlook [26] revealed that the annual growth of these countries is less than projected, seen in the slight downward revisions to growth forecasts. Currently the growth rate stand at 4.8% (2019) and 4.9% (2020), respectively which are less than the predicted rates. The actual growth of these economies can be a residual effect from future global economic condition, seen in US China trade war, fuel price stabilization, efforts for replacing old technologies of oil and to cleaner sources. A relatively lower projection is expected when the global economic growth begins to halt, resulting in lower prices of fuel and the increase in trade protection. Looking at both scenarios, energy consumption in Southeast Asia is expected to rise at different rates, as it fuels the region's economic growth. Based on the higher current projection, it is expected that consumption will increase by an average of 6.4% per year until

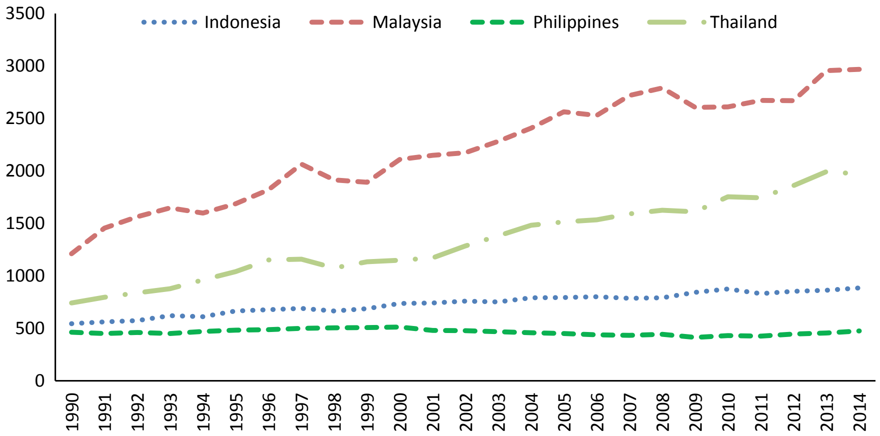


**Fig. 2** The trend of non-renewable energy consumption (kg of oil equivalent per capita) for ASEAN-4 countries [8]

2025. For the lower scenario, an increase of an average of 5% per year is expected [27].

In this section, special highlight is given to the four developing countries of ASEAN: Malaysia, Indonesia, Thailand and the Philippines based on their heavy reliance on non-renewable energy such as coal and oil to promote growth. The energy use trend for each ASEAN-4 countries that are based on non-renewable resources can be viewed in Fig. 2. Among the four developing ASEAN countries, Malaysia has the highest non-renewable energy usage and the list goes to Thailand, Indonesia and Philippines. Malaysia's consumption demand is relatively high, recorded at 12,000 kg oil per capita, accounting for more than double amount of 3000 kg oil per capita recorded in 2014 [8]. In Thailand, the energy demand is seen at 700 kg oil per capita and the number rose close to 2000 kg oil per capita in 2014 [8]. The remaining ASEAN countries, Indonesia and Philippines initially have steady growth in their energy demand, recorded at 500 kg of oil per capita in 1990 and it rose to 1000 kg of oil per capita, but then they decreased to 400 kg of oil per capita, respectively [8].

## *2.2 Trends in Renewable Energy*

Although the use of renewable energy in the world during the period 2009 to 2016 increased from 7.8 to 10.0%, the reverse is true for some ASEAN countries during the same period. The share of renewables in the total energy consumption decreased by 0.2% in ASEAN. The notable decrease were by Thailand (0.8%), Indonesia (1.8%) and the Philippines (10.8%) while Malaysia and Vietnam recorded increases [28]. The world has singled out anthropogenic climate change as a serious risk bringing

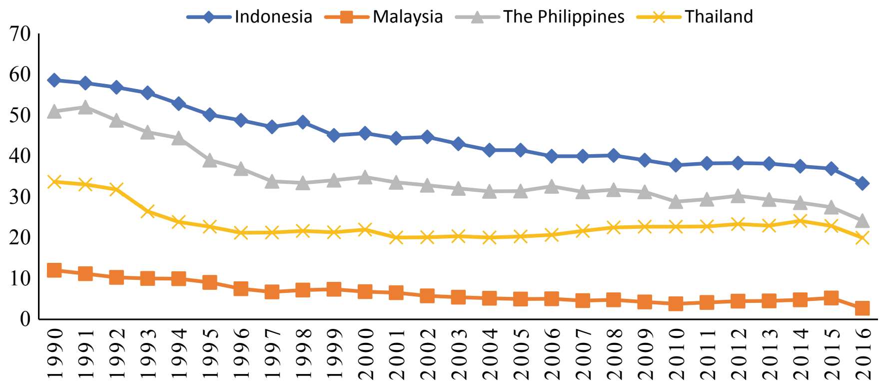


**Fig. 3** The trend of renewable energy consumption as % of GDP for ASEAN-4 countries [29]

major catastrophes. Records show that ASEAN-4 is decreasingly relying on renewable energy use, and this can impede the association's agenda to combat these environmental catastrophes. Alternative sources are now being considered, particularly renewable energy such biofuel, solar, wind and hydroelectricity. ASEAN has set up a monumental aim, ensuring that 23% of its primary energy comes from renewable sources by 2025 based on a projected 50% increase in demand [29].

Based on the same report by the World Bank [29], Malaysia seems to be lagging in championing the use of renewable energy compared to Indonesia, Philippines, and Thailand. Figure 3 highlights the ASEAN-4 consumption trend for renewable energy in percentage. Based on the current data for the renewable energy in in the report, Indonesia's renewable energy use in 2016 is 33.29% of GDP, and the Philippines trailing at 24.19% of GDP. As for Thailand, the data counts for 19.97% of GDP. Malaysia shows a poor record of renewable energy use compared to the other counterparts, accounting for only 2.70% of GDP. This trend indicates that the ASEAN-4 countries are not fully geared to move away from the non-renewable sources of energy. The main reason for the heavy reliance on non-renewable energy is due to the lower costs of fossil fuel and coals as compared to renewable energy.

Renewable energy is defined as unlimited source of energy, where the supplies are constantly replenished through natural processes, seen in solar energy, wind energy, hydroelectric energy, biomass, and biogas [30]. Choosing renewable energies have become the choice for replacing fossil fuels and coal, and they are also considered as a good alternative for reducing energy costs [31]. Every country in the Southeast Asian region has outlined their strategy for applying renewables to fuel their power. Indonesia and the Philippines are blessed with untapped potential in geothermal energy resources while Thailand can harness endless potential of generating power from hydropower, courtesy of their neighboring country, Lao PDR. Currently, the Philippines is the world's second leading nation for producing electricity energy through geothermal activity and its neighbor, Indonesia is trailing at the third place. The Philippines' record also shines in biofuel. Currently, The Philippines is placed second in total energy from biofuel. For Thailand, positive growth is seen in solar photovoltaics in recent years. 17% of total supply is supplied by renewable electricity in 2007, and most of the renewable energy is generated by the construction of large-scale hydroelectric power plants. Geothermal power plants make up for less than 3% of power while biomass is responsible for less than 2%, and wind plus solar production contribute less than 0.5% of total energy source [29].

Climate change is the goal outlined in the *ASEAN Plan of Action for Energy Cooperation 2010–2015*, a plan proposed by the ASEAN Ministers on Energy in 2009 [32]. This action plan sets three priorities concerning the energy sector: firstly, energy efficiency and conservation plan; secondly, conservation renewable energies and lastly, using clean coal technologies. The first effort, energy efficiency and conservation focus to gain maximum efficiency by conducting a more serious effort in regulations and market mechanism. It also aims to lower the intensity of current energy use and exploring ways and chances to investment in newer and more efficient energy technologies. Under the renewable energy plan, the target is set for the nations to have 15% of total installed capacity originating from renewable electricity sources. In the clean coal technology plan, it outlines measures that must be taken to widen to use of clean coal technology through regional cooperation.

So far, ASEAN-4 countries have made efforts to promote the use of renewable energy by outlining government policies. A notable example is Indonesia where its National Energy Policy targets an increase of renewable energy to 31%, by 2030 [8]. Malaysia's effort is by setting a goal of producing 2080 MW from renewable energy by 2020, and this would count for 7.8% of its total installed capacity. This aim is outlined in numerous policies and plans, such as the National Renewable Energy Policy and Action Plan [33] and 11th Malaysia Plan 2016–2020 [34]. Thirdly, the Philippines aims to have 15.3 GW of renewable energy by 2030 [8]. The Philippines has other plans to promote renewable energy in the country, as set in the National Renewable Energy Program Roadmap 2010–2030 [35]. Thailand targets 30% of renewable energy in the total energy consumption set to be achieved by 2036. The plan calls for the renewable energy to come from 20.11% of electricity, 36.67% of heat production, and 25.04% of biofuels in the transportation sector [8]. Overall, these plans and policies are indicators that ASEAN-4 is ready to be the leaders in renewable technologies and will be the voice to answer for the growing concern on the issues that have been plaguing the planet such as climate change, $CO_2$ emissions and energy shortage.

## 3 Sustainable Energy & Carbon Emission Targets

The average annual $CO_2$ emissions growth rate in Southeast Asia is between 2018 and 2040 is 2.3%, which is seven times as fast as the global annual average over the same period. While the region's current share of global emissions is relatively small at 4.3% in 2018, it is predicted to increase to 6.5% by 2040 [12]. Energy efficiency (EE) and Renewable energy (RE) are the two pillars of sustainable energy practices and carbon mitigation strategies which have been included in the national policies of all ASEAN states. The Paris Agreement on Climate Change has been ratified by all 10 ASEAN member states with the commitment to cut down the emissions of green-house gas within specific time frames [36]. To fulfil the pledges of the *Intended Nationally Determined Contributions (INDC)* for the Paris Agreement, all ASEAN states members have pledged to reduce their emissions through 2030 and have introduced numerous national policies. Table 1 shows the major sustainable energy policies in selected ASEAN states based on both RE & EE initiatives. While renewable resources provide attractive options for lowering carbon emissions, a switch from coal to natural gas also promotes lower-carbon electricity generation and enables higher penetration of intermittent renewables by serving as backup capacity [37].

In aggregate the ASEAN region is making good progress towards its Paris goals but still requires additional action to sufficiently decrease emissions from its current trajectory. Under the unconditional pledges, the ASEAN region faces an emissions gap of around 400 $MtCO_2e$, which indicates that the ASEAN region will have to reduce emissions by 11% by 2030 relative to its current trajectory. Under the conditional pledges, the emissions gap is about 900 $MtCO_2e$, which indicates a needed reduction of 24% by 2030 [37].

## 4 Energy Demand and Supply in Southeast Asia

The demand for energy is immense due to the economic drive in the Southeast Asia region, with electricity generation, industry and transportation sectors being the main drivers for energy consumption. The energy sector is expected to grow at 3.9% per year into 2040, which is much higher than the expected world average of 1% and the region's energy demand is projected to expand 2.4 times its 2015 level, by 2040 [9].

Based on today's policy settings, the demand for coal is projected to rise over the coming decades [9]. Natural gas may be a good replacement for this fuel but it is facing price competition. Overall the share of renewables will rise from 24 to 30% by 2040 (see Fig. 4 where wind, solar, hydropower and bioenergy are set to grow.

All ASEAN states are expected to experience sizeable growth in energy consumption, with Cambodia, Lao PDR and Vietnam growing the most during this period. However, in terms of *Total Final Energy Consumption (TFEC)*, the leading consumers of energy are still the most populated nations: Indonesia, Thailand, Vietnam, Malaysia and the Philippines, with a combined share of 388 Mtoe (90.8%) in 2015 to

**Table 1** Major sustainable energy policies in selected ASEAN states [37]

| Country | Sector | Policies and targets |
|---|---|---|
| Indonesia | Energy efficiency | Reduce energy intensity by 1% per year to 2025 |
| | Renewables | Increase share of "new and renewable energy" in primary energy supply to reach 23% by 2025 and 31% by 2050 |
| | Climate change | Reduce GHG emissions 26% by 2020 and 29% by 2030 from BAU levels, and 41% by 2030 with international support |
| Malaysia | Energy efficiency | Promote energy efficiency in the industry, buildings and residential sectors with methods of standard setting, labelling, energy audits and building design |
| | Renewables | Increase capacity of grid-connected renewables to 4000 MW by 2025 |
| | Climate change | Reduce GHG intensity of GDP by 35% by 2030 from 2005 level, increase to 45% reduction with enhanced international support |
| | Energy efficiency | Reduce energy intensity by 30% by 2036 from 2010 level |
| Thailand | Renewables | Increase share of renewables to 30% in total final energy consumption by 2036; increase share of renewables-based power to 36% in generation capacity and to 20% in generation by 2037 |
| | Climate change | Reduce $CO_2$ emissions from power sector to 0.283 kg $CO_2$ in 2037 from 0.413 kg $CO_2$ in 2018. Reduce GHG emissions by 20% from BAU level by 2030, increase to 25% with enhanced international support |
| | Energy efficiency | Reduce energy intensity 40% by 2030 from 2010 level |
| Philippines | Renewables | Triple the installed capacity of renewables-based power generation from 2010 level to 15 GW by 2030 |
| | Climate change | Reduce GHG emissions by 70% from BAU level by 2030 with the condition of international support |
| | Energy efficiency | Improve energy intensity by 35% by 2030 from 2005 levels |
| Singapore | renewables | Increase solar PV capacity to 350 MW by 2020 and 1 GW beyond 2020 |
| | Climate change | Reduce GHG emissions by 16% below BAU level by 2020, stabilise emissions with the aim to peak around 2030 |
| | Energy efficiency | Increase commercial electricity savings to more than 10% of total power consumption by 2020 relative to BAU |
| Vietnam | Renewables | Increase the share of non-hydro renewables-based generation capacity to 12.5% by 2025 and 21% by 2030 |
| | Climate change | Reduce GHG emissions by 8% by 2030 and by 25% from BAU levels with international support |

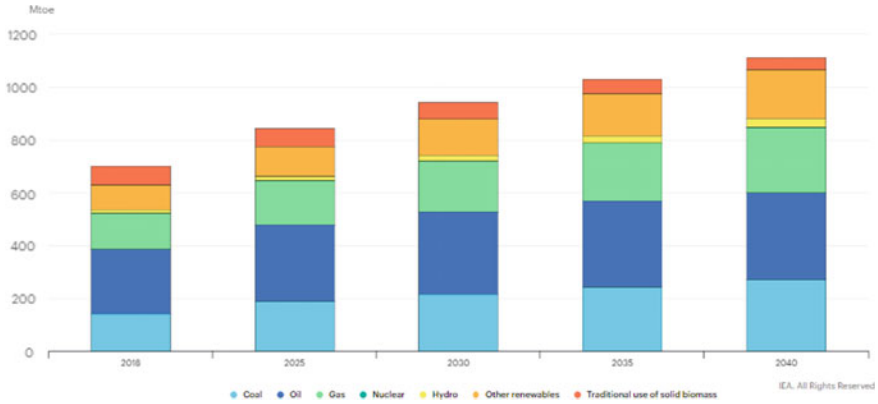


**Fig. 4** Primary energy demand in Southeast Asia in the selected policies scenario, 2018–2040 [9]

972 (92.9%) in 2040 [38]. Indonesia remains the most energy-consuming nation with 417 Mtoe (39.9%) of TFEC in 2040. Following the steep development and the rise of energy consumption, *the Total Primary Energy Supply (TPES)* is also projected to grow. TPES of ASEAN is estimated to experience a steady growth from 627 Mtoe in 2015 to 1450 Mtoe in 2040 [38]. Oil will still represent its dominance, having a 33% of TPES with 207 Mtoe, followed by natural gas at 23.7% or 150 Mtoe, and coal with the lowest share among fossil fuel with 18.5% or around 116 Mtoe [38]. ASEAN is projected to still be dependent on fossil fuels and will be accountable for 78.6% or about 1,139 Mtoe of the total 1,450 Mtoe in 2040. Renewable energy will experience a rapid expansion in TPES with compounded annual growth rate of 4%. In 2015, RE represents 13.6% of TPES, including 18 Mtoe (2.9%) of hydro, 12 Mtoe (1.9%) of geothermal, and 55 Mtoe of other RE (8.8%) [38]. In terms of TPES share by country, Lao PDR, Vietnam and the Philippines will experience the strongest growth, while the five dominant member states in TPES will still be Indonesia, Thailand, Vietnam, Malaysia and the Philippines. It is also anticipated that Vietnam will surpass Malaysia in 2023 to become the third largest contributor in TPES [38].

### *4.1 Oil, Coal and Gas*

Southeast Asia's oil demand is projected to surpass 9 mb/d by 2040, up from 6.5 mb/d in 2019 [9]. Oil continues to dominate road transportation demand, despite an increase in consumption of biofuels, especially biodiesel in Indonesia and Malaysia where vigorous efforts to integrate B30 palm oil-based biodiesel in the road transportation fuel are underway. However, the shift from the internal combustion engine vehicles are not expected to be in the very near future since the electrification of road mobility is projected to make only limited progress in next few decades. Singapore and the Philippines are almost totally dependent on non-renewables for primary energy use.

In the last 4 years Malaysia and Indonesia became dependent on external supplies (or imported) oil although both countries are producers of oil themselves.

Mat Sahid et al. [11] studied the energy scenario for ASEAN countries for the period 2010–2030. They found that Indonesia remains a major coal exporter in the region while Thailand, Malaysia, Philippines and Singapore are net importers of coal until 2030. For oil, Brunei is projected to remain as net oil exporter between 2010 and 2030 while all the rest of ASEAN remain as net oil importers. Due to increasing demand and depletion of resources, Malaysia and Vietnam will change their position from net oil exporters in 2010 to net oil importers by 2020. For natural gas Brunei and Malaysia are expected to remain as net exporters during the same period. Conversely, Indonesia and Vietnam are expected to change their positions from net exporters of natural gas in 2020 to become net importers of natural gas by 2030. Both are also projected to remain as net importers of electricity while Malaysia will remain as a net exporter of electricity.

Senderov and Vorobev [28] have analysed and summarised the energy consumption characteristics of the ASEAN countries. Indonesia is the largest consumer of energy in ASEAN and the largest exporter of coal and also exports liquefied natural gas (LNG). The second largest energy consumer is Thailand and is dependent on energy imports. Malaysia comes third largest energy consumer and the largest exporter of LNG and oil until 2012. Singapore depends entirely on imported oil and gas. Vietnam is considered self-sufficient with its own renewable energy resources, coal, gas, oil and nuclear. The Philippines produces its own gas and is an importer of oil. Myanmar is endowed with gas resources and hydropower. Laos is developing hydropower for its energy needs. Cambodia has potential oil and gas reserves. Brunei is well-known for its rich oil and gas resources which are exported. Senderov and Vorobev [28] conclude that by 2035 all ASEAN countries except Brunei will be 75% dependent on oil imports. Natural coal and natural gas are able to supply local needs except for Malaysia, Indonesia, Vietnam and Brunei. ASEAN except Indonesia and Singapore will also be dependent on imported coal.

Natural Gas has become a more important pillar of energy supply in the ASEAN region for the past three decades. In 2019, natural gas accounted for 24% of ASEAN energy mix or nearly 150 MTOE, and attributed as the second largest source of energy after oil. Natural gas has surpassed coal in ASEAN energy mix in 2005–2016 [39]. Other than power sector, natural gas also plays an increasing role in industry processes. Natural gas is not only consumed as a fuel to generate electricity but also as a feedstock of several petro-chemical based products such as fertilisers, polymers and methanol production, which has many industrial applications. In the power sector, natural gas has the highest installed capacity with more than one-third of total installed power capacity in ASEAN coming from natural gas. Increasing demand of natural gas have caused anxieties for the ASEAN state members in terms of security. One of the key findings of the 5th *ASEAN Energy Outlook 2017* projected that ASEAN will no longer be a gas net exporter by around 2025 [40]. Natural gas production in ASEAN is decreasing by about 1% annually from 2010 level, natural gas consumption keeps increasing in both end-use and power sector. There are also intentions in some ASEAN states to promote fuel-switching from coal to cleaner natural gas as part of their carbon mitigation effort in electricity generation sector.

In order to strengthen regional cooperation in gas supply connectivity as part of their energy security strategy, several ASEAN states have initiated a *Trans-ASEAN Gas Pipeline (TAGP)*, an interconnecting natural gas pipeline which connects several ASEAN states. *TAGP* aims to enhance connectivity for energy security and accessibility via pipelines and regasification terminals. More than 3,500 km of gas pipelines have connected six nations with around 22 million tonnes per annum of six LNG regasification terminals in the region [23]. This network of gas pipelines offer multiple benefits in terms of energy security, flexibility and quality of supply.

### 4.2 Electricity Generation

As the electricity demand increases rapidly due to economic and population growth and in-line with intensive plans for full electrification policies across all ASEAN states, the overall region's power capacity is projected to rise from 205 GW in 2015 to 323 GW in 2025 and rise further to triple its base value to 629 GW in 2040 [38]. To cater to this enormous demand for electricity, most of the ASEAN member states are projected to still rely on fossil fuel-based electricity followed by a slight increase in renewable energy usage. The installed capacity in ASEAN is currently dominated by natural gas but will be outstripped by coal in 2025. The projection is that coal will remain as the main resource for electricity generation in ASEAN following the commissioning of numerous coal power plants in the region starting from the early 2000s. Electricity generated from coal is expected to rise from 63 GW in 2015 to 119 GW in 2025 and will reach 267 GW in 2040. Natural gas-based power plants are projected to approximately double the base value, from 77 GW in 2015 to 156 GW in 2040 [38].

### 4.3 Renewable Energy

Despite the region's reliance on fossil-fuels, renewable energy is also projected to flourish. Renewable energy-based electricity is projected to rise from 50 GW in 2015 to 93 GW in 2025 and 183 GW in 2040. While renewable resources provide attractive options for lowering carbon emissions, a switch from coal to natural gas promotes lower-carbon electricity generation and enables higher penetration of intermittent renewables by serving as backup capacity [37]. Southeast Asia, which is in the tropical region, has considerable potential for renewable energy development especially from solar and biomass (excluding traditional biomass) but it currently meets only around 15% of the region's energy demand. In 2019, renewables accounted for one-quarter of total electricity generation in Southeast Asia. The share of renewables in electricity generation triples in the ASEAN *Sustainable Development Scenario* to around 70% in 2040 [36]. The share of renewable energy in electricity generation is projected to grow from 24% in 2018, 18% of which is hydropower, to 30% by 2040. However, this growth is still far behind the levels reached by other economies in Asia. Solar and wind are set to grow rapidly while hydropower and modern bioenergy—including biofuels, biomass, biogas—remain the mainstays of Southeast Asia's renewable energy portfolio [12]. Solar energy has the second largest share overall, while resources such as wind and geothermal are identified only in the countries with availability of potential resources, like geothermal in Indonesia and the Philippines, and wind in Vietnam.

Geographical and technical conditions are two main barriers faced by renewable energy development in ASEAN. For Indonesia and the Philippines, the major challenge of limited infrastructure capacity that hinders effective renewable energy deployment, in regard to electricity transmission since both countries are archipelagic in nature, resulting in fragmented electricity grids [41]. West Malaysia, where the main economic activities are located and East Malaysia on Borneo Island where major renewable energy resource potential in the form of large hydro are available, are separated by the South China Sea. Thomas [41] has expressed concerns regarding the lack of policies in place to regulate the proper use of land and the subsequent environmental impact when large scale renewable energy projects are carried out in the region. The lack of regulatory framework in some states is another major hurdle when it comes to the introduction and development of renewable energy projects.

### 4.3.1 Solar Photovoltaics

ASEAN is located within the tropical region, on both north and south of the Equator, hence receive almost continuous and uniform solar radiation trough out the year. The region's average annual irradiance rate lies between 1,500 and 2,000 kWh/m$^2$, allowing for capacity factors upwards of 20% [42]. ASEAN targets 23% of its energy mix to be made up of renewables by 2025 and to achieve this solar energy especially electricity generation from solar photovoltaics (PV) will play a huge role. Solar PV is the fastest growing grid connected electricity generation from renewable resources. The introduction of Fit-in-Tariff mechanism in several ASEAN states accelerated the growth of investment for solar PV installation projects in the past decade.

In 2019 as seen in Fig. 5, Vietnam's cumulative installed PV capacity reached 5.5 GW in just one year from only 134 megawatts (MW) in 2018–or 44% of ASEAN total capacity. Vietnam added 4.45 GW of new solar PV capacity from June 2018 to June 2019 which was well above the 1 GW target set for solar PV electricity generation by 2020 [43]. Malaysia intends to increase its renewable energy for electricity generation to 20% by 2025, the majority of which is expected to be from solar PV. The Feed-in-Tariff scheme for solar PV, both for individual and industrial scales was introduced in 2011. However, due to large demands, and lack of funds that was generated from levy imposed to all consumers, the scheme was replaced by Net-Energy-Metering NEM in 2016. Malaysia's PV industry is on the rise from the strengthening government support, growing investor confidence and reducing

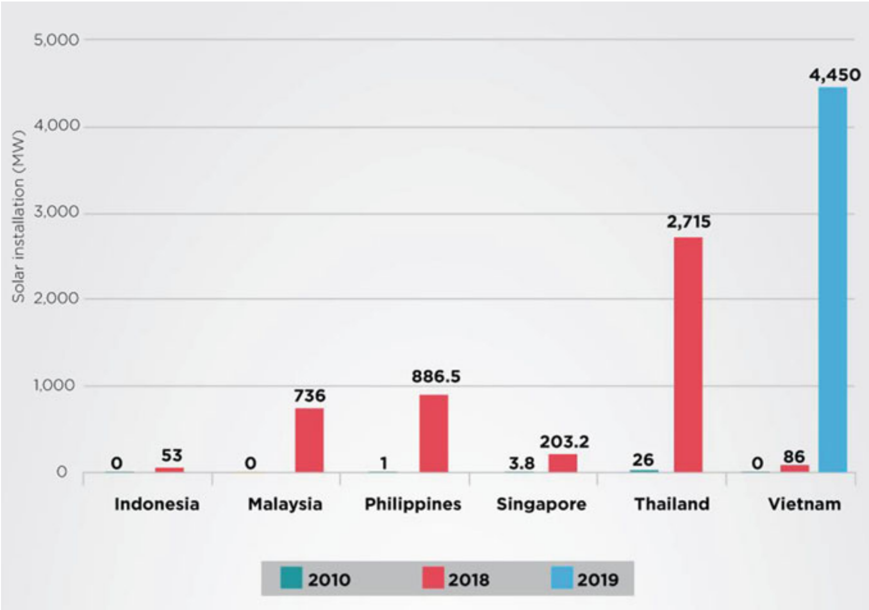


**Fig. 5** Solar installation progress in ASEAN (2010-2019) [5]

costs. The government of Malaysia launched Large-Scale Solar project exceeding 100 MW each and the cost of energy generation from solar PV has fallen below the gas-generation price in 2019 [41]. The quota of 500 MW Solar PV net metering project for individual ownership including residential home was also well received, and hence, the 4 GW targets of renewable electricity generation by 2025 could be reached.

Leading industrialised ASEAN members, such as Thailand have also focused on supporting utility-scale solar, while deployment of smaller-scale solar-plus-storage home systems. Off grids and microgrids solar PV have taken the lead in less industrialised countries, such as Indonesia and Myanmar. A mix of utility and small-scale solar-plus storage has and is being installed in the Philippines and Cambodia [41].

### 4.3.2 Solar Thermal

Compared to solar PV, solar thermal systems are much more compact and do not need much space for operation. Solar thermal systems also have higher efficiency, between 70 and 90% [44]. Solar thermal systems are relatively new to ASEAN and not many countries have implemented solar thermal systems yet, but research and development into solar thermal systems is vital to bring solar thermal as one of the mainstream technology to replace fossil fuels for sustainable development in ASEAN.

Currently solar thermal applications in ASEAN is more for residential use (solar water heating). Solar water heating (SWH) is picking up due to the applicability for water heating applications. Although there is no reliable official figure on the number of SWH units installed in each ASEAN countries, SWH market is expanding and most homes in ASEAN, especially middle and high income homes are equipped with this facility. Manufacturers or suppliers are rapidly expanding their development to have proper design, construction, installation and rating as this ‘green’ business is lucrative and has a very bright future.

Solar thermal applications in ASEAN varies according to country. Although most of the applications are for residential use but some countries in ASEAN also apply solar thermal in industrial systems [45]. In general, solar thermal energy in ASEAN is mainly focused on domestic use, in the low temperature applications. Clothes are dried under the hot sun and it is very rare to find an electrical machine dryer in ASEAN homes. Most of the agricultural and seafood products like shrimps, fish, tapioca, cocoa and others are dried under the hot sun utilising the thermal energy from the sun for evaporating the moisture contents of these products. Only recently, large scale applications of solar thermal energy are being pioneered and accepted in ASEAN for industrial applications. This section provides some examples of solar thermal installations for research and development and industrial applications in Southeast Asia specifically in 4 ASEAN countries.

The first experimental salinity gradient solar pond in Malaysia was constructed by Baharin et al. [46]. A salinity gradient solar pond was constructed to analyse the thermal storage capability. The heat energy stored in system can be used for electricity generation. This solar pond which acts as collector and storage system is a demonstration of the solar pond technology Fig. 6 research and development for low grade heat electricity generation.

Hospital Universiti Kebangsaan Malaysia (HUKM) is one of the teaching hospitals in Malaysia employing the use of solar thermal energy for hot water production [48]. The hot water system for the hospital was originally provided by a boiler with

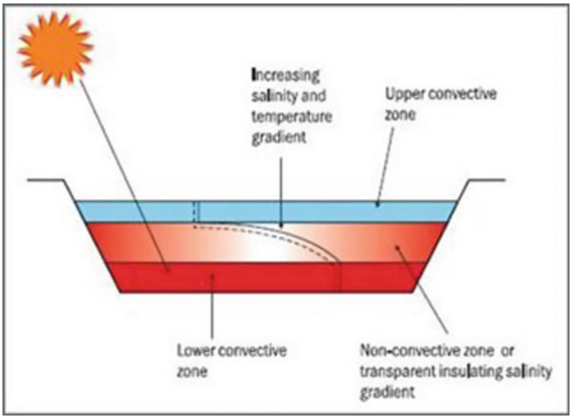


**Fig. 6** Three layers of salinity gradient solar pond (*Source* [47])

**Fig. 7** Solar thermal system in Hospital Universiti Kebangsaan Malaysia (*Source* [48])

a capacity of 2.1 million kcal/hr. This system is now running in tandem with a solar thermal system based on evacuated tubes as shown in Fig. 7. The system has helped the hospital save up to almost 40% LPG cost. A solar thermal system has also been installed to produce hot water using 3240 solar tube collectors. These solar evacuated tubes served dual purposes. One is for providing shade to the staff parking area and the other is to provide hot water to the hospital of which 20% of LPG usage is reduced.

In Indonesia, a greenhouse effect (GHE) solar dryer has been developed by CREATA-LP-IPB, to dry different kinds of crops such as coffee, cocoa, cloves, vanilla pods, pepper and also for fish and sea weeds [49]. The temperature of the hot air can reach as high as $50^0$C which can drive out the moisture effectively from the agricultural products, when compared to open air drying at ambient conditions. For night usage, heat from biomass gas stove with a help of a heat exchanger can be used to provide hot air necessary for drying Fig. 8.

The Thai Solar Energy (TSE) of Thailand and Solarlite GmBH of Germany have constructed the first concentrating solar thermal power parabolic trough plant in Southeast Asia Fig. 9. The solar thermal power plant is located in the Thai province of Kanchanaburi. The solar field has a nominal power of 19 $MW_{thermal}$ driving a 5 MW turbine by superheated steam at 30 bars and 330 °C [51]. Currently the power plant only produces electricity.

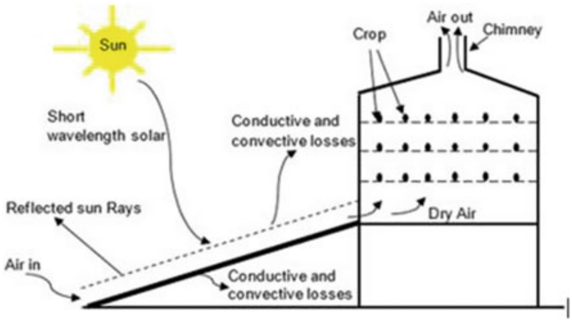


**Fig. 8** Schematic view of the indirect type solar dryer in Indonesia (*Source* [50])

**Fig. 9** Kanchanaburi concentrating solar thermal power parabolic trough plant in Thailand (*Source* [51])

Another solar thermal system with an installed collector gross area of 1890 $m^2$ related to the manufacture of leather and related products at Ayutthaya, Thailand. This system does not use a heat exchanger as water is warmed up to 70 °C and used directly in retanning process of the leather products [51]. A similar leather company, Sadesa Leather located at Sena, Thailand also uses solar evacuated tube to process their leather products (SHIP [52]. The system uses open cold water at 30 °C, which is warmed up to 80 °C for retanning processes. The Inter Rubber Latex Co. Ltd at Surat Thani, Thailand uses air heated by solar collectors and dries natural rubber with this solar thermal energy. This system involves no storage system as air is heated directly to dry the rubber products. Annual useful solar heat delivery of 50 MWh/a is achieved by the system. Figure 10 shows the solar evacuated tube thermal system used by Inter Rubber Latex Co. Ltd for rubber drying process (SHIP [52].

A new indirect solar dryer was constructed and installed in Mapandan, Pangasinan in the Philippines [53]. The solar dryer is mainly used for agriculture drying process and provides an innovation as the solar dryer and solar collector are integrated as one unit. Mainly cocoa beans are dried using the above technology. This solar dryer is much efficient and faster than the traditional open air solar drying because the air is

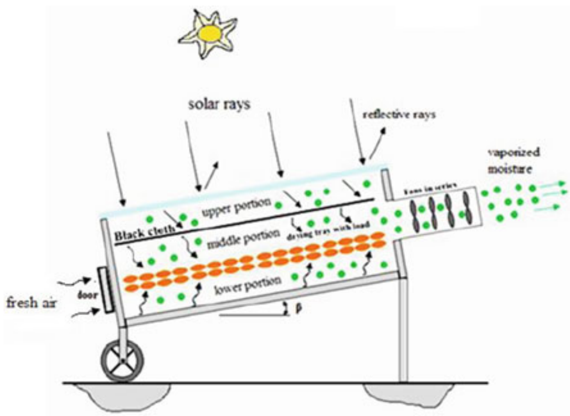


**Fig. 10** Indirect solar dryer in Mapadan, Pangasinan, Philippines (*Source* [53])

**Fig. 11** Solar thermal system for hot air at textile manufacturing plant in Vietnam (*Source* SHIP [52])

forced to move in the solar dryer based on natural draught and also forced convection assisted by fans, as shown in Fig. 10.

Grammer Solar Vietnam uses solar thermal energy for their textile manufacturing plant in Vietnam. Air collectors with a gross collector area of 480 $m^2$ provides hot air for the textile manufacturing process. The solar thermal system is used for general process heating with no requirements for storage. Annual useful solar heat delivery of 300 MWh/a is achieved by the system used. Figure 11 shows the system at the rooftop of their manufacturing plant (SHIP [52]. Saigon Tantec, a leather processing company in Saigon, Vietnam uses evacuated tube solar collectors for manufacture of leather and related products. The collectors have 1000 $m^2$ installed collector area, with a short term water storage of 70 $m^3$. Open cold water of 25 °C is warmed up to 70 °C and used directly in retaining process without any heat exchanger [52]. A denim processing plant, Saitex Jeans in Saigon, Vietnam also uses evacuated tube solar heaters for manufacture of denim wearing apparel. The size of the installed collector area is 420 $m^2$, with a short term hot water storage of 20 $m^3$. The solar thermal heat is used in for jeans washing process. The system uses open cold water of 25 °C, which is warmed up to 60 °C [52].

A summary of the some solar thermal application examples in ASEAN are listed in Table 2. This list is not exhaustive due to unavailability of data.

The main challenges to the implementation of solar thermal energy systems in ASEAN are related to the regulatory requirements and clear direction for the implementation at the policy level [48]. Subsidies by the government and international agencies can be used to attract industrial players to implement solar thermal systems. Governmental policies that implement taxes such as Carbon Tax to mitigate the use of fossil fuel can be seen as a step closer to encourage the use of renewable energy. Ismail et al. [48] went on to report that solar thermal systems are also still under demonstration stage due to lack of funding. Hence, the governments and private sector should invest more in infrastructure and research and development (R&D) of renewable energy to raise the renewable energy technology development. A skilled workforce is also needed especially for installation, operation and maintenance.

**Table 2** Solar Thermal in Industrial Systems in ASEAN countries

| Country | Name of solar thermal plants | Sector | Solar thermal implementation | Source |
|---|---|---|---|---|
| Malaysia | Experimental solar pond, Universiti Teknologi MARA, Shah Alam | Thermal heat storage and collector (Demonstration) | Salinity Gradient Solar Pond | Baharin et al. [46] |
| | Poultry processing Malaysia PPNJ | Processing and preserving of meat and production of meat products | Using evacuated tube collector to heat scalding tank | SHIP Plants [52] |
| | Solar thermal system in HUKM | Preheating water for hospital use | Using evacuated tube collector | Ismail et al. [48] |
| | Solar thermal system in Hospital Sungai Buloh | Preheating water for hospital use | Using evacuated tube collector | Ismail et al. [48] |
| Indonesia | Malabar Tea Drying | Manufacture of food products | Using solar dryers to dry tea leaves | Lingayat et al. [50], Farjana et al. [49] |
| | CREATA-LP-IPB | Drying of coffee, cocoa and spices | Uses indirect solar dryer | Farjana et al. [49] |
| Thailand | Inter Rubber Latex Co. Ltd | Manufacture of rubber and plastic products | Uses air collector to dry natural rubber | Khanessi et al. [51] |
| | Ayutthaya tannery | Manufacture of leather and related products | Uses evacuated tube collector to heat leather | SHIP Plants [52] |
| | Sadesa Leather | Manufacture of leather and related products | Uses evacuated tube collector to heat leather | SHIP Plants [52] |
| Philippines | Solar Dryer | Drying of cocoa beans | Uses integrated solar dryer and collector | Burguillos et al. [53] |
| Vietnam | Saigon Tantec | Manufacture of leather and related products | Uses evacuated tube collector | SHIP Plants [52] |
| | Saitex Jeans | Manufacturing of wearing apparel | Uses flat plate collector for jeans washing | SHIP Plants [52] |
| | Grammer Solar Vietnam | Manufacturer of textiles | Uses air collector | SHIP Plants [52] |

### 4.3.3 Bioenergy

There is the enormous potential of biomass energy in ASEAN since the region has the capacity to produce large quantities of biomass all year round. Many Southeast Asian countries are among the top producers of agricultural commodities such as rice, sugar cane, palm oil, coconut, and rubber, and the most promising residues are oil palm residue, rice husk, sugarcane bagasse and wood residues. The total annual quantity of the biomass potential from agriculture and forest sector in the region is estimated to be more than 500 million tons per year and equal to over 8000 million gigajoules of total energy potential [54]. Woody biomass from forests still constitutes a valuable source of energy in the form of domestic fuel for local residents. Biomass especially from agricultural and wood industry waste are also widely used for heat and electricity generation. However, the grid connected electricity generation from biomass is limited due to the scattered resources mostly in remote areas far from the grids [55]. In addition, some sources of bioenergy are sources of $CO_2$ emissions and therefore are not considered as clean fuels.

### 4.3.4 Hydropower

Hydropower contributes 16% to region's electricity generation mix. Large hydropower comprises more than 75% of the region's renewable energy mix. Vietnam leads the way in Southeast Asia with 17 GW megawatts (MW) in 2017 [9]. In the last decade, a significant number of hydroelectric dams were built across the region. The total installed hydropower capacity in ASEAN increased more than double between 2006 and 2017 from 19.8 to 46.6 MW. In 2006, Indonesia, the Philippines, Thailand, and Vietnam accounted for about 92% of the total installed hydropower generation. Vietnam accounted for 27% of the total capacity whilst Indonesia, the Philippines, and Thailand each accounted for slightly below 20%. In 2017, the installed capacities in Malaysia and Vietnam rose approximately 6 MW and 17 MW, respectively. Cambodia, the Lao PDR, and Myanmar increased their installed capacities more than five times due to significant increases in their energy demand. Lao PDR has 46 operating hydroelectric power plants and intends to almost double that number by 2020. The IEA [12] reports that Lao PDR exports two-third of all its hydropower generated electricity, accounting for almost 30% of the country's total exports. Small hydropower which include dam-less mini and micro hydro also gained a lot of attention both for grid connected and micro grids. Hydro-electric projects up to 30 MW to obtain a feed-in tariff as defined in the Malaysian Renewable Energy Act 2011 [5].

### 4.3.5 Wind

Wind energy has been a relatively low priority renewable sector in ASEAN. Only Philippines, Thailand, and Vietnam have taken substantial efforts to promote the

**Table 3** The targets of wind energy in the AMS [42]

| Member State | Wind energy target |
|---|---|
| Lao PDR | 73.0 MW in 2025 |
| Indonesia | 1.5 GW in 2025 |
| Philippines | 2.3 GW in 2030 |
| Thailand | 3.0 GW in 2036 |
| Vietnam | 12.0 TWh in 2030 |

wind energy sector. The Philippines has the largest wind potential with an estimated wind energy of around 70 GW and is the largest market for wind power in ASEAN, adding 350 MW of new capacity in 2014–2015.It was driven by Fit-in-Tariff for wind energy introduced in 2013 but stopped at the end of 2015 after its capacity quota was full [44]. They report that the technical potential of wind sources along the more than 3000 km coastline in Vietnam is estimated at 27 GW. However, only a fraction of which could be developed. Vietnam announced its wind power targets following the wind Feed-in Tariff programme in 2011 and plans to increase its wind energy capacity in the national energy mix up to 800 MW by 2020, 2,000 MW by 2025 and 6,000 MW by 2030 [56]. Significant wind energy potentials are also recorded in Cambodia, Myanmar and Lao PDR. With the introduction of FIT for wind energy in several ASEAN states, the cumulative wind power capacity in the region has more than tripled in just 3 years, from 145 MW in 2012 to 750 MW in 2015 [42]. The capacity of wind power in ASEAN in the latest policy scenario for 2016 is 1 GW and is expected to increase by 22 GW by 2040 [12]. Thailand, the Philippines, Indonesia, Vietnam and to some extent Lao PDR have stated their commitment to wind power by including it in their RE target. The targets of wind energy in the AMS are shown in Table 3.

### 4.3.6 Geothermal

Southeast Asia is home to around a quarter of the world's geothermal generation capacity. Most of this geothermal capacity is located in the Indonesia and the Philippines who are currently ranked as the second and third largest producers of geothermal energy in the world, after the United States, since both nations are located in the Pacific Ring of Fire, a geological term to describe the volcanic lines between Indian and Pacific Ocean. This area consists of active volcanoes and hot spots which have high potential of geothermal source. Indonesia alone has 29 GW of geothermal potential or about 40% of total world's geothermal resources [57]. The Philippines has geothermal potential of 4 GW. Other ASEAN countries that have a considerable amount of geothermal resources are Myanmar, Lao PDR, Thailand, and Vietnam. Malaysia have identified only one significant geothermal site with a capacity of 70 MW in East Sabah on Borneo Island.

Several major geothermal projects have been commissioned in the past decade, with the additional electricity generation capacity of 529 MW from 2,827 MW in

2006 to 3,356 MW in 2015 of which the Philippines was the main contributors of the increase, followed by Indonesia [57]. Both nations have included geothermal source as part of their renewable energy target policies. The Philippines aims to have additional 1,495 MW of geothermal installed power capacity between 2011 and 2030, while Indonesia sets a target of 7.1 GW geothermal power by 2025 [57]. Indonesia has also issued feed-in tariffs scheme for the geothermal electricity generation. While geothermal resources take time to develop, this decision will enhance Indonesia's energy diversity, and security in the long term with renewables tipped to contribute 23% of the total national energy mix by 2025, and geothermal accounting for 8% of the total electricity generation [57].

The development of the geothermal energy in ASEAN however, is still facing challenges such as technological costs, land acquisition and competition with fossil fuels. However, with an abundant potential of geothermal source especially in Indonesia and the Philippine, and full support from the governments and private sectors, the future of geothermal sector in the ASEAN particularly in Indonesia and the Philippines, is very promising.

## 5 Energy Efficiency

Together with renewable energy target and initiatives, energy efficiency will be key to building a reliable and sustainable energy system for the future of ASEAN. All ASEAN countries have already their own energy-efficiency targets. ASEAN has successfully achieved an energy intensity reduction by 18.3% in 2015, compared to 2005 levels. ASEAN aims to increase energy intensity by 20% in 2020 and 30% by 2025 [37]. Energy intensity is the measure of energy efficiency, calculated in terms of units of energy per unit of GDP. There is a high potential for EE savings and EE will reduce 18–28% ASEAN demand by 2040 [40]. Buildings account for about 40% of total final energy consumption in ASEAN, hence they hold the highest potential for cost-effective energy savings. Cooling and air-conditioning have The use of building energy codes is one example of an energy-efficient strategy. Malaysia, Thailand and Indonesia are among ASEAN states which have building codes to encourage energy-efficient design and construction. Singapore has set an ambitious target of greening 80% of its buildings by 2030, and its current challenge is on greening its existing stock of buildings [58]. Energy efficiency practices must be given importance as they are the most environmentally friendly when properly implemented [20].

## 6 Possible Solutions

There are a number of options in Southeast Asia to replace fossil fuels by renewable sources. Solar and wind energy could fill the needs of most of the countries [15]. The applications of hydropower, geothermal and bioenergy can complement the use of solar and wind technologies. Renewable energy technologies can produce and contribute electricity to the grid efficiently even if the grid is not functioning properly especially in the rural areas. The cost of installing renewable energy systems has already decreased since 2016 to match the cost of conventional energy. For Southeast Asian countries to use the diverse renewable energy potentials, there must be regional cooperation using existing frameworks to fully realise this potential.

Mat Sahid et al. [11] propose that to mitigate the energy security issues include the diversification of sources of energy supply such as supply infrastructure to facilitate regional interconnection, promotion of more renewables,reducing the carbon content of energy such as increasing the use of bioenergy and promote green technology; efficient utilisation of energy such as improvements in energy efficiency, energy demand and supply, low-carbon emission public transport and introducing smart and green cities; facilitating low-carbon industries and service development to promote economic growth; and regional interconnection of energy supply infrastructure and resources. Regional interconnection may prove to be difficult due to political, geographical, technological and socio-economic factors. Real energy security issues are more micro in nature [59] and each country needs to have its own recipe for addressing these issues.

Quirapas and Narasimalu [60] have recommended that the use of ocean renewable energy may a viable option of alternative energy use in the long term to achieve energy security. However, they also warn that there will be non-technical and non-economic barriers including political approaches in decision-making as energy security in Southeast Asia is complex due to the growing economy, population and the consequences of environmental impact.

Hydrogen may be another alternative solution to add to the ASEAN energy mix. Gao [61] reports that Singapore has begun test-bedding hydrogen systems with the Energy Integration Demonstrator Singapore (REIDS). Brunei has set up an international hydrogen supply chain with the Advanced Hydrogen Chain Association for Technology Development (AHEAD) while Malaysia has started to introduce hydrogen buses in the city of Kuching, Sarawak. All these attempts are still at the infancy stage and it is suggested that ASEAN and Southeast Asia could learn from Japan and the European Union on the hydrogen economy.

Peimani and Taghizadeh-Hesary [62] propose that renewables are the best option for the majority of the Southeast Asian countries, which are developing and low or middle-income. Technology-wise, a combination of intermittent (wind, solar and ocean energy) and continuous (mainly hydro, run-off river hydro and geothermal) energy needs to be used together to ensure the availability of reliable alternative energy to oil, gas and coal for a large part of countries' energy needs for commercial, industrial, residential and agricultural activities. The authors also suggest sustainable practices should be put into place where fossil fuels cannot replace such as environmentally clean alternatives to fossil liquid fuels (gasoline and diesel fuel) for transportation. All the Southeast Asian countries have yet to harness their full renewable potentials due to cost factor and technological challenges. The countries should opt for less-technologically challenging and less expensive renewable systems, which are environmentally clean such as solar boilers to convert solar energy into electricity. These countries should also look into small hydro-generators (example in the Philippines) and vertical wind turbines (installed in Singapore) or solar panels (as in Singapore and Malaysia) which can be installed on rooftops [62]. It is also possible for the richer Southeast Asian countries to export their systems to the poorer neighbours in the future.

The International Energy Agency [63] reveals that the global energy-related $CO_2$ emissions stopped growing in 2019. This is most certainly a piece of good news despite the world economy expanding by 2.9%. This shows how current efforts to implement real-world energy solutions and policies are able to reach or even exceed climate goals.

Apart from the the development and implementation technologies, policies must be in place to harness the potential of renewables in Southeast Asia. Mat Sahid and Tan [22] have recommended a general policy framework to formulate sustainable policies. The region needs to: formulate long-term energy mix containing a target for renewable energy,a renewable energy power regulation or strategy; or application; develop focused, coherent and complete renewable energy guidelines complementing global climate change regulations; decrease non-economic limitations and barriers; expansion of the ASEAN Power Grid; expand electricity use from domestic consumption to more productive uses; offer incentives for capital finance in renewables; establish systems to exchange expertise; introduce economic incentives (such as carbon tax); develop strategies, initiatives and investments to prioritise use of electricity from renewables and optimise and maximise the aid given by international agencies such as ADB, World Bank and APEC.

The Asian Development Bank is currently and will continue to be in the forefront of assisting Southeast Asia to mitigate climate change by mobilising additional finance, developing knowledge products and enhancing partnerships with other contributors [64]. The main sectors that require adaptation actions which are primarily water resources, agriculture, coastal and marine resources, forestry, and health by adopting more proactive and integrated approach in development and poverty reduction. Southeast Asia is an important region in the development of global solutions, but requires international funding, technology transfer and cooperation. The process of finding solutions to climate change, provides an avenue towards developing sustainable, climate-resistant and low-carbon economies in Southeast Asia. ADB also promotes energy efficiency, invests in renewable energy technologies, low-carbon public transport and initiatives to reduce GHGs.

## 7 Closing Remarks

We have seen that energy insecurity spreads across all Asian countries and it is especially so for Southeast Asia. Although there are many examples of efforts towards the use of renewables, fossil or non-renewables still dominate the energy mix [62]. There are many obstacles hindering the increase of renewables in the energy mix and therefore there needs to be a very comprehensive sustainable approach to ensure that the demands of the countries are met without compromising their social and economic development. Some Southeast Asian countries have done better than the rest. A 2020 report by the World Economic Forum (WEF) has revealed that the energy Transition Index (ETI) which ranked 115 economies on how well they are able to balance energy security and access with environmental sustainability and affordability is focused on ASEAN countries based on their current energy systems and readiness to adapt to future needs [2]. In the report, it was established that Malaysia ranked highest in emerging and developing Asian country with energy access and security scores among the top 15 out of 115 countries analysed due to high electrification rate, low usage of solid fuels, diversity of fuel mix and high quality of electrical supply. Therefore, there is much hope for the Southeast Asian countries to mitigate their energy security issues by not only learning from other Asian and European countries but also from their ASEAN counterparts.

Despite all the global efforts by various organisations, agencies and governments to mitigate climate change, energy security that affect health and the environment, there is always a degree of uncertainty. Health can be a major factor that reverses the situation. Most recently the pandemic caused by Covid-19 have grave implications on the global economy, energy use and $CO_2$ emissions and Southeast Asia is no exception. Global energy demand declined by 3.8% and predicted to be 6% by the end of 2020, where demand for all fuels (except renewables) declined [65]. The IEA predicts that global electricity demand due to lockdowns in most countries may decline between 5 and 10%. Most importantly, the aftermath of the pandemic may cause the increase of energy demand and $CO_2$ to outweigh the decline unless the economy is redesigned for cleaner and more resilient energy infrastructure [65.

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# Energy Security: A Case Study of Indonesia

**Qodri Febrilian Erahman and Widodo Wahyu Purwanto**

**Abstract** Indonesia as the largest country and the highest population in the Southeast Asia region results in the greatest value of energy consumption, therefore, being a huge energy-consuming country may represent the situation in that region. Various kinds of energy policies have been carried out by the Government of Indonesia, resulting in a situation, where energy production, energy exports, energy access, are increased, while energy imports, energy reserves, and emission intensities are decreased. However, these situations have never been well concluded. The energy security index provides information that can summarize all of the energy situations. The aim of this paper is to conduct an assessment of Indonesia's energy security index within the period of 2000–2018. The energy security index consists of dimensions, namely availability, affordability, accessibility, and acceptability. Each dimension consists of indicators, in which there are twelve indicators used in the assessment. All indicators and dimensions subject to the same weight, so that the selection of indicators is important to represent the energy situation in accordance with Indonesia's perspective on energy security. The indicator normalization uses the min–max method, in which the maximum indicator obtained based on the highest value owned by countries in the Southeast Asia Region, therefore the indicator value will be relative to it. The results show an increase for almost all dimensions except the affordability dimension. In general, Indonesia's energy security index has increased by 29.9%, which is 0.330 and 0.428 in the year of 2000 and 2018, respectively. The Indonesia's energy security index showing a value below 0.5 indicates that Indonesia is in an unfavorable situation of energy security. Furthermore, the improvement of energy security should be focused on the dimension that has the lowest value.

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## Nomenclature

| | |
|---|---|
| *BFP* | Biofuel Production |
| *BIOPOP* | Traditional biomass users, population |
| $C_{exp}$ | Coal export |
| $C_{imp}$ | Coal import |
| *CP* | Coal production |
| *CPR* | Coal proven reserves |
| $EMCO_2$ | CO2 emissions |
| *EPOP* | Electricity users, population |
| *GDPP* | GDP per capita |
| $G_{exp}$ | Gas export |
| $G_{imp}$ | Gas import |
| *GP* | Gas production |
| *GPR* | Gas proven reserves |
| *HH* | Number of household |
| $HH_g$ | Number of household using natural gas |
| $OGC_{EXP}$ | Oil, gas, coal export |
| $O_{imp}$ | Oil import |
| $O_{imp}$ | Oil export |
| *OP* | Oil production |
| *OPR* | Oil proven reserves |
| *POP* | Population |
| *PRd* | Diesel price |
| *PRe* | Electricity price |
| *PRg* | Gasoline price |
| *PRl* | LPG price |
| *RS* | Renewable supply |
| *TPEC* | Total primary energy consumption |
| *TPECP* | TPEC per capita |
| *TPEP* | Total primary energy production |
| *TPEPP* | TPEP per capita |

## 1 Introduction

Energy is a strategic commodity that it's availability is important to sustain economic activity. The high use of fossil fuels to meet the energy demands lead to the global decline of fossil energy availability, meanwhile, energy consumption continues to rise following the economic growth. This situation brings up the meaning of energy security.

The definition of energy security first appeared, since the oil crisis occurred in 1970. At that time, the concept of energy security is solely to avoid the occurrence of oil supply disruption. Changes in energy supply and demand led to growing the definition of energy security. The considerations of energy not just limited to the availability of oil, but other types of energy also being considered. Furthermore, other aspects are also being considered to describe the level of energy security [1].

All the situations regard to the high energy price, low accessibility of energy, inefficient energy use can be defined as a lack of energy security. Previous research has reported the measurement of energy security i.e. the measurement of the oil vulnerability index [2], the measurement of the gas supply resistance index [3], the measurement of energy security based on the level of diversity of energy sources [4]. However, these kinds of measurements describe energy security just focuses on the specific aspects, while there are still many other aspects that need to be considered, therefore multidimensional measurements are needed to describe all aspects of energy security. Meanwhile, a number of researchers and international organizations have developed various dimensions to measure energy security [5]. The previous study conducted by Erahman et al. has also reported an assessment of Indonesia's energy security using various dimensions [6], however, the assessment ranges in a narrow period from 2008 to 2013. Therefore, in this article, multidimensional measurements will be conducted to determine Indonesia's energy security with a broader period of assessment.

The definition of energy security itself is relative due to the perspective of each country to determine the level of success on its national energy policy. In Indonesia, the notion of energy security is not only a matter of energy availability but, affordability, accessibility, and acceptability are also being considered as stated in Energy Law 30/2007 [7]. Energy is a primary commodity for modern society to sustain daily activities however, its consumption will impact the environment, particularly the $CO_2$ emissions. Excessive $CO_2$ emissions from energy consumption can also be defined as poor energy security. The Indonesian Government has determined the greenhouse gas emissions reductions by 26%, which is based on the Copenhagen agreement, on January 2010 [8], Since then, the Government is committed to taking action to mitigate the $CO_2$ emissions. Implementation regards this target will certainly affect the level of energy security in the future.

Indonesia as an archipelagic country with the largest area and highest population may portray the energy situation in Southeast Asia. In addition, the best situation of the particular aspect of a country in Southeast Asia will be used as the highest parameter value in the process of measuring Indonesia's energy security.

# 2 Energy Security

## 2.1 Definition of Energy Security

Energy plays an important role in any economic activity, such as transportation, communications, security, health, education, services, etc. [9]. Based on Energy law 30/2007 the various definitions of energy are mentioned as follows [7]:

1. Energy is the ability to do work that can be heat, light, mechanical, chemical and electromagnetic;
2. The energy source is something that can generate energy, either directly or through conversion or transformation process;
3. Energy Resources is a natural resource that can be used both as a source of energy and as an energy.

The awareness of energy security began to recognize since the increase of crude oil prices occurred in 1970, in which the oil supply was controlled by oil producer. The impact of this crisis and the emergence of the OPEC cartel is a first milestone, which encouraged several countries to increase their energy security. For instance, Japan almost completely dependent on imported energy supplies, thus Japan continuously applies the principle of energy diversification through the development of natural gas infrastructure [10], nuclear power, renewable energy, and any type of energy. This situation brings the definition of energy security based on energy diversification. Below here are some definitions regards energy security according to several institutions:

| | |
|---|---|
| 1. APERC | the ability of an economy to guarantee the availability of energy resource supply in a sustainable and timely manner with the energy price being at a level that will not adversely affect the economic performance of the economy [11]; |
| 2. European Commission | uninterrupted physical availability on the market of energy products at a price which is affordable for all consumers [12], |
| 3. The International Energy Agency | the uninterrupted availability of energy sources at an affordable price [13]; |
| 4. World Bank | ensuring countries can sustainably produce and use energy at a reasonable cost in order to facilitate economic growth and, through this, poverty reduction, Directly improve the quality of peoples' lives by broadening access to modern energy services [14]. |

### 2.2 Energy Security Indicators

Indicator is a quantitative or a qualitative measure derived from a series of observed facts that can reveal relative positions [15]. The indicators are used to identify trends, predict problems, find out the various options, set targets and evaluate the decisions. The indicator determination should be selected in terms of highly useful information. In many cases a single indicator is not enough, therefore a set of several indicators that summarize a variety of information ought to be used. The indicator selection should meet the following criteria [15]:

| | |
|---|---|
| 1. Comprehensiveness | indicators must reflect on the targets measured |
| 2. Quality | the data should be accurate and consistent |
| 3. Comparable | the data should have clear definitions and comparable |
| 4. Understandable | could be understood by decision-maker |
| 5. Accessible and transparent | indicators and detailed explanation should be available to all stakeholders |
| 6. Cost-effective | the data for Indicator should consider cost-effective |
| 7. Net effects | indicator should indicate a change |
| 8. Functional | the selected indicators are appropriate to explain the measurement. |

Various indicators that will be used to measure energy security can be based on previous research. Specific indicators will be selected based on the definition of energy security. The various definition of energy security will result in different compositions of indicators, whereas each country has own definition of energy security. In general, energy security used to measure the level of success on the energy policy of a country. Since the definitions are country-based, therefore no exact definition of energy security.

Based on a review of previous studies concluded that energy security has at least four basic dimensions, namely availability, affordability, accessibility, and acceptability, or better known as 4A's, subsequently these four dimensions will be used in this paper. The four dimensions are in line with the provision of Energy Law 30/2007, where the objective of energy security by the Government are as follows [7]:

1. Achievement of energy independence (self-sufficiency);
2. Energy availability, both from domestic and foreign sources;
3. The management of energy resources in an optimal and sustainable manner;
4. The efficient use of energy;
5. Achieving energy access for society;
6. Affordable energy prices for the society;
7. The use of energy should environmental-friendly.

Furthermore, determining the definition of each dimension is translated based on the explanation above. Table 1 explains the definition of the energy security dimension.

Dimension consists of indicators, therefore the composition of indicators should be able to represent the closest meaning with its dimension. In this case, we only

**Table 1** The definition of the energy security dimension

| No. | Dimension | Definition |
|---|---|---|
| 1 | Availability | The availability of energy production, energy independence, and energy reserves for the future |
| 2 | Affordability | The affordable energy price which considers people's income |
| 3 | Accessibility | Commercial energy access for society |
| 4 | Acceptability | The energy consumption should environmental-friendly |

need to use 3 indicators from each dimension that can represent the equal meaning of each dimension, therefore the total number of indicators is 12. Previous research has reported, that the effective use of energy security indicators is not more than 20 indicators [5]. Below are the explanation of indicators for each dimension.

1. Availability

The availability indicators consist of energy production, self-sufficiency, and available energy reserves. Energy production denotes domestic ability to produce energy. Self-sufficiency relates to the capabilities of domestic to supply energy, while the available energy reserves indicate the number of days of available energy reserves owned by a country.

2. Affordability

The final energy commodities that often be the main issue of energy prices in Indonesia are diesel, gasoline, and electricity. As a matter of fact, these final energies have always been subject to political discussion in Indonesia. Moreover, to bring a closer meaning to the definition of affordability dimension, the energy price should be divided by GDP per capita, since GDP per capita reflects the people's income. Therefore, the higher GDP per capita will have an impact on higher energy security.

3. Accessibility

The indicators for accessibility dimension consist of electrification ratio, percentage of households relying on traditional use of biomass, and the percentage of households using pipeline natural gas. The indicators are chosen based on the Government program implementation. The Government is working on to increase the electrification ratio throughout the region, that the most difficult task is to provide electricity to remote areas. Besides, a program of natural gas pipeline for households is being aggressively implemented by the Government. These two indicators are good enough to describe the energy access situation, however, the addition of the percentage of households relying on traditional use of biomass will provide a complete picture of the accessibility dimension.

4. Acceptability

The energy consumption should environmentally friendly means that the use of energy should efficient, less emission, and sustain. Therefore, indicators that can be chosen are energy intensity, emission intensity, and renewable energy utilization. The energy intensity describes how efficiently the use of energy in its contribution to the economy, while emission intensity shows how much emissions from the use of energy to boost the economy. These two indicators are complementary, therefore the renewable energy utilization in total energy consumption will describe the remaining definitions.

Based on the above explanation, it can be summarized, that the energy security indicators are as explained in Table 2.

**Table 2** The energy security indicators

| No. | Dimension | Code | Indicator | Equation | Increasing impact |
|---|---|---|---|---|---|
| 1 | Availability | Avail 1 | Per capita energy production | $\frac{TPEP}{POP}$ | + |
| 2 | | Avail 2 | Self-sufficiency | $\frac{(TPEP-OGC_{EXP})}{TPEC}$ | + |
| 3 | | Avail 3 | Reserves (oil, gas, coal) to production ratio (RPR) | $\frac{OPR}{OP}+\frac{GPR}{GP}+\frac{CPR}{CP}$ | + |
| 4 | Affordability | Afford 1 | Diesel oil price to GDP per capita ratio | $\frac{(PR_d)}{GDPP}$ | – |
| 5 | | Afford 1 | Gasoline price to GDP per capita ratio | $\frac{(PR_g)}{GDPP}$ | – |
| 6 | | Afford 2 | Electricity price to GDP per capita ratio | $\frac{PR_e}{GDPP}$ | – |
| 7 | Accessibility | Access 1 | Electrification ratio | $\frac{EPOP}{POP}$ | + |
| 8 | | Access 2 | % Household relying on traditional use of biomass | $\frac{BIOPOP}{POP}$ | – |
| 9 | | Access 3 | % Household using pipeline natural gas | $\frac{HHg}{HH}$ | + |
| 10 | Acceptability | Accept 1 | Energy intensity | $\frac{TPEC}{GDP}$ | – |
| 11 | | Accept 2 | Emissions intensity | $\frac{EMCO_2}{GDP}$ | – |
| 12 | | Accept 3 | Renewable energy utilization to energy consumption | $\frac{RS}{TPEC}$ | + |

### 2.3 Methodology

Several steps to assess energy security are describes in Fig. 2, that the details explanation are as follows:

1. Data preparation according to the range of 2000–2018, followed by input data to the indicator equations as described in Table 2;
2. Indicators and dimensions calculation

   a. Indicator normalization into values in the range of 0 to 1, using the min-max method, below are the normalization equations.

$$I'_{it} = \frac{I_{it}}{\mathrm{Max}(I_i)} \quad (1)$$

$$\mathrm{Max}(I_i) = \mathrm{Max}\{I_1, I_2 \ldots I_i\}$$

   For indicators that have a negative impact should applied inverse indicator, as explained in the following equation.

$$I'_i = \frac{I_{INV,i}}{\mathrm{Max}_{INV}(I_i)} \quad (2)$$

$$I_{INV,i=\frac{1}{I_i}} \quad (3)$$

$$\mathrm{Max}_{INV}(I_i) = \mathrm{Max}\left\{\frac{1}{I_1}, \frac{1}{I_2} \cdots \frac{1}{I_i}\right\} \quad (4)$$

   The maximum value is based on the highest value achieved by countries in Southeast Asia, except for indicators that have been determined on other considerations and had a maximum value of 1 due to equations.

   b. The dimension value obtained by averaging all the indicators;

3. Averaging all dimensions will result in the energy security value (Fig. 1).

## 3 Indonesia's Energy Situation

### 3.1 Primary Energy Reserves

Fossil energy reserves in Indonesia, especially oil and gas tend to decrease until 2018. Indonesia and Malaysia have proven oil reserves that are nearly identical to around 4 billion barrels. Meanwhile, Indonesia's natural gas reserve is the largest reserves in Southeast Asia Region, which is reached 43% of the total gas reserves in Southeast Asia.

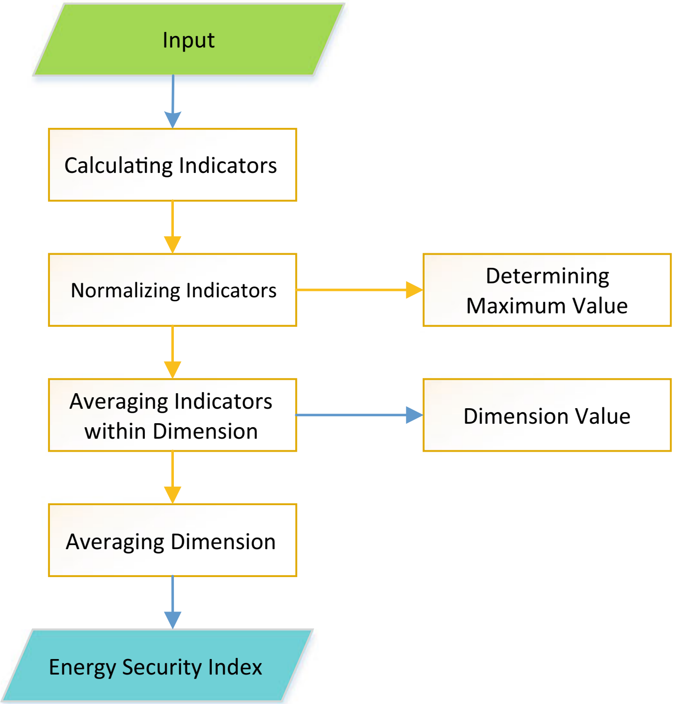


**Fig. 1** Flowchart of energy security assessment

Figure 2 shows Indonesia's proven oil and gas reserves in 2000–2018.

Proven coal reserves have increased significantly started in 2006. This increase is the result of significant exploration and exploitation due to export demand. Indonesia's coal reserves reach 93% of all reserves in Southeast Asia. The rest are spread in Thailand, Laos, and Philippines. Figure 3 shows proven coal reserves in 2000–2018.

### *3.2 Primary Energy Production and Consumption*

Primary energy production consists of production comes from fossil and renewable energy. Fossil energy production is the summation of petroleum, natural gas, and coal production. Indonesia's energy production is increasing with an increase of 3.84% per year. In 2018, the primary energy production was significantly increased that contributed by coal production. Primary energy production is larger than its consumption. Excess energy production was contributed largely by coal. Figure 4 shows the comparison of energy production and consumption in 2000–2018.

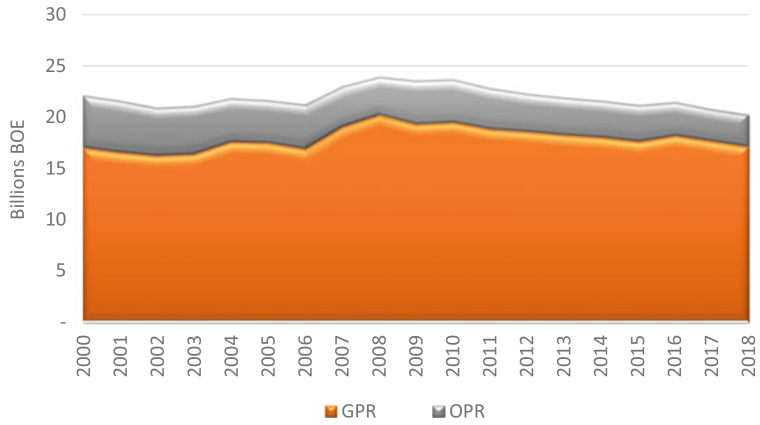


**Fig. 2** Proven oil and gas reserves in 2000–2018

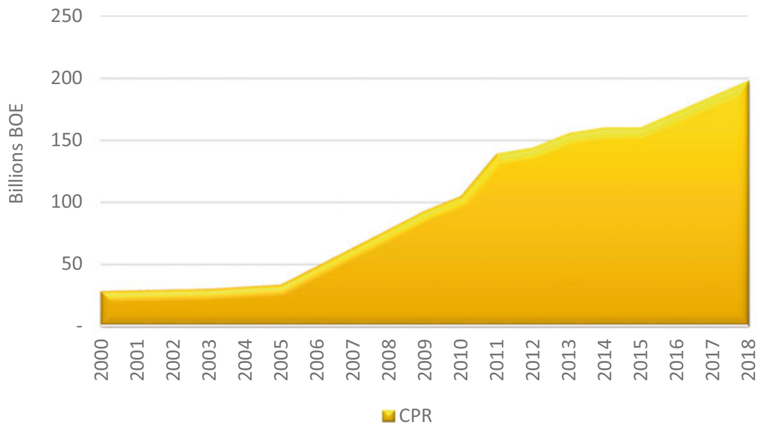


**Fig. 3** Proven coal reserves in 2000–2013

Indonesia is the largest energy producer in Southeast Asia, with a share of 53% by total energy production in this region, followed by Malaysia with a share of 18% [16]. Indonesia's primary energy production was contributed largely by coal production. Figure 5 shows the production of primary energy by type of energy, namely oil production (OP), gas production (GP), coal production (CP) and renewable energy production (RP).

Coal production has increased significantly throughout the year. The high coal production caused Indonesia becomes the second-largest coal exporter globally and a significant supplier of coal to Asian countries. Meanwhile, crude oil production tends to decline from year to year, due to the numerous oil fields that experiencing a decline, while natural gas production was relatively stable throughout the year, especially in

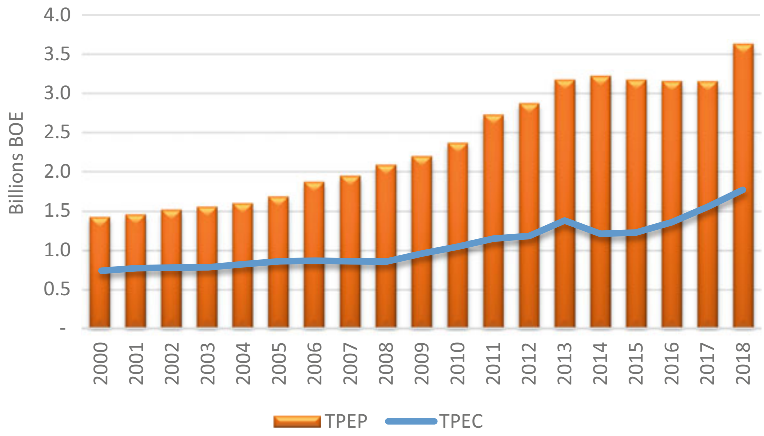


**Fig. 4** Primary energy production and consumption in 2000–2018

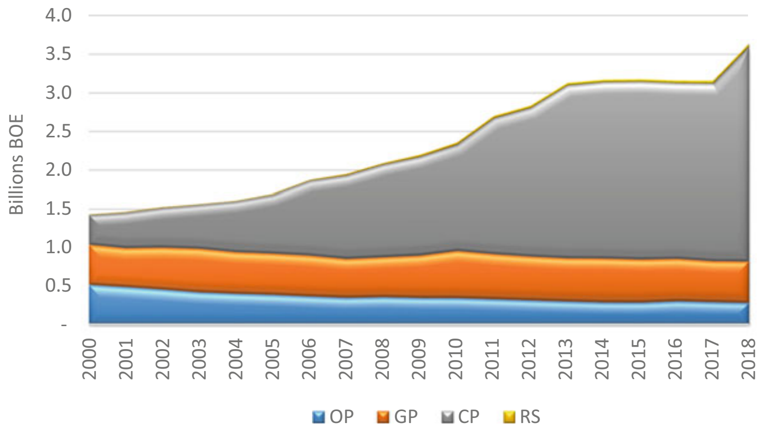


**Fig. 5** Primary energy production by type in 2000–2018

the last few years. Production of renewable energy has increased throughout the years due to the increase of biofuels and geothermal energy. However, the renewable production share is still very small compared to the fossil.

### *3.3 Export—Import of Primary Energy*

The exports of crude oil and natural gas simultaneously decreased, due to Government policies that increase the utilization of domestic energy to meet national needs. Figure 6 shows the export of oil and gas in 2000–2018.

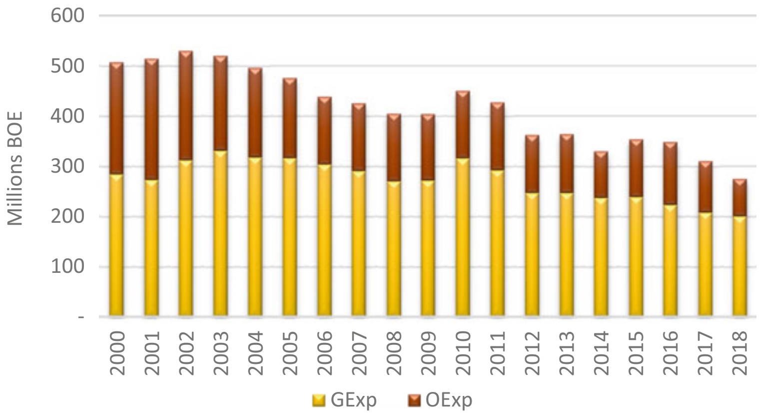


**Fig. 6** Export of oil and gas in 2000–2018

On the contrary, coal export has increased significantly in 2010 with an average of increase by 26% per year. Figure 7 shows the export of coal in 2000–2018.

The energy imports contributed by crude oil and a small amount of coal. In recent years, crude oil and coal imports reached 150–175 million and 3–27 million BOE per year, respectively. Meanwhile, there is no import in natural gas. Figure 8 shows the import of fossil energy in 2000–2018.

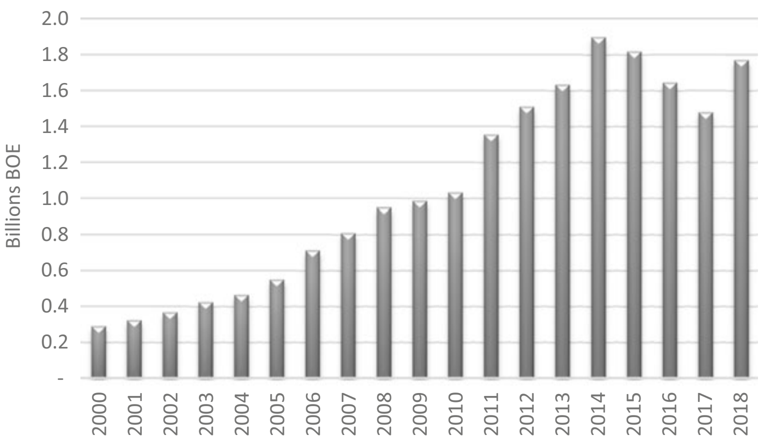


**Fig. 7** Export of coal in 2000–2013

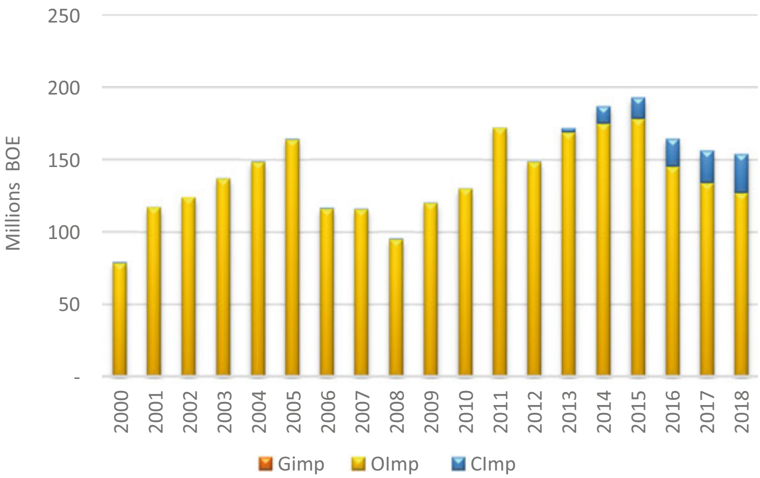


**Fig. 8** Imports of fossil energy in 2000–2013

## 3.4 Primary Energy Supply

The energy supply is known through calculation, which can be obtained from total energy production minus total energy exports plus total energy imports. The primary energy supply continues to increase throughout the year. Figure 9 shows the primary energy supply by type in 2000–2018.

The primary energy supply for crude oil fell slightly throughout the year, from 350 thousand BOE in 2000 to 334 thousand BOE in 2018, due to the decline of crude oil supply to domestic refineries. Oil refineries are not having significant additional

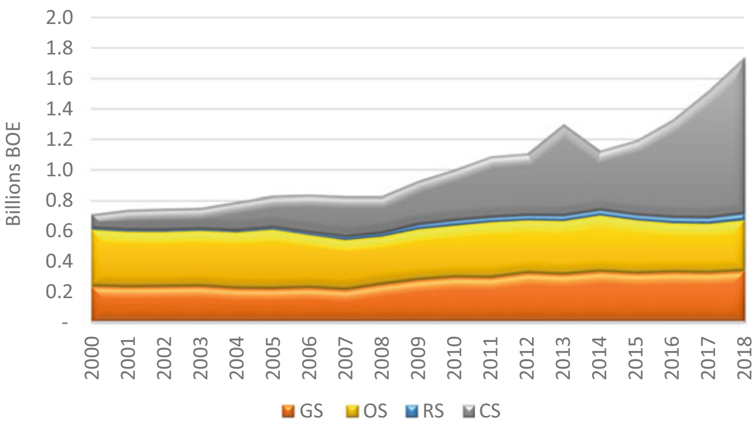


**Fig. 9** Primary energy supply by type in 2000–2018

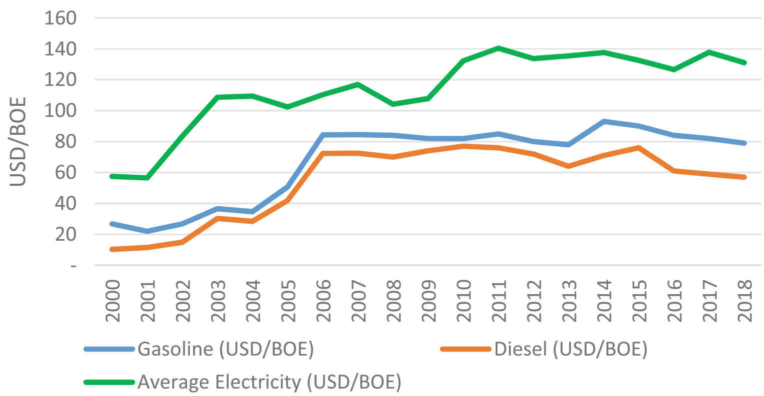


**Fig. 10** Price of gasoline and diesel fuel in 2000–2018

production capacity throughout the year, instead of having a slight decrease in oil refining activity. In contrast, natural gas supply continues to increase throughout the year with the percentage of increase is equal to 2.24% per year. The increase of natural gas supply is as a result of Government domestic market obligation of natural gas. Meanwhile, the supply energy derived from coal shows a significant increase which is occurred after 2010 due to the supply of coal for domestic power generation.

## *3.5 Energy Price*

Energy price plays an important role in stimulating the national economy. The lower the energy price, the better the energy security. Indonesia still applies subsidized prices, especially diesel fuel for certain users. The diesel fuel price refers to diesel fuel with cetane number 48, while gasoline refers to gasoline with octane number 88 [17]. The following Fig. 10 shows the fuel prices of diesel fuel and gasoline in 2000–2018. Furthermore, electricity prices determined by Government pricing regulations, which is differ for each electricity consumer, therefore the presented price in the Fig. 10 is the average price of electricity to all types of consumers.

## *3.6 Energy Access*

The electrification ratio continues to increase throughout the year, due to the implementation of the rural electrification development program by the Government. This program has instructed the local Government to implement the accelerated development of rural electricity in each province.

Indonesia's population which has not been connected to electricity remained 6.6 million inhabitants in 2018. Besides, some households still depend on the use of traditional biomass, mostly it occurs in remote areas or away from commercial energy infrastructure.

Figure 11 shows the electrification ratio in 2000–2018 and Fig. 12 shows the percentage of households relying on traditional use of biomass in 2008–2013.

The Indonesian Government nowadays is implementing the natural gas distribution networks for domestic customers. The availability of natural gas resources, provide benefits in the development of distribution networks. The program is implemented gradually each year and giving more access to commercial energy. Figure 13 shows the number of households that connected to natural gas pipeline in 2000–2018 (Fig. 13).

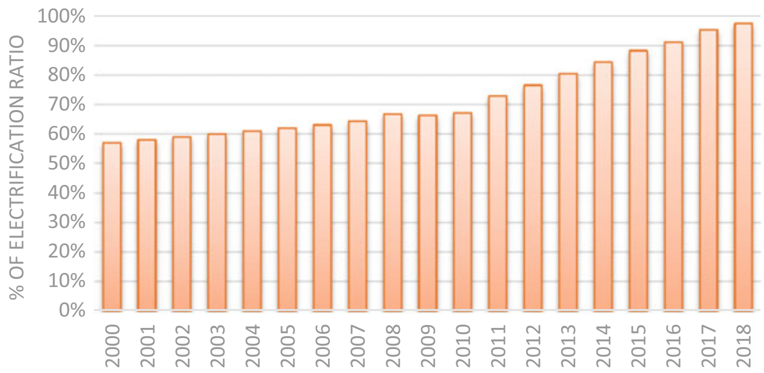


**Fig. 11** Electrification ratio in 2000–2018

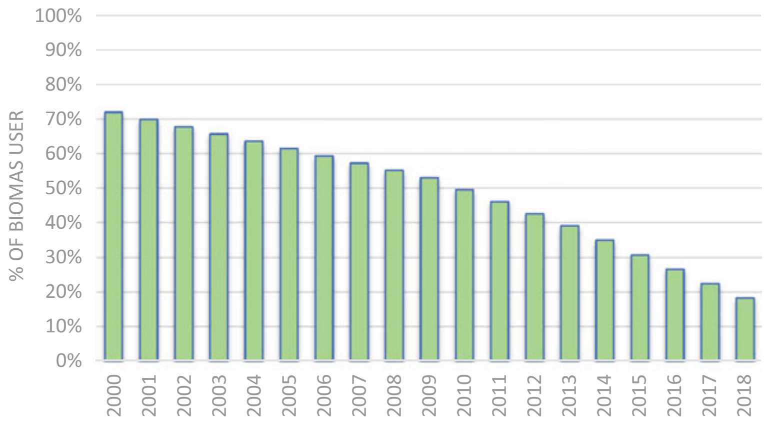


**Fig. 12** Percentage of households relying on traditional use of biomass in 2000–2018

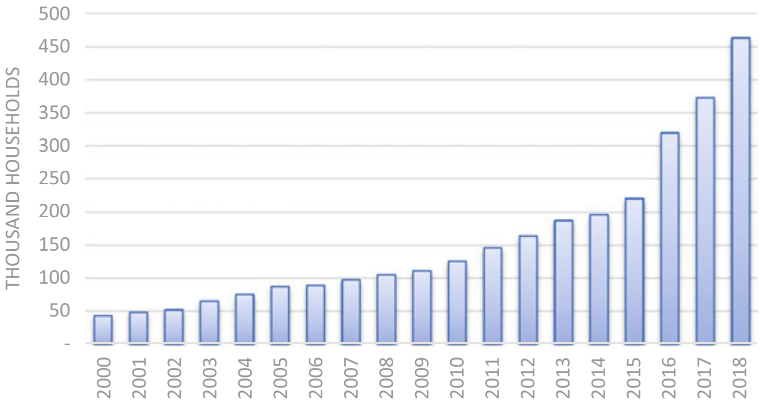


**Fig. 13** Number of household connected to natural gas pipeline in 2000–2018

# 4 Energy Security Assesment

## *4.1 Data and Indicators*

The data should be collected, before performing the calculations. Table 3 shows the data for indicator calculation.

All data is inputted into the energy security indicator equation as described in Table 2. Furthermore, the normalization process is conducted by specifying the maximum value of each indicator. The maximum value of each indicator is described in Table 4. Most of the data are sourced from U.S energy information administration [18].

The normalization results of the indicators will provide a value between 0–1. Furthermore, this value is used until the energy security index is obtained.

## *4.2 Dimension Results*

### 4.2.1 Availability

The availability dimension consists of the national per capita energy production, self-sufficiency, reserves to production ratio. Based on the Fig. 14, the availability dimension has increased by 3.24% between years 2000–2018. The increase in availability dimension is largely due to the contribution of self-sufficiency indicators. The self-sufficiency was quite good, although crude oil production continues to decline.

The second contribution comes from energy production per capita indicator. The per capita energy production is largely due to an increase in coal production. Finally, the smallest contribution comes from reserves to production ratio indicator due to

**Table 3** The data input for indicator calculation [17]

| NO | DATA | UNITS | 2000 | 2005 | 2010 | 2015 | 2018 |
|---|---|---|---|---|---|---|---|
| 1 | TPEC | BOE | 736,999,657 | 857,360,844 | 1,054,376,994 | 1,238,180,042 | 1,787,659,021 |
| 2 | TPEP | BOE | 1,456,364,696 | 1,719,907,387 | 2,408,984,865 | 3,217,990,119 | 3,680,592,533 |
| 3 | OPR | BOE | 5,120,000,000 | 4,190,000,000 | 4,230,000,000 | 3,600,000,000 | 3,150,000,000 |
| 4 | OP | BOE | 517,489,000 | 386,483,000 | 344,888,000 | 286,814,000 | 281,826,000 |
| 5 | OExp | BOE | 223,500,000 | 159,703,000 | 134,473,000 | 115,017,000 | 74,449,000 |
| 6 | OImp | BOE | 78,615,000 | 164,007,000 | 130,060,000 | 178,313,000 | 126,904,000 |
| 7 | GPR | BOE | 17,017,100,000 | 17,467,896,000 | 19,468,640,000 | 17,599,004,000 | 17,095,509,229 |
| 8 | GP | BOE | 521,073,839 | 536,167,244 | 612,003,523 | 559,659,103 | 538,225,639 |
| 9 | GExp | BOE | 284,551,954 | 316,569,785 | 316,439,036 | 239,311,253 | 200,830,183 |
| 10 | Gimp | BOE | 0 | 0 | 0 | 0 | 0 |
| 11 | CPR | BOE | 28,462,086,194 | 33,600,519,570 | 105,052,716,192 | 160,392,432,384 | 198,309,879,735 |
| 12 | CP | BOE | 382,989,872 | 759,229,056 | 1,367,923,768 | 2,294,583,454 | 2,772,856,617 |
| 13 | CExp | BOE | 290,624,644 | 550,768,836 | 1,034,030,400 | 1,818,748,166 | 1,771,744,907 |
| 14 | CImp | BOE | 696,559 | 488,077 | 274,565 | 14,953,342 | 27,186,578 |
| 15 | BFP | BOE | 0 | 0 | 28,503,000 | 19,075,000 | 18,991,683 |
| 16 | RS | BOE | 34,811,985 | 38,028,087 | 56,956,785 | 59,946,858 | 97,134,099 |
| 17 | DPR | USD/BOE | 10 | 42 | 77 | 76 | 57 |
| 18 | GPR | USD/BOE | 17,017,100,000 | 17,467,896,000 | 19,468,640,000 | 17,599,004,000 | 17,095,509,229 |
| 19 | EPR | USD/BOE | 57 | 102 | 132 | 133 | 131 |
| 20 | LPGPR | USD/BOE | 246,300 | 498,600 | 833,533 | 966,533 | 1,006,867 |
| 21 | EPOP | % | 57% | 62% | 67% | 88% | 98% |

(continued)

**Table 3** (continued)

| NO | DATA | UNITS | 2000 | 2005 | 2010 | 2015 | 2018 |
|---|---|---|---|---|---|---|---|
| 22 | EMCO2 | Million ton | 257 | 295 | 386 | 392 | 486 |
| 23 | BIOPOP | % | 72% | 61% | 50% | 31% | 18% |
| 24 | Population | Jiwa | 208,726,109 | 223,183,718 | 238,518,800 | 255,461,700 | 264,824,520 |
| 25 | GDPPPP | USD | 347,930,725,256 | 434,129,181,596 | 709,190,823,320 | 971,494,144,095 | 1,151,397,753,124 |
| 26 | GDP Perkapita USD | USD/Person | 1,667 | 1,945 | 2,973 | 3,803 | 4,348 |
| 28 | GHH | % | 0.08% | 0.16% | 0.20% | 0.33% | 0.66% |

**Table 4** The maximum data for indicator calculation

| Indicator | Parameter | Maximum value | Units | Annotation |
|---|---|---|---|---|
| AVAIL 1 | Per capita energy production | 364.65 | BOE/person | Refers to Brunei Darussalam energy production per capita in 2013 |
| AVAIL 2 | Self-sufficiency | 1.00 | Unitless | No import at all (highest value) |
| AVAIL 3 | Reserves (oil, gas, coal) to Production ratio (RPR) | 573 | Year | Refers to Laos reserves to production ratio in 2013 |
| AFFORD 1 | Diesel Oil Price to GDP per capita ratio | 0.0019 | Person/BOE | Refers to Brunei Darussalam affordability diesel oil price in 2013 |
| AFFORD 2 | Gasoline Oil Price to GDP per capita Ratio | 0.0019 | Person/boe | Refers to Brunei Darussalam affordability of gasoline price in 2013 |
| AFFORD 3 | Electricity Price to GDP per capita ratio | 0.0280 | Person/boe | Refers to Brunei Darussalam affordability of electricity price in 2013 |
| ACCESS 1 | Electrification ratio | 1.00 | % | Maximum achievable electrification ratio |
| ACCESS 2 | % Population relying on traditional use of biomass | 1.00 | % | Maximum possibilities of % population relying on traditional use of biomass |
| ACCESS 3 | Number of household gas pipeline connections | 0.50 | % | Maximum achievable pipeline household gas connections |
| ACCEPT 1 | Energy intensity | 0.46 | BOE/thousand USD | Refers to Burma energy intensity in 2013 |
| ACCEPT 2 | Emissions intensity | 0.1092 | Tonnes $CO_2$/USD | Refers to Burma energy intensity in 2013 |
| ACCEPT 3 | Renewable energy share | 12 | % | Refers to Laos renewable energy share in 2013 |

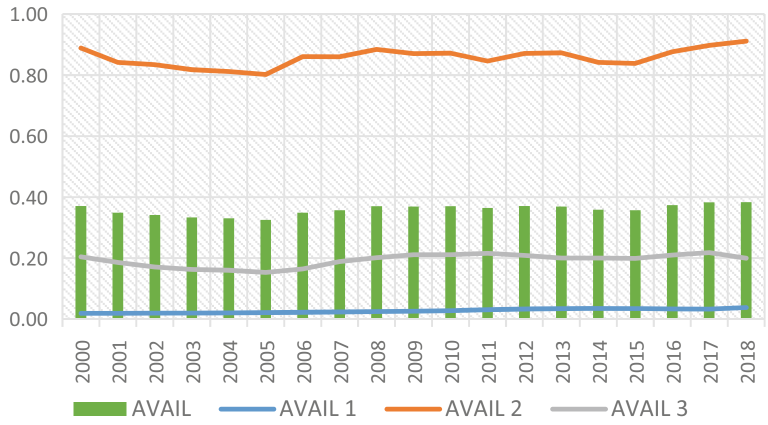


**Fig. 14** The results of availability dimension in 2000–2018

a very high maximum reference in the Southeast Asia Region. Laos has 573 days of reserves to production ratio compared to Indonesia which is only one-fifth from Laos.

### 4.2.2 Affordability

Based on the Fig. 15, the affordability dimension resulting in fluctuates value. The affordability of the electricity contributed largely to the dimension. Whereas,

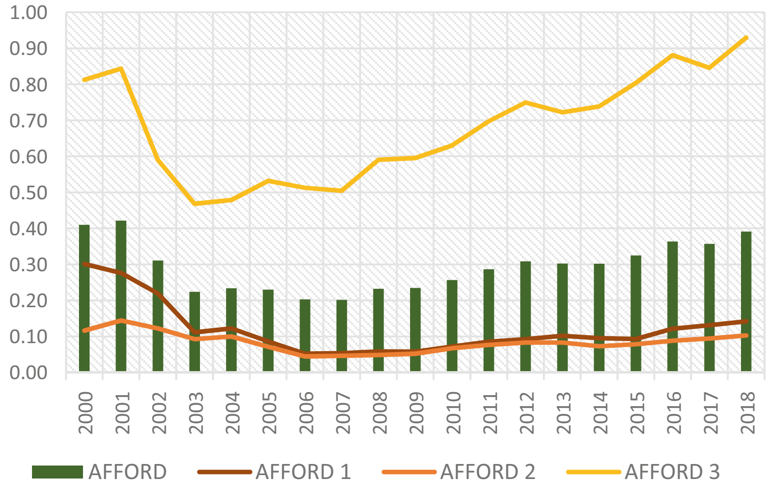


**Fig. 15** The results of affordability dimension in 2000–2018

since 2015 the electricity subsidy policy as regulated in Ministry Energy Regulation 31/2014 [19] has been changed to no more electricity subsidies given to all types of users such as household, business, industrial, office government, public street lighting, and specialized services. The electricity subsidy removal increased the prices of electricity, however, the situation is still showing good to the affordability due to the increase of GDP per capita.

Moreover, gasoline subsidy was also removed, due to the decline of the oil price since 2015. However, subsidies for diesel fuel still exist and reduced to only Rp. 2000 per liter. Subsidy reductions have an impact on the price hike of diesel fuel and gasoline, however, it can be offset by the GDP per capita, so the value of affordability unchanged. The small affordability value of diesel fuel and gasoline caused by the high disparity from the maximum reference in Southeast Asia. Brunei Darussalam has the highest affordability energy in Southeast Asia. Figure 15 shows the results of the affordability dimension in 2000–2018.

### 4.2.3 Accessibility

The accessibility dimension consists of electrification ratio, percentage of households relying on traditional use of biomass, and the percentage of households using pipeline natural gas. The accessibility dimensions increased by 111.98% between 2000 and 2018. Contributions largely contributed by the electrification ratio. The increase of accessibility dimension occurs gradually and consistently, which describes better energy commercial access for society. Indonesia continues to improve the electrification ratio that the highest challenge is to build electricity connections in remote areas. This challenge has to deal with a difficult location, a small number of customers, but the investment required is huge. The percentage of households relying on traditional use of biomass throughout the years continued to decrease. This occurred due to household commercial energy access developed by the Government, particularly the household LPG conversion program. The maximum target is no longer households still relying on the use of traditional biomass.

The last indicator is the percentage of households using pipeline natural gas, which describes the development of natural gas users, particularly household. The achievement of the indicator is supported by the acceleration of natural gas distribution network development program. The development priorities are carried out in areas that already have natural gas transmission pipelines or natural gas sources. The development program serves to replace LPG for households, which is mostly domestic LPG consumption derived from imports. The amount of natural gas pipeline connections for households is still very low compared to the total number of households. For instance, in 2018, the number of household connections just reached only 460 thousand connections, while total Indonesia's registered household reaches 70 million households. The program currently relies on the Government budget, while high capital is required, therefore the role of the private sector is needed to succeed in this program. Figure 16 shows the results of the accessibility dimension in 2000–2018.

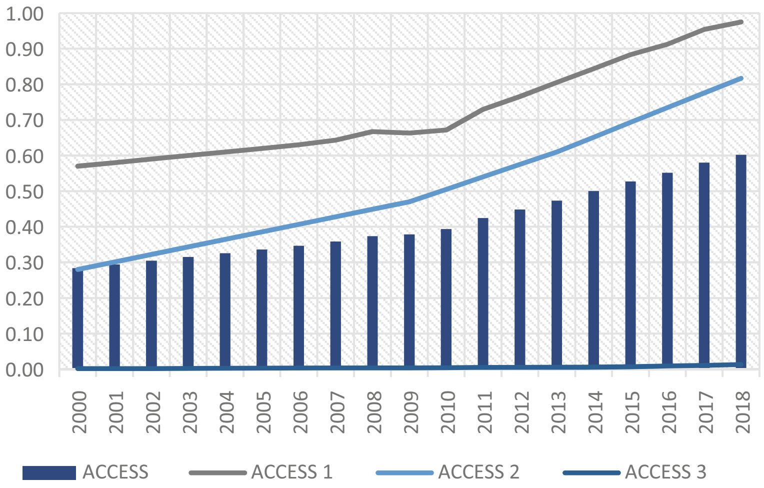


**Fig. 16** The results of accessibility dimension in 2000–2018

### 4.2.4 Acceptability

The acceptability dimension is related to the environment, especially $CO_2$ emissions as a result of energy consumption. As stated in Law 30/2007, energy management in the context of promoting national energy security should pay attention to the environment. Indonesia, in the UNFCCC declaration and Pittsburg's agreement, stated its commitment to reduce GHG emissions by 26% with own effort and 41% with international assistance from Business as usual (BAU) conditions. Following up on the commitment, the Government of Indonesia issued the Presidential Regulation 61/2011 [20] on national plan to reduce greenhouse gas emissions. Moreover, The Presidential Regulation 22/2017 [21] was issued to support previous regulation, particularly the implementation of emission reductions in the energy sector. These regulations are the legal basis for regional Governments, which is mandated to reduce greenhouse gas emissions on activities that occurs in their respective regions. The activities are divided into agriculture, forestry and peatland, energy and transportation, industry, waste management, and other supporting activities. In terms of energy security, emission reduction is related to energy and transportation activity. Based on the Presidential Regulation 22/17, the target of 26% greenhouse gas emission reductions from Business As Usual (BAU) should contribute to a reduction of 356 million tons, while 41% should contribute to a reduction of 562 million tons in 2025, with a BAU situation estimated to 1,370 million tons of $CO_2$ emissions.

Based on this situation, the emissions from the energy sector in 2000, 2005, 2010, 2015, and 2018 are 257, 295, 386, 392, and 486 million tons of emissions, respectively. The results show that Indonesia's emission intensity is slightly decreased throughout the year, from 0.739 ton/thousand USD in 2000 to become 0.422 ton/thousand USD in 2018. The reduction in emission intensity is caused by the GDP growth which higher than the emission rate. The lowest emission intensity achieved by Burma, that in 2013 the emission intensity reaches 0.109 ton/thousand USD.

Meanwhile, Indonesia's energy intensity reaches 1.5 BOE/thousand USD. For this situation, Indonesia still uses energy quite efficiently compared to countries in the Southeast Asia region, such as Brunei Darussalam which the energy intensity reaches 4.54 BOE/thousand USD. The lowest energy intensity achieved by Burma reaches 0.46 BOE/thousand.

The renewable energy utilization indicator shows an increase throughout the years. The value of renewable energy utilization is still relatively small with a percentage of 4–6% by total energy consumption. These contributions were obtained from the utilization of biofuel, hydro and geothermal. Laos has the highest value for the percentage of renewable energy utilization to total energy consumption, which amounted to 10%, therefore it is used as a maximum reference. The increases in renewable energy utilization due to the higher renewable utilization growth than total energy consumption.

The acceptability dimensions increased by 32.86% between 2000 and 2018. The dimension largely contributed by the renewable energy share indicator. The increase in acceptability dimension occurred gradually and consistently. Figure 17 the results of the acceptability dimension in 2000–2018.

All dimension values result in the energy security index, where the index values are in the range of 0–1. The results of the energy security index are shown in Fig. 18. Based on the figure, Indonesia's energy security index has increased from 0.330 becomes 0.428 in 2000 and 2018, respectively, which shows a 29.9% increase. Despite the increase, Indonesia's energy security index still relatively low due to

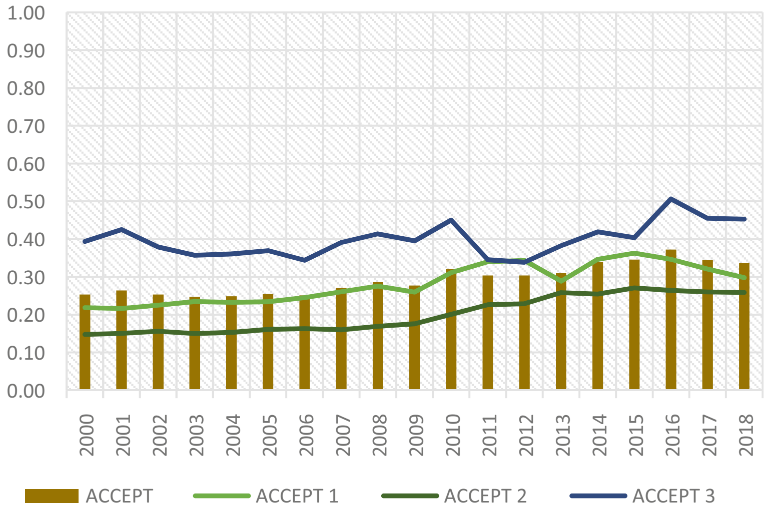


**Fig. 17** The results of acceptability dimension in 2000–2018

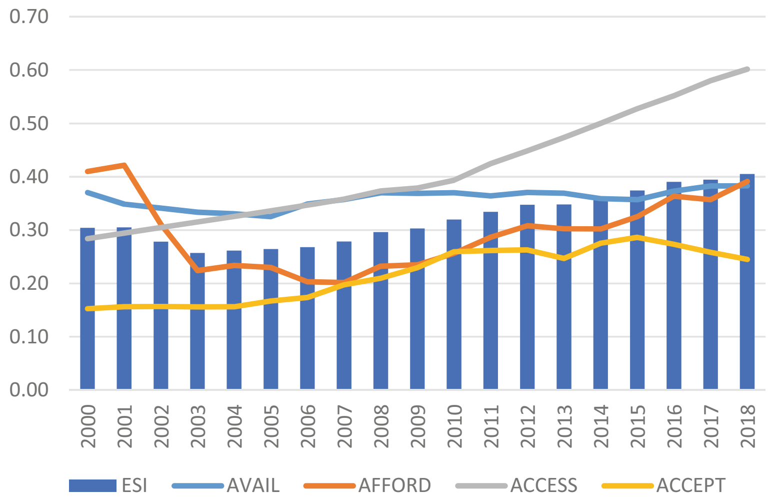


**Fig. 18** the results of energy security assessment in 2000–2018

the lower value than 0.5. Therefore, improvement of all aspects needs to be done immediately by evaluating policies that are not supportive to increase the energy security index. Priority improvements can be made on the dimension that has the lowest value.

## 5 Conclusion

The assessment summarizes that Indonesia's energy security index is still relatively low due to the lower index value than 0.5. The energy security index has increased from 0.330 becomes 0.428 in 2000 and 2018, respectively, which shows a 29.9% increase. Several improvements need to be done to improve energy security, especially acceptability dimension which has the lowest value. Increasing the acceptability can be conducted through policies which stimulating the higher economic activity, but consume less energy. Moreover, it is necessary to transform the use of fossil energy towards renewable energy for all sectors, especially for industrial and transport sectors.

The availability dimension is necessary to focus on self-sufficiency. Indonesia needs to set a strategy that the exploitation is conducted at an optimum amount, especially coal. High coal production should be directed to higher domestic purposes than export. Energy exploration should continuously be improved in order to increase the number of primary energy reserves.

Regarding the affordability dimension, the Government should begin to involve more private sector's role in the final energy business, thus providing competitive energy prices. Furthermore, the Government should create regulations to business entities that energy providers which in a good market, have an obligation to serve areas with a less attractive market, therefore the affordable prices apply throughout the region.

Finally, for the accessibility dimension, the Government needs to focus on providing access to commercial energy in all regions of Indonesia, particularly in the remote areas. Providing access to natural gas across the region for domestic use, as well as to take the advantage of large Indonesia's natural gas reserves. For regions that are still using biomass, at the early stage can be supplied through the use of LPG, therefore the access to commercial energy occurs in all regions.

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# Energy and Environmental Scenario of South Asia

**Vikrant P. Katekar, Muhammad Asif, and Sandip S. Deshmukh**

**Abstract** South Asia is one of the most important regions in the world for its large population base, vast natural resources, significant geographic positioning, vibrant culture and rich history. Made up of eight countries: Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka—South Asia is home to almost a quarter of the world population. South Asian countries are facing severe energy and environmental challenges that are affecting their broader socio-economic developments, technological advancements, and national security. The chapter discusses the energy and environmental scenario of South Asia. Details of each country in terms of energy resources, supply mix, access to electricity, and cooking fuels have been discussed. Emerging trends and renewable energy developments are also reflected. The environmental scenario of the region has also been presented taking into account the implications of climate change. The perspective of the region in terms of Sustainable Development Goals (SDGs) has also been discussed.

**Keywords** Energy · Environment · Sustainable development · Renewable energy · South Asia

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# 1 Introduction

In the twenty-first century, a realization about the growing energy and environmental challenges has become an essential cornerstone of national and international developmental frameworks. Energy being the backbone of modern societies, concerns about its security are growing ever more apparent. Energy security is an issue deemed critical for socio-economic development across the world. In the age of fossil fuels, energy, and environmental scenarios are closely interlinked. Global warming is one of the most profound environmental challenges the world faces today, which is leading to alarming consequences. According to the US National Aeronautics and Space Administration (NASA), 2014–2018 has been the hottest five years on record. With the average atmospheric temperature in 2018 recorded to be 0.83 °C warmer than 1951 to 1980 mean, almost 400 all-time high temperatures were reportedly set in the northern hemisphere over the 2019 summer [50]. The phenomenon of global warming and climate situation is regarded to be leading to wide-ranging implications such as flooding, droughts, wildfires placing a large proportion of the global population at serious risk. The growing magnitude of these natural disasters can be gauged from estimates suggesting that by 2060, over 1 billion people are reported to be at risk of serious flooding due to climate change [SWEDES]. It is also forecasted that in business as usual scenario, by 2070, up to 3 billion people could end up living in areas too hot for humans [53].

South Asia is one of the most densely populated regions in the world, which is home to nearly 2 billion people. Countries in the region are traditionally classified as developing or underdeveloped. South Asian countries also face wide-ranging energy and environmental challenges. This chapter provides an overview of the energy and environmental scenario of South Asia. Wide-ranging energy developments have been discussed both at the regional as well as national levels. Details of each country in terms of energy resources, supply mix, access to electricity, and cooking fuels have been discussed. Emerging trends and renewable energy developments are also reflected. The environmental scenario of the region has also been presented in terms of the implications of climate change and other environmental problems. The perspective of the region in terms of Sustainable Development Goals (SDGs) has also been discussed.

# 2 South Asia: Regional Overview

South Asia is the southern region of the Asian continent comprising of sub-Himalayan countries, as shown in Fig. 1. The region has over 20% of the global population living in around 3% of the world's total area. Traditionally the region has been regarded to be consisting of seven countries: Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka as shown in Fig. 1. In 1985, these countries established a regional intergovernmental platform South Asian Association for Regional


**Fig. 1** Map of South Asian countries

Cooperation (SAARC) to promote economic cooperation and development in the region. In 2007, Afghanistan was also formally included in the SAARC. Demographically, South Asia is dominated by India that has a population of 1.35 Billion. Other most populated countries in the region are Pakistan and Bangladesh, with respective populations of 213 Million and 167 Million. There are also countries in the region with a tiny fraction of these populations. Maldives and Bhutan, for example, have approximate populations of 0.54 Million and 0.77 Million, respectively.

South Asia is one of the most important regions in the world in terms of its large population base and significant energy and environmental challenges. Countries in the region face wide-ranging energy problems, including but not limited to lack of access to refined fuels, weak gird reliability, unaffordable energy prices, and import dependency. The International Energy Agency (IEA) projects that the energy demand in South Asia would grow at more than double of the world over the next several decades. On the other hand, the region is suffering from a lack of resources and robust policy formulation and implementation. The consequent lack of access to energy is one of the main barriers to the socio-economic prosperity of a large section of the population [SWEDES]. The region also suffers from acute environmental problems.

## 3 Energy Scenario of South Asia

Energy is the driving force of nature. It is a fundamental factor behind the social and economic development of every country. The South Asia region is facing the problem of energy scarcity to sustain economic growth. Most of the population of this region is living in rural and remote regions do not have access to clean energy and electricity. Even today, they use biomass for cooking and other domestic use largely. To fulfil the demand for electrical energy, South Asian countries are mostly dependent on fossil fuels. They pay the heavy bill for the import of fossil fuel. This section illustrates the energy scenario of South Asian countries.

### *3.1 Energy Accessibility*

Energy is essential to meet our fundamental needs, such as to cook our food, to light our homes, to power our machines and technologies. Easy and inexpensive access to energy is a key requirement for the agricultural sector, commerce, and industries. It is also important to provide public services such as education and health care. A lack of access to modern energy services badly affects health care services; it decreases opportunities to grow economically and, consequently, broaden the gap between the rich and the poor communities. This section provides an overview of electrical and cooking energy accessibility in the South Asian countries.

Electricity is necessary to run our home and business administration effortlessly. It powers transportations, which takes people to work, school, and other business places. It operates most of the day to day essential appliances in all sectors. Electricity consumption per capita measures the average kilowatt-hours (kWh) of electric power generated by the country per person. Figure 2 illustrates that among the South Asian countries, Bhutan has the highest, and Afghanistan has the lowest energy consumption per capita. The people of Afghanistan have poor access to energy; consequently, the economic growth of Afghanistan is found to be very slow, which can be easily recognized using the GDP growth rate, as shown in Fig. 3.

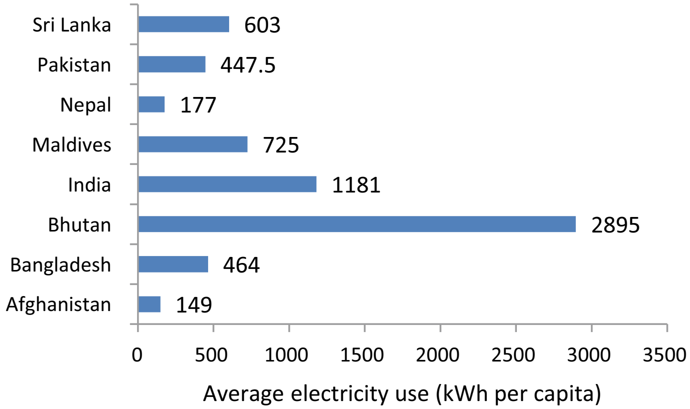



**Fig. 2** Per capita energy consumptions of South Asian countries

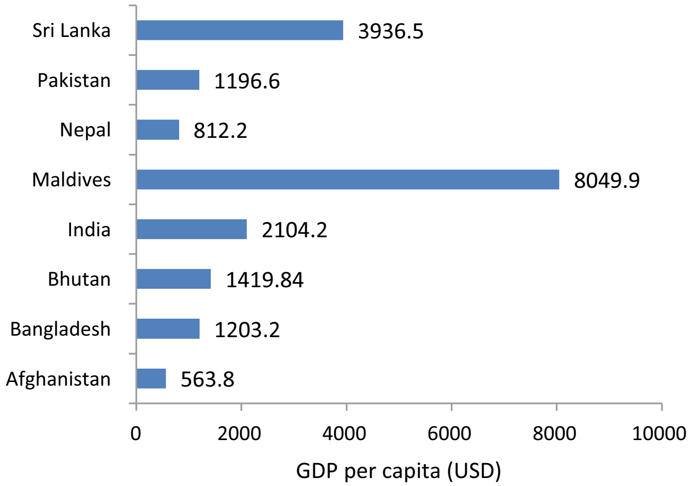



**Fig. 3** GDP per capita of South Asian countries

Figure 4 shows that most of the South Asian countries except Bhutan use fossil fuel for electricity generation. The Maldives uses 100% exported fuel for electricity generation; however, Bhutan generates all required electricity using hydropower.

Clean and reasonably priced cooking fuel is the foremost need of each household in every country. The Economic and Social Survey of Asia and the Pacific (ESCAP)-2018 [59] says that almost 2.1 billion people in Asia do not have the accessibility of clean cooking fuel sources. Of these, over 1.2 billion people are based in South Asia alone, as shown in Table 1.

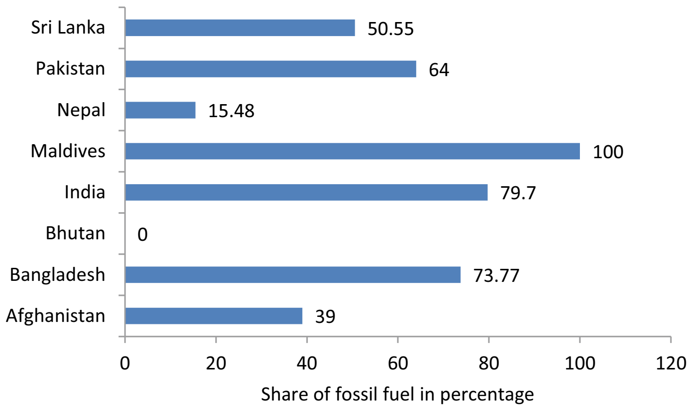



**Fig. 4** Share of fossil fuel in electricity production

**Table 1** Population without access to clean cooking fuel in some South Asian countries (million) [59]

| Country | Number of people (millions) |
|---|---|
| India | 853 |
| Bangladesh | 143 |
| Pakistan | 102 |
| Afghanistan | 26 |
| Nepal | 23 |
| Sri Lanka | 17 |

It is evident that except for the Maldives, all South Asian countries have the majority of their population relying on crude bio-fuels to satisfy their cooking and heating requirements.

## 3.2 *Afghanistan*

Afghanistan is in the category of the least developed country in the world. Presently 35% of the country is electrified. The electricity is reached only 10% of the rural households [55]. Wood, charcoal, agricultural and animal wastes are mainly used for cooking and other domestic application. Households lighting is mostly done using kerosene, candles, and biogas. The country has an overall electricity generation capacity of around 519 MW. Hydropower contributes 49%, gas, and oil (thermal) contribute 39%, and distributed generators add up 12% in the primary energy mix, as shown in Fig. 5 [3].

Afghanistan imports around 80% of fossil fuels, which adds an enormous burden on the economy of the country. Records showed that expenditure on import of fossil fuel had been increased by 14 times from 2007 to 2015. The future energy demand

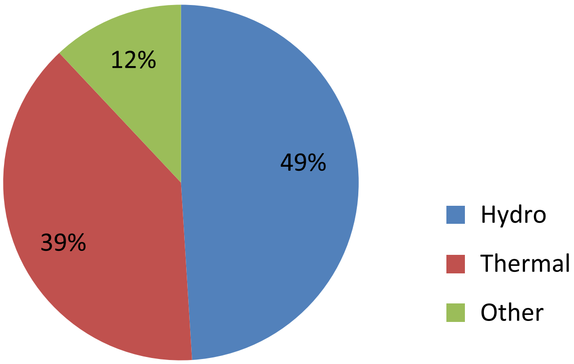



**Fig. 5** Share in electricity generation [3]

in Afghanistan is estimated at 3500 MW in 2032. This demand can be easily fulfilled by well-organized planning of available energy potential of the country. As shown in Fig. 6 the country has 23 GW of hydropower, 67 GW of wind power, and 222 GW of solar power production potential. The natural gas resources are estimated at around 36.4 trillion cubic feet. The well-planned utilization of these energy resources will boost Afghanistan's energy sector to self-sufficiency; consequently, it will strengthen the economy of the country [46].

People of Afghanistan mostly use firewood, animal dung, straw/grass, and LPG for cooking. The firewood is mostly used for cooking in the rural region. Urban people purchase firewood from markets. LPG is commonly used by high income and middle-income families in urban areas [49]. In Afghanistan, the Government has initiated projects such as the North East Power System in 2006 and the Western Urban Energy Program to fulfil the demand of the country. These projects are catering energy needs of the country through energy imports in the short-run. The country

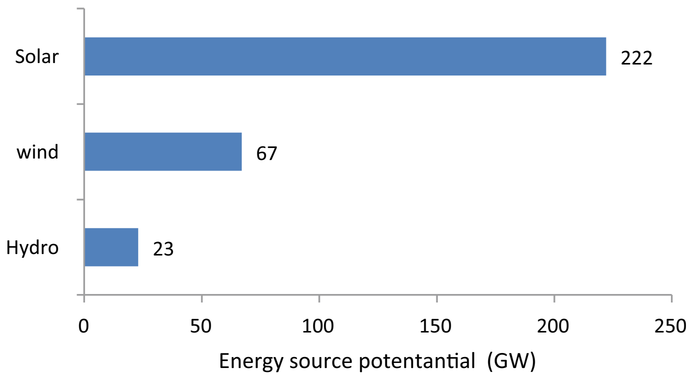



**Fig. 6** Renewable energy potential [46]

is also developing resource-based power projects by tapping hydro and wind power potential and launching thermal and diesel-based power plants [20].

### *3.3 Bangladesh*

Bangladesh has a total energy consumption of around 47 MTOE per year. Records show that the demand for energy is increasing at a rate of 6% per annum. Presently, the per capita generation of electricity is 464 kWh. Electricity access to households is 90% [55]. Natural gas contributes about 49.2%, biomass 34.6%, petroleum 15.6%, coal 0.4%, and hydro 0.3% as primary energy mix (Fig. 7) [25].

As per the report of the Ministry of Power, Energy and Mineral Resources- January 2019, the domestic gas production of Bangladesh is depleting day by day; consequently, consumption of coal and imported LNG is expected to increase as shown in Fig. 8 [2].

Every year Bangladesh imports around 6.6 million metric tons of crude oil and other refined petroleum products to satisfy the need for electricity generation and transportation. The Government is promoting the use of biogas for cooking and power generation. Solar home systems contribute around 325 MW of electricity [2]. According to Multiple Indicator Cluster Survey (MICS) 2012–2013 conducted by UNICEF-2015, 88.2% of households use solid fuels, and 67.6% of household use of wood for cooking in Bangladesh. Around half of the urban households (50.5%) and 72% of rural households use firewood for cooking [60]. Indoor air pollution affects 138 million people in Bangladesh. The Government is promoting the use of efficient cooking stoves. Its cost is about 450 taka (a little over $5.5). This program is gaining momentum now. One million clean stoves were installed in homes by January 2017. The Government is now planning for the next phase of the program to install an additional 4 million stoves in the next five years and 30 million cooking stoves

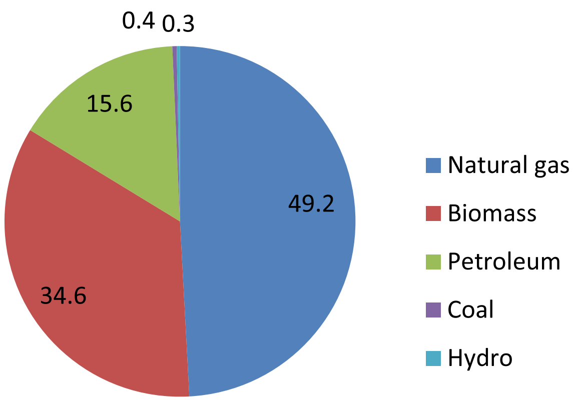



**Fig. 7** Energy share in percentage [25]

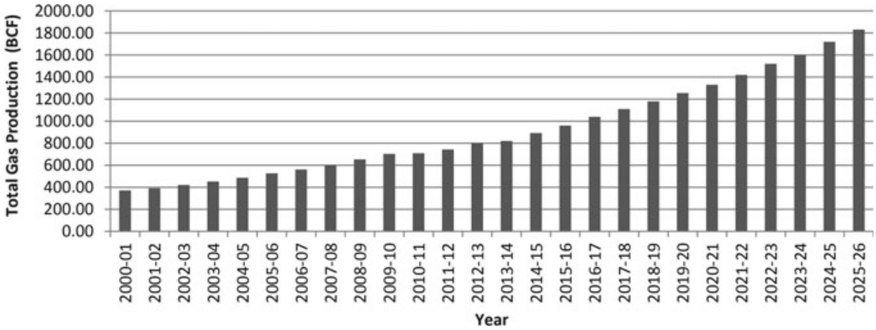



**Fig. 8** Yearly natural gas consumption rate [2]

by 2030 [24]. Another initiative taken by the country is to generate electricity by Bio-Mass Gasification Method. The country is also planning to develop a coalfield of Phulbari, Dighipara, Khalashpir, and Jamalganj region [2]. The Government has the vision to provide electricity to all citizens by 2021. To achieve this target government has established the Power System Master Plan 2010. Efforts to use renewable energy and rice husks to generate energy are also in progress [20].

## *3.4 Bhutan*

At present, Bhutan generates an overall 99.5% of power using the hydro resource, and the remaining is generated from imported liquid fuel. Bhutan has no major fossil fuel reserves except a small coal reservoir located in the south-western region. Bhutan imports liquid fossil fuel for automobiles and other essential uses. For cooking and other domestic need, people use biomass, which constitutes about 87%, followed by electricity 8%, LPG 3%, and kerosene 2%. A total of 1615 MW of hydropower capacity has been installed in the country to date [6]. The country provides electricity to 100% households, and the remaining amount is exported to the neighboured country. However, export is not proportionally increasing, and the gap between the exports and total domestic electrical generation is elevating from 17% in 2008 to 26% in 2013, which results in a loss in the economy (Fig. 9). Bhutan has good potential for other renewable energy sources such as solar energy, wind energy, and municipal solid waste. These sources have not been used till today except for some solar installations. In the urban area, the use of liquefied petroleum gas and kerosene will likely grow up significantly by 2035. The requirement of oil and coal will also increase to 9.9% and 11.6% in 2035, respectively [26].

The Bhutan Living Standard Report (BLSS) 2012 states that in urban Bhutan approximately 92%, 98%, and 2% people use LPG, electricity, and firewood respectively, and in rural Bhutan, 45%, 76%, and 51% of households use LPG, electricity, and firewood for cooking respectively. Less than 2% of households use coal and

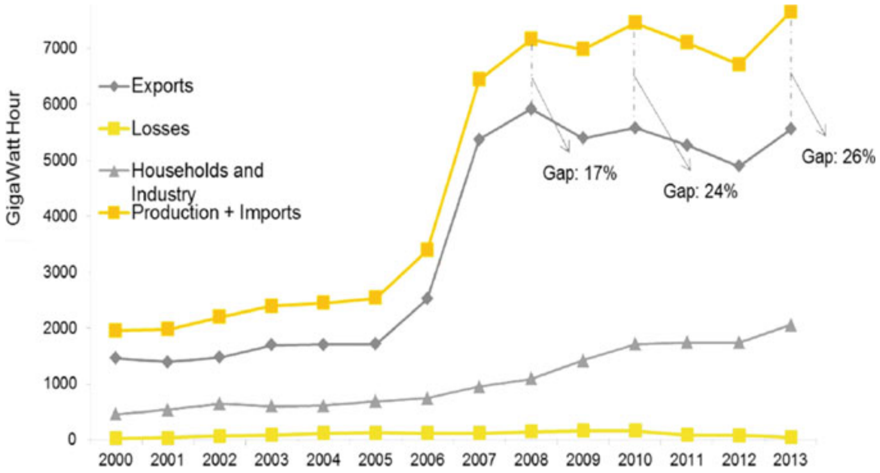



**Fig. 9** Power demand and supply scenario [26]

kerosene for cooking [14]. Bhutan government has proposed several new hydropower projects to generate 10 GW by 2020. The country has targeted to develop about 20 MW using renewable energy by 2020–25 [15]. The Bhutan Biogas Project (BBP) and Bhutan Sustainable Rural Biomass Energy (BSRBE) program are launched to support biogas and improved cookstoves (ICS) as clean cooking fuel in rural areas. Bhutan is providing100 units of free electricity per month for each rural household. The National Water Plan 2005, Ten-Year Hydropower Development Plan 2009, Twenty Year Hydropower Development Plan 2009, and Three-Year Plan of 2013 are some examples of the initiatives undertaken by the government to use hydropower potential of the country. The Government is also targeting to reduce the use of fuelwood, install improved cookstoves, and replace incandescent bulbs with compact fluorescent lamps [8, 35, 57].

## *3.5 India*

India has an installed capacity of 319.60 GW as of 2017. More than 70% of the primary energy needs of India are fulfilled through imported crude oil and natural gas. Coal contributes 58.1%, oil 27.9%, natural gas 6.5%, hydro 4%, renewable 2.2% and nuclear 1.2% in the primary energy mix respectively (see Fig. 10) [7]. The renewable energy mix of the country has been highlighted in Table 2.

Various reports of the Indian Government say that nearly 304 million people do not have access to electricity, and 800 million people have no access to clean cooking fuels to date. The Government has kept the aim of 175 GW of installed capacity of renewable energy by 2022, 24 $\times$ 7 electricity to all households by 2022, and 10%

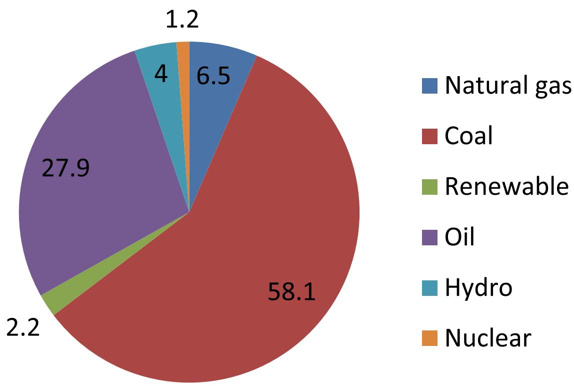



**Fig. 10** Energy share in electricity generation as of 2017 [7]

**Table 2** Total installed capacity of renewable energy in India (*Source* [38])

| Renewable energy | Total installed capacity (MW) |
|---|---|
| Wind power | 35,625 |
| Solar power—ground mounted | 26,389 |
| Solar power—roof top | 1796 |
| Small hydro power | 4593 |
| Biomass power (biomass and gasification and bagasse cogeneration) | 9778 |
| Waste to power | 138 |

reduction of oil and gas import by 2022 as compared with the consumption in 2014–15 levels. Table 3 describes the road map of the Indian Government to fulfil the demand for energy in 2030 [42].

**Table 3** Projected electricity capacity in 2030 [42]

| Fuel type | Capacity (GW) | % |
|---|---|---|
| Hydro (large, small, and imports) | 73.44 | 9 |
| Coal + Lignite | 266.82 | 32 |
| Gas | 24.35 | 3 |
| Nuclear | 16.88 | 2 |
| Solar | 300 | 36 |
| Wind | 140 | 17 |
| Biomass | 10 | 1 |
| Total installed capacity | 831.5 | |
| Total non-fossil fuel (hydro, nuclear, solar, wind, and biomass) | 540.32 | 65 |
| Total renewable (solar, wind, biomass) | 450 | 54 |

In India, about 800 million people rely on traditional biomass for cooking [48]. As of 2011, 53 percent of households in India had an LPG connection [13]. The use of electricity for cooking is very less [30]. The recent efforts taken by the Government to improve access to clean cooking fuel is the Pradhan Mantri Ujjawala Yojana (PMUY). This scheme provides free LPG connections to all economically weaker families [14]. The PMUY supported 20 million connections in 2016–2017.

India has the highest population without access to clean cooking fuel sources in Asian countries [31]. Clean cooking policies, programs, and schemes have been implemented by the Indian Government for increasing the use of clean fuel LPG in India [19]. The Indian Ministry of Petroleum and Natural Gas (MoPNG) is managing the Pratyaksha Hastaantarit Laabh (PAHAL) scheme-2014 to transfer the subsidies to households directly to prevent the subsidy leakages. MoPNG launched the "Give it up" scheme in March 2016 to surrender LPG subsidies voluntarily. As a result of this program, almost 10 million households agreed to give up their subsidies. Ujjwala Plus Scheme (UPS) is another program managed by MoPNG to provide free LPG connections for low-income households. The SAHAJ program is launched in August 2015 to make online the application for new LPG connections. The Unnat Chulha Abhiyan (UCA) was stated to target 2.75 million people in 2014. The National Biogas and Manure Management Program (NBMMP) is the main supportive scheme for promoting biogas in India [17]. NBMMP provides financial support for installing biogas plants for households, as well as training courses on the use and maintenance of the biogas plants. The Deendayal Upadhyaya Gram Jyoti Yojana (DDUGJY) is a program launched to improve electricity access in rural areas to reach 100% electrification of rural villages. The Pradhan Mantri Sahaj Bijli Har Ghar Yojana (SAUBHAGYA) scheme is working on universal household electrification [5, 42, 48].

## *3.6 Maldives*

The Maldives is completely dependent on imported fossil fuel. Eighty percent of primary energy demand, as well as the energy demand of the transportation sector, is satisfied with diesel fuel (Fig. 11). Electricity is generated on every island autonomously employing small diesel electricity generators. The nation provides 100% electricity access to people from 2008. The generation of electricity in the Maldives is costly and sensitive to international diesel fuel prices. To satisfy future demand, the Maldives is planning to generate 60% of the country's electricity from solar panels by 2020 [39].

In 2017, 561,435 metric ton of fuel was imported by the Maldives. Out of this, 14,483 metric tons were cooking gas, 447,555 metric tons was diesel, 57,730 metric tons was petrol, and 41,666 metric tons was aviation gas. Most of the population uses kerosene, LPG, Diesel, Gasoline for cooking [40]. Maldives government decided to reduce its dependence on imported fossil fuels. The country sets the goal of

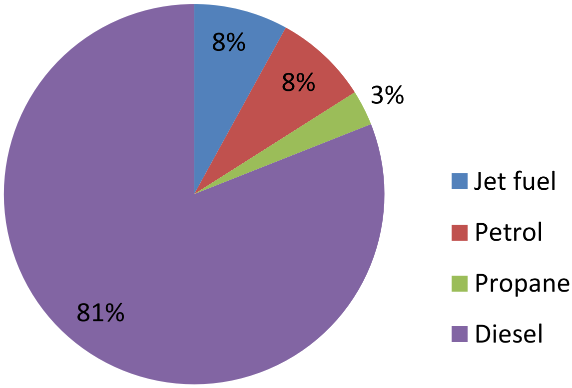



**Fig. 11** Percentages share of energy resources for electricity generation [39]

adding 20 MW of solar capacity by 2020 and 100% energy generation using renewable sources by 2050. The country also encourages concepts of integrated transport networks and green buildings to reduce climate impacts [28].

## *3.7 Nepal*

Nepal generates most of its energy using traditional biomass. Most of the households use fuelwood for cooking and other domestic work. The transportation sector uses imported petroleum products. Nepal spends an enormous share of its earnings on importing petroleum products. Figure 12 shows the primary energy mix of Nepal as of 2014 [57].

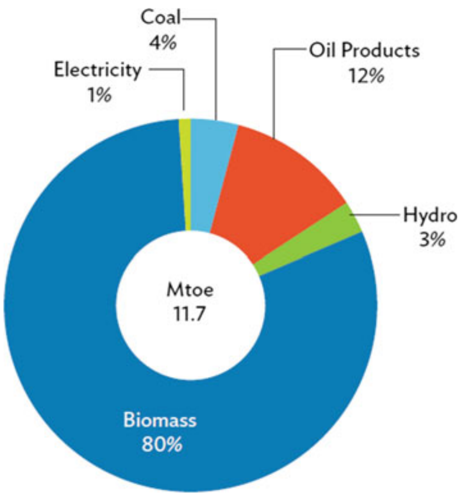



**Fig. 12** Primary energy supply mix, 2014 [57]

In Nepal, two-thirds of households rely on biomass as the main cooking fuel. They mostly live in rural areas. Surveys of household energy indicate that wood is mostly used for cooking, space heating, and lighting. Very few high-income families use kerosene, LPG as cooking fuel [35]. Nepal's Government accelerates the development of its abundant hydropower potential as an important step to reduce poverty and stimulate economic growth. Hydropower development will provide clean energy to enhance economic and social development in the rural and urban areas. It enables Nepal to generate revenue from exports of excess energy to neighbouring countries [8].

### *3.8 Pakistan*

Primary energy needs in Pakistan are mostly satisfied by oil and gas. Oil and gas are producing 64% of electricity [55]. Pakistan Economic Survey 2018–19 states fossil fuels contribute 64%, 27% hydro, and 7% nuclear. The share of renewable energy is just 2% of total energy generation, as shown in Fig. 13.

Presently, Pakistan has a total installed capacity of 33 GW. The electricity demand and supply trends are shown in Fig. 14. Natural gas will be the main source of energy until 2035. It will contribute 43.8% in the primary energy mix by 2035. It is forecasted that the domestic production of natural gas will decline from the current production of 38.4 BCM to 13 BCM by 2035. Therefore, in the future, Pakistan will be more dependent on imported gas [29].

Nearly 64% of the population of Pakistan has a residence in rural areas. People found little access to commercial and clean energy. Consequently, they use traditional fuels such as charcoal, firewood, grass/straw/shrubs, animal dung, and coal for domestic cooking. The use of LPG and electricity for cooking is found in urban communities [43].

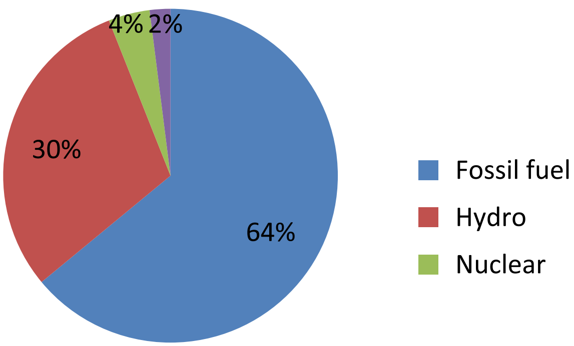



**Fig. 13** Share of fuel sources in energy production [29]

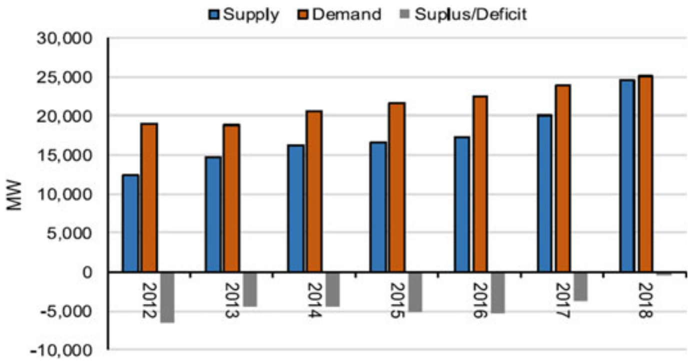



**Fig. 14** The trend of power-supply from 2012–18 [29]

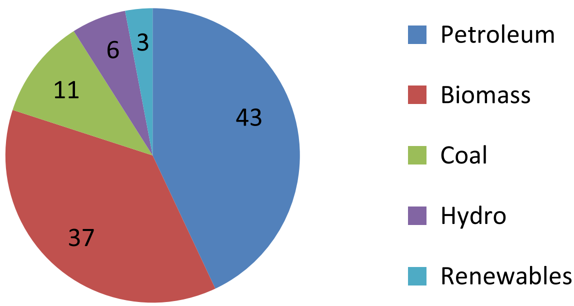
## *3.9 Sri Lanka*

Sri Lanka fulfils the demand for energy mostly by petroleum products. As of 2017, petroleum products have the highest share of 43% followed by biomass 37%, coal 11%, hydro 6%, and renewable energy 3% (Fig. 15). The greatest achievement of the country is that the electrification of households has been done 100% in 2017 [1].

Sri Lanka uses bio-energy for both household and commercial use. Twelve million tonnes of biomass used was consumed in 2017 [55]. It is projected that the coal demand of Sri Lanka will increase by 4.9 MTOE from 2010 to 2030; however, the oil will become the key source of energy with a 42.9% contribution in the primary energy mix by 2030 [20]. In Sri Lanka, the main household energy sources are biomass, liquefied petroleum gas (LPG), electricity, and kerosene. In the urban area, 95% of households use LPG while in the rural region, 95% of households use biomass for cooking. The people in the semi-urban region use a mixture of all the sources (LPG-70%, biomass-85%). Nowadays, day biomass is replaced with LPG and kerosene, which will significantly reduce harmful emissions in kitchen air [12].

Sri Lanka is focusing on the development and adoption of renewable energy sources to reduce the economic burden of imports. During the 22nd UNFCCC

**Fig. 15** Energy share in percentage [1]



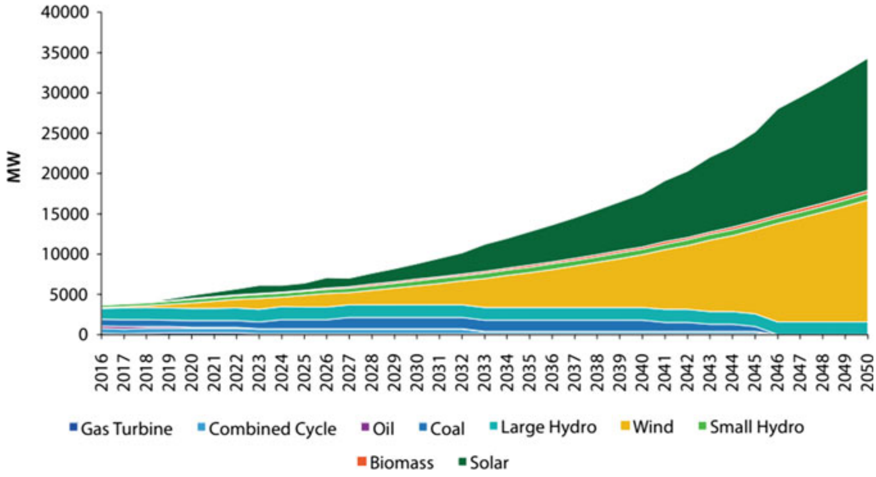



**Fig. 16** Renewable energy electricity generation mix progression [55]

Conference of Parties in Marrakech, Morocco, Sri Lanka pledged to use only RE for electricity generation by 2050. Figure 16 demonstrates the planning of the Sri Lankan government to use renewable energy for electricity generation until 2050. It is forecasted that by 2050 the renewable energy utilization will save US$18–US$19 billion by avoiding the use of imported fossil fuels [1].

Sri Lankan government has started a mandatory energy labelling program for commonly used appliances. To inculcate energy efficiency features in building design and construction, the Code of Practice on Energy Efficient Buildings-2009 has been implemented. National Energy Management Plan 2012–16 is also established to increase energy efficiency. Sri Lanka is more focusing on small-scale hydropower schemes and wind power projects [21].

## 4 Renewable Energy Developments in South Asia

South Asian countries largely depend on imports to satisfy their energy needs. The region is, however, rich in renewable resources like hydropower, solar energy, wind power, and biomass. These resources, however, have not been adequately capitalised yet (see Fig. 17) [32].

### *4.1 Renewable Energy Advancement in India*

The Indian renewable energy sector is the fourth most attractive renewable energy market in the world [36]. India is ranked 5th in installed renewable energy capacity

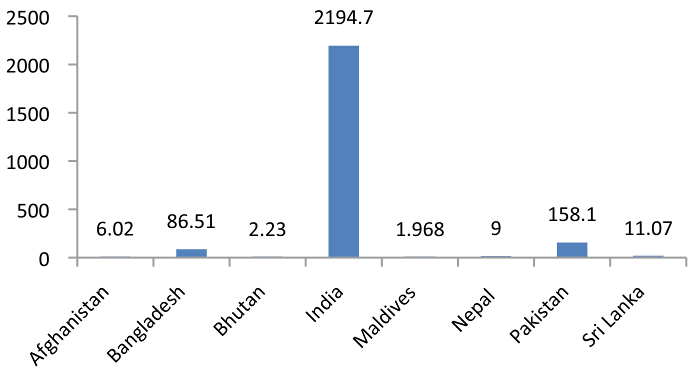



**Fig. 17** Share of renewable sources in energy generation in percentage [32]

in 2018. India looks to meet its energy demand of 15,820 TWh on its own by 2040 [27]. As a part of its Paris Agreement commitments, the Government of India has set a target of achieving 175 GW of renewable energy capacity by 2022 and 500 GW by 2030 [56]. During the year 2019–20, a total of 7591.99 MW renewable energy capacity has been added to the national grid as given in Table 4 [38].

There have also been several small and micro-scale initiatives undertaken by the government. For example, more than 74 lakh solar lanterns and study lamps, and more than 17 lakh home lights have been distributed under the Off-Grid and Decentralised Solar Program. Besides, more than 6.80 lakh street lights have been set up in the villages of India. The renewable energy accomplishments have been made possible owing to a series of policy initiatives. Some of the conducive policy developments are as followings [38]:

- All States to reach 8% Solar Renewable Energy Purchase Obligation (RPO) by the year 2022.

**Table 4** Achievement in grid-connected renewable power

| Sector | Achievement (MW) (April–Dec 2019) | Cumulative achievement (MW) (on 31.12.2019) |
|---|---|---|
| Wind power | 1879.21 | 37505.18 |
| Solar power (ground-mounted) | 5013.00 | 31379.30 |
| Solar power (rooftop) | 536.88 | 2333.23 |
| Small hydropower | 78.40 | 4671.55 |
| Biopower | 83.00 | 9861.31 |
| Waste to power | 1.5 | 139.80 |
| Total | 7591.99 | 85908.37 |

- Rooftop systems and solar water heaters are promoted through regulatory intervention.
- Off-grid and rooftop solar applications are promoted through the provision of subsidies from the central Government.
- Research and development funding.
- Guidelines for procurement of solar and wind power through the tariff-based competitive bidding process.
- To enhance farmers' energy independence, the Government has announced a scheme Pradhan Mantri—Kisan Urja Suraksha Evam Utthan Mahaabhiyan (PM-KUSUM).
- National Solar Mission is launched to establish India as a global leader in solar energy.
- The Government is giving fresh project finance at competitive rates to all new projects in renewable energy.
- An online portal has been developed and launched in December 2019 by Ministry for issuing concessional custom duty exemption certificates (CCDC) to the manufacturers of wind operated electricity generators.
- Under the Suryamitra program, during the year 2019–20, 20,700 youth were trained as Suryamitras in 690 batches across the country. A total 40,441 Suryamitras had been trained cumulatively up to 31st December 2019.

### *4.2 Renewable Energy Developments in Pakistan*

Pakistan has been slow to respond to the renewable energy trends in the world, although several initiatives were taken as early as in the 1980s. These include village electrification and the application of wind turbines. The most significant of renewable energy developments were made in the area of biomass as over 4,000 biogas units were set up during the 1970s and 1980s. Over the years several departments such as Appropriate Technology Development Corporation (ATDC); National Institute of Silicon Technology (NIST); Pakistan Council for Appropriate Technologies (PCAT); and Pakistan Council of Renewable Energy Technologies (PCRET) were set up to promote the cause of renewable energy. These departments, however, could not deliver as they largely remained constrained to demonstration projects. Alternate Energy Development Board (AEDB) was set up in 2002 as the focal point to promote renewable energy [11].

In 2009, Pakistan Domestic Biogas Program (PDBP) started in collaboration with the Netherlands Development Organization, Winrock International, and United Nations Development Program (UNDP). The target of this program was to provide incentives to install 14,000 biogas plants in Central Panjab by 2014. They installed a 5360 biogas plant in Central Panjab by 2014 [23, 47, 58]. Pakistan has started multiple initiatives to increase the use of wind, solar, and hydropower. National Power Policy-2013 and Vision-2025 visualize a considerable increase in access to

**Table 5** Progress in the field of wind power and solar energy (MW)

| Resource/Year | 2015 | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|
| Hydropower | 7116 | 7116 | 7116 | 8713 | 9761 |
| Wind | 256 | 306 | 785 | 1048 | 1398 |
| Solar | 100 | 400 | 400 | 430 | 480 |
| Biomass/Bagasse | 83 | 146 | 280 | 301 | 369 |
| Total modern renewables | 439 | 852 | 1465 | 1779 | 2247 |

clean energy in the national grid system. The Government is creating an environment and confidence of investors, developers, and lenders. The Government is setting Pakistan Energy Efficiency and Conservation Act to standardized equipment performance. Private investment is also stimulated to expand their existing capacity to generate an additional 2,000 MW by 2016 [29, 51]. In recent years Pakistan has made some progress in the field of wind power and solar energy, as shown in Table 5 [41].

Pakistan has a rich resource base for hydropower, solar energy, and wind power. Hydropower has traditionally been the cheapest source for power generation. Solar and wind power have only come into the equation over the last few years. Given the import dependency, the country needs to boost its indigenous renewable supplies.

## *4.3 Renewable Energy Progress in Bangladesh*

The renewable energy developments in Bangladesh have been mainly in the form of small scale projects. The country has seen some excellent micro-generation renewable energy programs evolve to help meet energy needs.

### 4.3.1 Grameen Shakti

Grameen Shakti (GS) is one of the world's largest micro-generation renewable energy programs that started in 1996 in Bangladesh to provide affordable and environmentally friendly energy to remote communities in the country. Established as a not-for-profit organization, it is a sister entity of Grameen Bank. Emphasis was placed to address the needs of people living in rural and remote areas without access to national electricity and gas networks [9].

GS started by employing solar photovoltaic technology to install solar home systems (SHSs). The electricity grid has a weak penetration in Bangladesh, especially in rural areas. People without access to electricity rely mostly on kerosene lanterns for lighting needs. Having realized the importance of electricity in the socio-economic well-being of people, Grameen Shakti initiated the solar home system (SHS) program in 1996. Solar home systems have gained immense success both within the domestic and commercial sectors. An SHS is attractive to the customer for several reasons. It is, for example, a cost-effective alternative to grid electricity and has very little running cost. Solar home systems present numerous benefits to customers in comparison to the traditional choice of kerosene lanterns. The success of SHSs is evident from the fact that the cumulative number of the installed systems has jumped from 228 in 1997 to over 1.71 million in 2018.

In Bangladesh, the pipeline network of natural gas is very limited. The situation forces the vast majority of people to resort to relatively crude and inefficient forms of fuels to meet cooking and heating requirements. Biomass fuels are the obvious choice in such a case. Compared to traditional means of cooking, biogas systems offer a much more efficient, quicker, and environmentally cleaner mode of cooking. In 2005 Grameen Shakti started to develop biogas systems. The number of installed systems has increased from 30 in 2005 to over 33,100 in 2018. The economic payback period of biogas systems has been observed to be as little as one year.

The majority of the population in Bangladesh relies on biomass for cooking and heating. The efficiency of these stoves is extremely low, typically between 5 and 15%. Furthermore, since most cooking is an indoor activity, the indoor air pollution generated from the biomass burned in these stoves results in serious respiratory diseases and infections. To improve the health conditions and to save the amount of fuel consumed for cooking, in 2006, Grameen Shakti introduced improved cooking stoves (ICSs). An ICS not only improves the indoor health conditions by exhausting all the smoke and pollutants to outdoor but also reduces the cooking time. The ICS program has attracted huge interest from the public, as is evident from the exponential growth in the number of installed systems both in the domestic and commercial sectors—the number of installed ICSs has increased from 410 in 2006 to over 952,000 in 2018.

## 5 Prospects of Sustainable Development Goals

In September 2015, the world accepted the 2030 agenda for sustainable development to end poverty and hunger from the world and to build up a sustainable world. There is a total of 17 sustainable development goals (SDGs) and 169 targets associated with them. Out of that, SDG-7 is associated with energy. Its details are given in Table 6 [44].

Forty percent of the poor people of the world are living in South Asia. Figure 18 shows the global economic rank and score of South Asian countries. Due to wide infrastructure gaps compared to other countries of the world, people in South Asia are relatively poor. The SDG 2030 agenda gives a pathway for South Asia to eliminate poverty, hunger, and provide a life of dignity to all communities [34].

However, energy availability and access to energy (SDG-7) are vital to achieving other sustainable goals also. Educational attainment is dependent on the availability of electrical energy at schools, homes, and other public places. The literacy rate is found to be higher for those countries having better access to energy. Figure 19 shows

**Table 6** Details of sustainable development goal-7 [44]

| Goal 7: Affordable and clean energy | |
|---|---|
| Target 7.1 | Make sure worldwide access to reasonably priced, reliable, and contemporary energy services by 2030 |
| Target 7.2 | Significant increase in the share of renewable energy in the universal energy mix by 2030 |
| Target 7.3 | Doubling the global rate of improvement in energy efficiency by 2030 |
| Target 7.4 | Improve worldwide cooperation to make easy access to clean energy research and technology by 2030 |
| Target 7.5 | Expand infrastructure and advancement in technology for supplying modern and sustainable energy services for all in developing countries by 2030 |

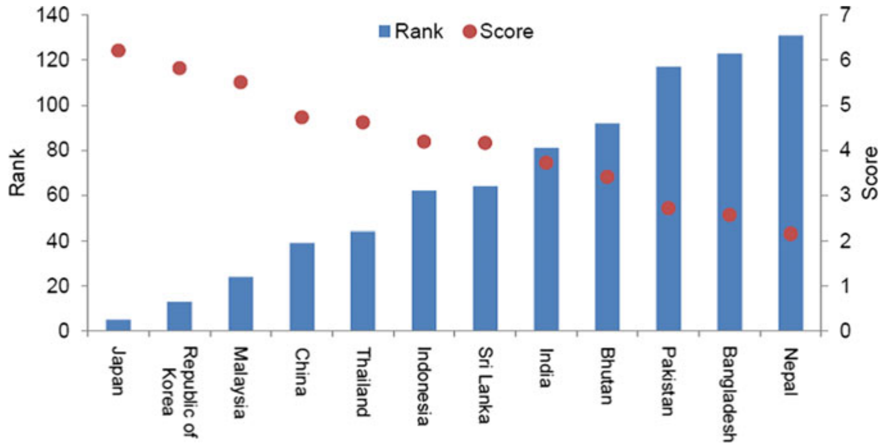



**Fig. 18** Score and rankings of selected Asia-Pacific countries in the Global [34]

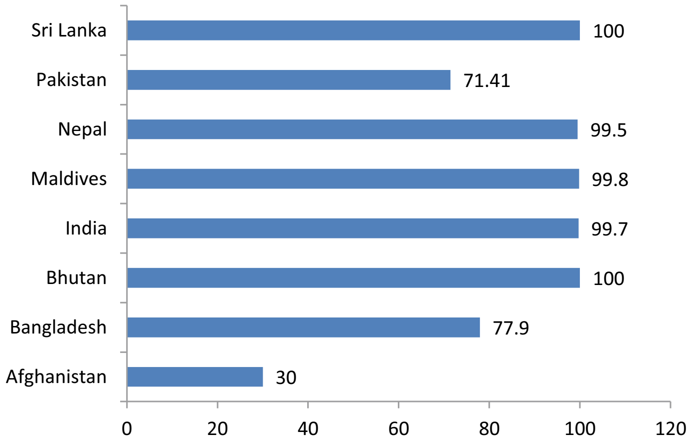



**Fig. 19** Electricity coverage in different South Asian countries

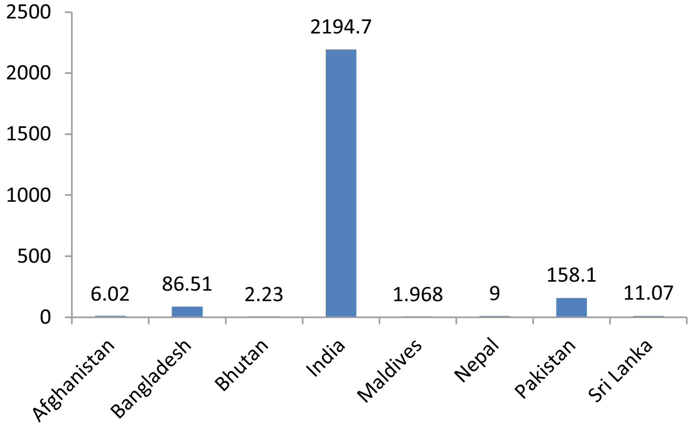



**Fig. 20** GHG emissions (MtCO2)

that Bhutan and Sri Lanka succeeded in providing 100% electricity access to people of the country as per the requirement of SDG-7; however, other countries are also proceeding to achieve the goal in recent years.

With the huge availability of renewable energy potential, South Asian countries will not only solve the problem of energy scarcity but also save huge expenditure on imports of hydrocarbons. South Asia can utilize its huge solar and wind energy potential. It can switch over to cleaner fuels such as natural gas and clean coal technologies in coal-based power generation. They will be surely benefited by developing a combined energy market with interlinked energy grids, pipelines. They can have combined forums for sharing excellent practices of energy conservation and energy efficiency across the sub-region [3]. SDG-13 is associated with climate change. Attainment of SDG-13 someway depends on SDG-7. It is well-known that greenhouse gas is a major contributor to climate change. Most of the South Asian countries except Bhutan use fossil fuel and/or biomass for energy generation; consequently, they contribute to huge GHG emissions. Figure 20 shows that among all South Asian countries, India is emitting more GHG as it generates 58.1% of its electricity by burning coal.

## *5.1 Challenges Towards Sustainable Energy Solutions*

In recent years South Asia countries have made considerable progress in improving the energy situation, especially in terms of electrification. The progress made is, however, slow compared to the scale of challenges. The followings are the main challenges these countries are facing in this respect [33, 37]:

Policy level challenges

- Issues with policies formulation and implementation
- Less priority is given to use renewable energy in nationwide scheduling
- Poor execution of renewable energy policies
- Unnecessary fuel financial assistance
- Lack of incentives for participation in renewable energy programs
- The feed-in tariff structure is absent

Economic challenges

- High installation costs at the end-user level
- High initial capital costs
- High risks and uncertainties
- Long payback periods
- Inadequate knowledge of market potential
- Insufficient financial support from the government

Technical challenges

- Inadequate local manufacturing of specific equipment
- Limited technical capability to design, install, operate and maintain renewable energy services
- Lack of standardized technology

Information challenges

- Limited facility for renewable energy data collection, analysis, and project development
- Insufficient knowledge associated with renewable energy technologies, equipment suppliers, and financiers
- Inadequate training infrastructure facility
- Lack of information about renewable energy for policies
- Lack of business management and marketing skills.

## 6 Environmental Challenges Facing South Asia

The South Asian countries are facing serious environmental challenges on multiple fronts. South Asia is amongst the most vulnerable regions of the world in terms of the implication of global warming. Warmer temperatures as a result of global warming are fast melting Himalayan glaciers, a lifeline for the freshwater supplies to satisfy the drinking water and agricultural needs. Rising sea level is posing numerous challenges to all of the countries with coastal belts. Problems like seawater intrusion, loss of wetland and mangroves, displacement of human settlements are common in these countries. Destruction of agricultural land and loss of sweet water fauna and flora also add to the list of concerns. The situation with Maldives and Bangladesh is especially critical also from the perspective of a shrinking land area. In the case of Bangladesh, for example, some scenarios suggest that by the year 2050, one-third of the country could be underwater, making more than 70 million people homeless [10]. Countries in the region are experiencing increased frequency and intensity of climate change-driven extreme weather events such as seasonal disorder, flooding, drought, and heatwaves. The Global Climate Risk Index 2019 regarded Bangladesh and Pakistan as the 7th and 8th most affected countries in the world from extreme weather-related natural disasters over the period 1998–2017 [22]. A recent study by HSBC regarded India to be the most vulnerable country to climate change, followed by Pakistan, the Philippines, and Bangladesh [54]. Drought is a serious problem in these countries. In 2016, India reported having around 350 million people affected by severe drought. Climate change is expected to impose serious economic penalties too. Maldives and Bangladesh, both low-lying countries, are projected to annually experience an economic loss of 12.6% and 9.4% respectively by the end of the century. Nepal may also suffer heavily due to melting glaciers with a projected of 9.9%. India is expected to annually bear an economic loss of 8.7% by the end of the century [4].

Many of the environmental challenges facing the South Asian countries are directly associated with their use of energy. Air pollution, especially as a result of unchecked industrial and transport emissions, is a major concern in the region. In some cases, the use of substandard fuels aggravates the level of dangerous emissions. Illegal burning of plastics and used tyres as fuel in industrial activities leads to serious health problems in surrounding localities. Pollution caused by the use of crude energy resources and inefficient technologies is a major environmental concern for these countries. Over 1.2 billion people in South Asia meet their cooking and heating requirements through unrefined and polluting energy sources. Simple stoves and open fires fuelled by biomass (wood, animal dung, and crop waste), kerosene oil, and coal are used for cooking and heating. In India, over 850 million people use biomass while in Nepal, it is the backbone of the national energy mix, making up 80% in total primary energy supplies. The use of biomass in these countries leads to severe environmental and health issues. According to the World Health Organization, annually, around 4 million people die prematurely from illness attributable to household air pollution from inefficient biomass-based cooking.

South Asian countries are also experiencing exposure to dangerously high levels of particulate matter 2.5 (PM 2.5), as shown in Fig. 21. According to the 2019 World Air Quality Report, 21 of the world's 30 cities with the worst level of air pollution are in India, with six of the top ten. The report uses PM 2.5, widely regarded as the most harmful pollutant to human health, as the yardstick. Ghaziabad in India has been ranked as the most polluted city in the world. Delhi and Dhaka are the world's leading capital cities in terms of the concentration of PM 2.5 with respective values of 98.6 $\mu g/m^3$ and 83.3 $\mu g/m^3$. Based on the weighted population average, Bangladesh is the most polluted country for PM2.5 exposures. Four of the top five countries in terms of PM2.5 are in south Asia—Bangladesh, Pakistan, Afghanistan, and India at respective positions 1, 2, 4, and 5 in the world.

South Asian countries are thus experiencing serious environmental issues both at the micro and macro-levels. Efforts are needed on multiple fronts to combat these environmental challenges to improve the well-being of societies.

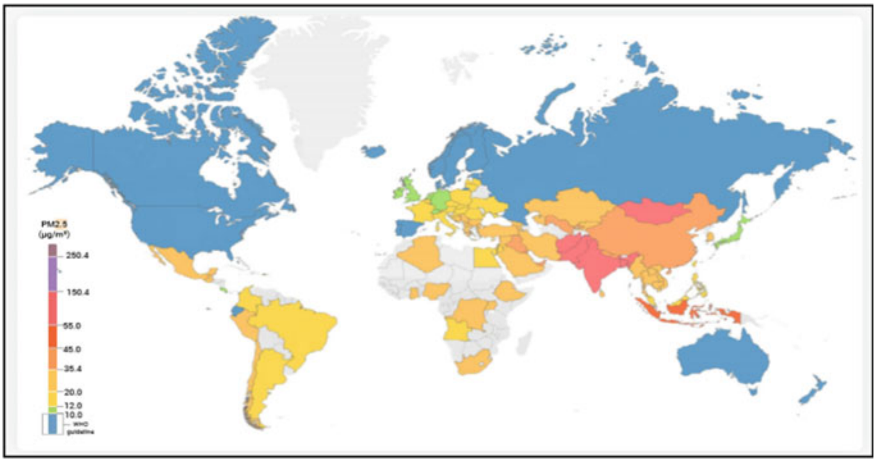



**Fig. 21** Global map of PM 2.5 exposures by country/region in 2019

## 7 Regional Energy Trade

South Asia is heavily suffering from regional disputes. Different South Asian countries have fought wars and have experienced civil wars. The geopolitical issues amongst various countries are still alive, undermining international cooperation and development in the region. There are many opportunities for energy trade between South Asian Countries. Presently regional energy trade in South Asia is, however, less than 5% of the total trade within the region. SAARC Inter-Governmental Framework Agreement (IFA) for energy cooperation was established between SAARC nations to address the electricity crises in South Asia using cross-border electricity exchange. Energy surplus countries such as Nepal and Bhutan could benefit economically by exporting the energy to energy-deficient counties such as India, Afghanistan, Pakistan, and Bangladesh. In the 16th SAARC Summit 2010, SAAEC nations adopted guidelines for the establishment of a regional market for electricity. All South Asian countries agreed on the establishment of a regional energy grid during the 18th SAARC Summit in November 2014. Following are some existing energy trade between South Asian countries [45, 52, 55]:

- India-Bhutan electricity trade 1974.
- India to Bhutan petroleum trade 1974.
- India-Nepal electricity trade 1971.
- India and Sri Lanka petroleum trade 2017.
- India and Bangladesh electricity trade in 2014.
- Afghanistan has imported a total of 230.14 GWh of energy from Tajikistan, Turkmenistan, Uzbekistan, and Iran in 2006.
- Turkmenistan-Afghanistan-Pakistan-India (TAPI) is a forthcoming project for natural gas supply.

- Central Asia-South Asia 1000 MW project which involves the building of more than 1200 km of electricity transmission lines to supply electricity to Afghanistan and Pakistan from the Kyrgyz Republic and Tajikistan.
- Energy trade between Pakistan and Iran.
- To establish support in between regional countries in Trade Facilitation, Transport, and Energy Central Asia Regional Economic Cooperation Programme began in 1997 amongst China Afghanistan, Azerbaijan, Kazakhstan, Kyrgyz, Mongolia, Pakistan, Tajikistan, Turkmenistan, and Uzbekistan.

The most energy sources (natural gas, coal, hydropower, renewable energy) of South Asian countries are not fully utilized [18, 16]. India, Pakistan, and Bangladesh have significant coal reserves. They are, however, not exploited to their potential. Many South Asian countries lack the diversification of fuel in primary energy consumption patterns. India is heavily dependent on coal, Pakistan, and Bangladesh dependent on gas. Bhutan and Nepal are hydro-based energy generators. Overall, there is an enormous dominance of a single fuel in the energy mix across all SAARC nations, with limited focus on renewable energy.

## 8 Conclusions

South Asia is the southern region of the Asian continent comprising of eight sub-Himalayan countries. The densely populated region has almost a quarter o the global population living in around 3% of the world's total area. South Asian countries meet the bulk of their energy requirements through imported fossil fuels. South Asian countries at large suffer from a lack of access to refined energy resources. Although significant progress has been in recent decades in terms of electrification, the reliability of the grid remains to be an issue. As over 1.2 billion people in the region lack access to gas networks, except for the Maldives, all South Asian countries have the majority of their population relying on crude biofuels to satisfy their cooking and heating requirements. Despite having a rich renewable energy base, fossil fuels meet the bulk of their energy requirements. India has made significant progress in the field of wind power and solar energy with respective installed capacities of 36 GW and 28 GW. South Asia is amongst the most vulnerable regions of the world in terms of the implication of global warming. Rising sea level is posing numerous challenges to all of the countries with coastal belts. Problems like seawater intrusion, loss of wetland and mangroves, displacement of human settlements are common in these countries. They are also experiencing increased frequency and intensity of climate change-driven extreme weather events such as seasonal disorder, flooding, drought, and heatwaves. To address their energy and environmental problems and to help meet Sustainable Development Goals (SDGs), South Asian countries need to substantiate the share of renewable resources in their energy mix. There is also a need to tap on regional energy trade opportunities.

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# Energy and Environmental Scenario of India

**Sainath A. Waghmare and Bhalchandra P. Puranik**

**Abstract** As one of the fastest developing countries, India's energy demand is continuously growing to compete in the globalization of industries. This competition overstrains the conventional energy sources of the country like coal, petroleum, and natural gas. Due to high output and limited stock of such energy sources, their market prices are increasing day by day. Besides, the carbon emission after the combustion of such fuels is high, which adversely affects the environment. Therefore, the balance between energy and environmental safety receives prime importance. The proposed chapter emphasizes the status of the energy utility, energy sources, ecological impacts, Government role, and techniques to reduce pollution based on recent researches and reports available publically. The industrial revolution of India had started very late as compared to developed countries; therefore, the environmental condition is quite better as compared to developed nations. But population and energy demands are rising tremendously, which creates severe crises for natural assets of the country. The chapter also highlights the way-out ideologies to tackle energy scarcity and environmental security.

## 1 Introduction

India, the nature blessed country with great geographic location promises an abundance of energy resources, great bio-diversity, forests, and farmlands, coastal and other valuable living-things. Hence, even after delayed industrial globalization, the Indian industrial pace could manage the country to stand in a strong economic position and emerged as the fastest developing nation. However, the prolonged use of fossil fuels creates worry about the environmental aspects as there is a tradeoff between energy and the environment.

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## 1.1 Indian Geography

India is the largest country in South Asia and the seventh-largest country in the world, which accumulates 3,287,263 sq. km land area. The entire country is lying in the Northern Hemisphere and has a great spread of latitude from 8°4′ to 37°6′ and longitude from 68°7′ to 97°25′. Geographically, the Himalaya Mountains have separated this country from mainland Asia, which provides a climatic difference among other Asian countries. India constitutes 7,517 km of coastline surrounded by the Arabian Sea, the Bay of Bengal and the Indian Ocean. Lakshadweep, Andaman, and Nicobar are the major islands out of total 1208 islands of India. The country is blessed with a marvelous diversity of ecological habitats, which comprises forests, deserts, wetlands, grasslands, coastal regions, and marine ecosystems. Bio-graphically, India is in Indo-Malaya and Pale-Artic realms with the proximity of the Afro-Tropical region that offers a wide range of biodiversity. Primarily, the 29 Indian states are categorized in regions or zones to develop the habit of co-operative working, as shown in Table 1.

India is pleased by natural resources, which is one of the most favorable countries in the world for a living. Due to proximity to the Tropic of Cancer, the climate is mostly warm except the Himalayan regions. The widespread net of rivers and appreciable terrains makes this country agriculturally dominated. This nature-blessed country nurtures 1.3 billion populations, which is 17.7% of the total global population. It is growing at a rate of 1.02% in the last year and records an increment of 12.2% in the last decade [1, 2]. It makes India the second most populated country in the world after China.

Due to latitudinal widespread land and proximity of seas, there is no fixed weather for India through a year. Indian weather has three seasons viz. monsoon, summer, and winter. The regional temperature range varies with seasons and terrain too. Being in the Northern Hemisphere with Tropic of Cancer, India is blessed with plenty of sunshine except the four months of monsoon. The average intensity solar radiation recorded is 20 MW/km [3], which is fair enough for solar power plants. The annual average wind velocity recorded in vital areas of the country is 9 m/s [4], which is favorable for wind turbine plants. The annual average rain of 1100.2 mm is recorded

**Table 1** Regions of India

| Region | States |
|---|---|
| Northern | Haryana, Himachal Pradesh, Punjab, Jammu and Kashmir, Rajasthan, Uttarakhand, Uttar Pradesh |
| Western | Chhattisgarh, Gujarat, Goa, Madhya Pradesh, Maharashtra |
| Southern | Andhra Pradesh, Karnataka, Kerala, Tamil Nadu, Telangana |
| Eastern | Bihar, Jharkhand, Odisha, Sikkim, West Bengal |
| North-Eastern | Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Tripura |
| Islands | Lakshadweep, Andaman, and Nicobar |

in the past 10 years [5], which supports agriculture and allied professions to be the main occupation of the nation.

## 1.2 Energy Demand

Food, cloth, and shelter are the basic needs of the human, but energy is the key to achieve it. Human needs energy in every aspect of life. Before the industrial revolution in India, the primary fuels used for cooking were wood, cow dung, and kerosene. It is still used in many villages but mostly taken over by Liquefied Petroleum Gas (LPG) cylinder, biogas, induction cooker, and solar cookers. Bull-kart and horse-kart are replaced with a petrol car, diesel trucks, and nowadays, Compressed Natural Gas (CNG) and electric driven vehicles are running on Indian roads. Trains, ships, airplanes are the biggest boosts of revolutionary Indian transport. These developments are mandatory to fulfill the needs of the exceedingly growing Indian population. This need ultimately stresses the energy sources and enforces production and distribution rates. Figure 1 shows the total installed electricity capacity and gross electricity generation in India at the end of March 2019. Coal-based electricity generation is the prime contributor, followed by hydro plants. This generated electricity has vast demand in the core areas like industries, agriculture sector, domestic and transportation, as shown in Fig. 2. Almost 50% of electricity is consumed by the industrial and commercial sectors that indicate the massive industrialization growth of the country. These sectors show a higher Compound Annual Growth Rate (CAGR) of the decade than that of agriculture, which is the primary profession of India. Figure 3 shows the generation and consumption of electricity to fulfill the demands of the increasing

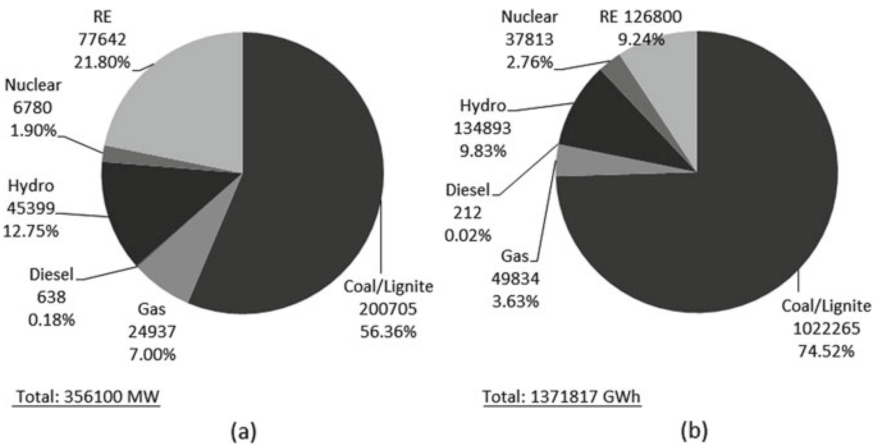


**Fig. 1** Electricity scenario in India at the end of March 2019. **a** Total installed capacity (MW). **b** Gross electricity generation (GWh) [6]

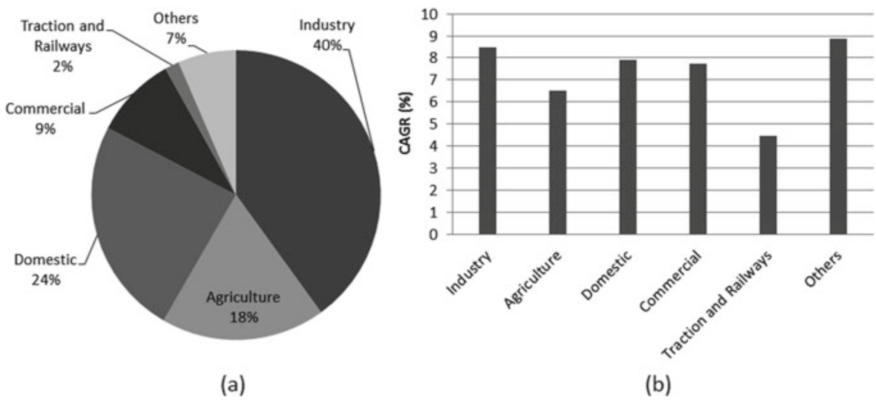


**Fig. 2** Trades in electricity consumption in India [8]. **a** Distribution recorded at March 2019 end. **b** CAGR for years 2008 to 2018

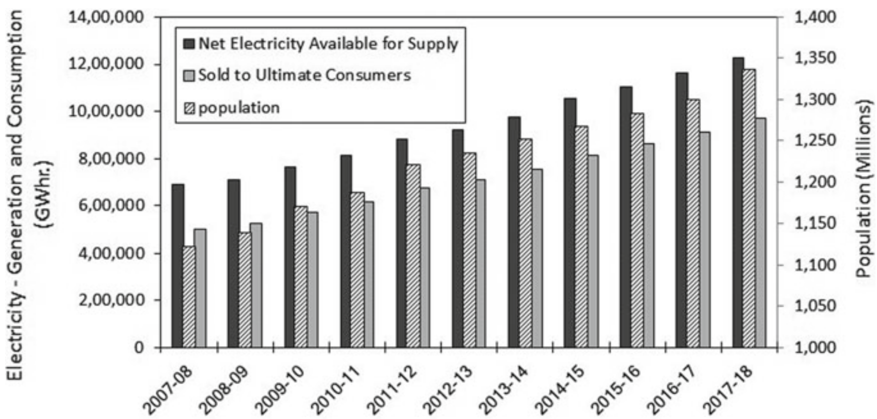


**Fig. 3** Electricity generation, consumption, and population from the Indian perspective [8]

population in the last 10 years. The CAGR of electricity generation and population in this period is 1.47, and 5.47 respectively, indicate the demand of modern India. The demand is increasing so rapidly that the per capita electricity consumption in the year 2018–2019 is 1181 kWh, compared to 733.5 kWh in the year 2008–2009 [6, 7].

Indian as well as foreign investors and industrialists seek profit in the energy business as it is one of the fastest-growing and profiting streams. A huge wealth has been invested by the Government of India (GOI) along with private shareholders in various schemes viz. Impacting Research Innovative and Technology (IMPRINT) initiative with budget ₹1000 Crore for the year 2016–2017, Integrated Power Development Scheme (IPDS) with components (i), (ii) and (iii) having an estimated outlay of

₹76,623 Crore with budgetary support of ₹48,081 from GOI and significant components of Deen Dayal Upadhayay Gram Jyoti Yojana (DDUGJY) ₹43,033 Crore [9]. Likewise, many energy sectoral schemes have been implemented with massive financial support from GOI as well as their shareholders. A massive financial investment was seen in Renewable Energy (RE) sector as well. As per the latest report of 2018–2019 by the Indian Renewable Energy Development Agency (IREDA), the shareholders have sanctioned the loan amount of ₹11,941.87 Crore and disbursed ₹9385.37 Crore for RE sector. The cumulative amount of loan sanctioned and disbursed at the end of this financial year was ₹72,903.77 Crore and ₹45,503.95 Crore, respectively [10].

## *1.3 Energy Versus Environment*

As per the law of conservation of energy, energy neither created nor destroyed. It can transform from one form into another. The useful form of energy is heat energy, which is collected by burning fuel like substance. Cooking and transportation are some of the essential applications of heat energy. The combustion of fuel releases harmful gases, soot, and small solid particles, ashes in the air that cause air pollution. Traditional and obvious fuel i.e., wood, causes the formation of smoke during its burning. Therefore, in the process of gaining a useful form of energy, the unwanted and unavoidable extracts are formed, which pollute the environment. In India, coal is the primary and widely used fuel for electricity generation. And it is the major contributor to the pollution right from the mining to the disposal in the form of ash. In light of fulfilling the drastically increasing demand for energy, coal demand also hits high, and it affects adversely on the environment. Similarly, extraction, process, and utilization of crude oil and natural gases contribute to air pollution, soil pollution, water pollution, health hazards, etc.

Figure 4 shows the steps of energy extraction and utilization for various applications and their environmental impact. It can be explained with the help of an example of a transportation system. The energy extraction starts from a point of 'need' of energy for moving from one place to another. The environmental problems start with deforestation to build roads, bridges over rivers, tunnels, etc. The second step is the 'extraction' of metals or fuels, which harms the ecosystem with all types of pollution, biodiversity problems, and health issues.

The next step is 'process' where the extracted fuels and metals pass through various processes to build a vehicle. It may include an automobile industry, tyre and rubber industry, plastic industry, and other part manufacturing firms. These processes result in all types of pollution, land overuse, health hazards, and biodiversity crises. Further the utilization or 'utility' of a vehicle, which may create air and sound pollution, and carbon emission. The last step is the disposal of the vehicle when it breakdowns or becomes outdated. Here, two possibilities occur i.e., either the vehicle becomes junk or gets recycled for other applications. In both cases, the environment may get ruined by various means of pollution. In the whole process, we have to note

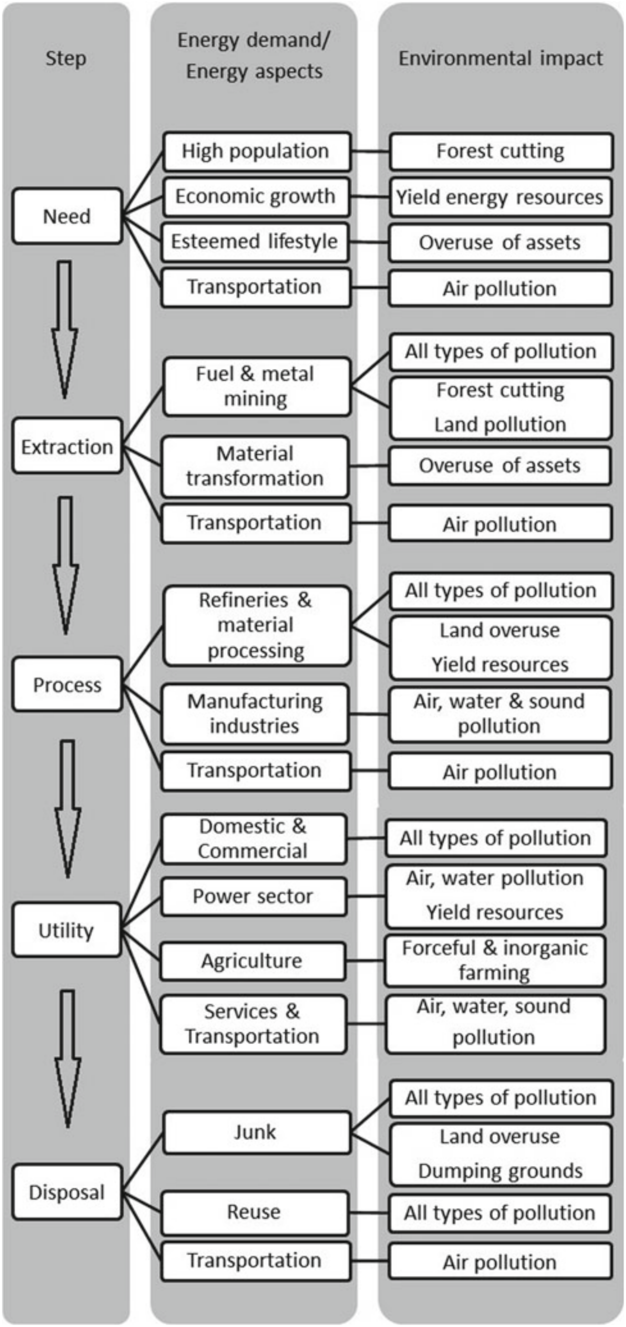


**Fig. 4** Process of energy extraction, application, and its environmental impact

that the transportation phase is present in every step right from extraction to disposal or reuse. Therefore, it is an important factor that needs much focus to protect the environment. Following are the principal causes of the environmental problems in India:

- The growing population demands more energy for living, which yields over-extraction and overuses of fossil fuels.
- Tree-cutting and deforestation to build colonies, industries, rails, and roads.
- Overused lands and water to compete with global industrialization for profit-making.
- Unlimited use of fossil fuels for the esteemed lifestyle and transportation of people.
- Overhunting of animals and species causes imbalances in the natural lifecycles and hierarchy.
- High population overloads farms and agriculture sectors with inorganic procedures that spoil land, air, water, and human health.
- Improper practice and lack of technology for utilizing energy resources.

GOI has started taking the necessary steps to protect the natural wealth of the nation without much influence on the economy. The use of renewable energy sources with cutting-edge technology would be the better option to keep a balance between environment and economy. The overview of energy in India, its environmental influences and protective steps are discussed in detail in subsequent sections.

## 2 Energy Sources and Availability

India is rich in land, human power, and energy resources of both conventional and non-conventional. In the view of increasing energy demand, GOI has increased and achieved an addition of a power capacity of 9.505 GW by conventional energy sources and 11.778 GW by RE raising the installed generation capacity around 344 GW during the year 2017–2018 [9].

### *2.1 Conventional Energy Sources*

India has much relied on conventional energy sources like coal, natural gas, crude oil for energy needs. Coal is the primary fuel and it is abundantly available in the country. However, the availability of oil and gas is insufficient to bear the current demand hence imported from other countries. Therefore, their price experiences lots of ups and downs in the international market and significantly influences the Indian economy.

### 2.1.1 Coal

India is the sixth-largest producer of coal in the world proves 322.92 billion tonnes of coal in the year of 2018 [8, 11]. Coal is the highest contributor to energy sources among all conventional fuels, especially in electricity generation. Coal-based electricity generation is the main asset to support the country's Gross Domestic Product (GDP) growth targeted by the GOI over the years. Figure 5a, b show the sector-wise utilization of coal and lignite respectively. Almost 90 and 62% of produced coal and lignite are utilized solely for electricity generation respectively. Figure 5c gives an idea of coal and lignite utilization in India since the year 2007. Ministry of Coal (MoC) [12] has estimated reserves of coal and lignite in March 2018 are 322.92 and 45.66 billion tonnes respectively. Coal mines are mostly found in eastern and south-central regions of the country. Indian states of Jharkhand and Odisha proved a maximum share of 26.06 and 24.86% of total available coal in India [12]. Other states viz. Chhattisgarh, West Bengal, Telangana, and Madhya Pradesh have 44% of coal

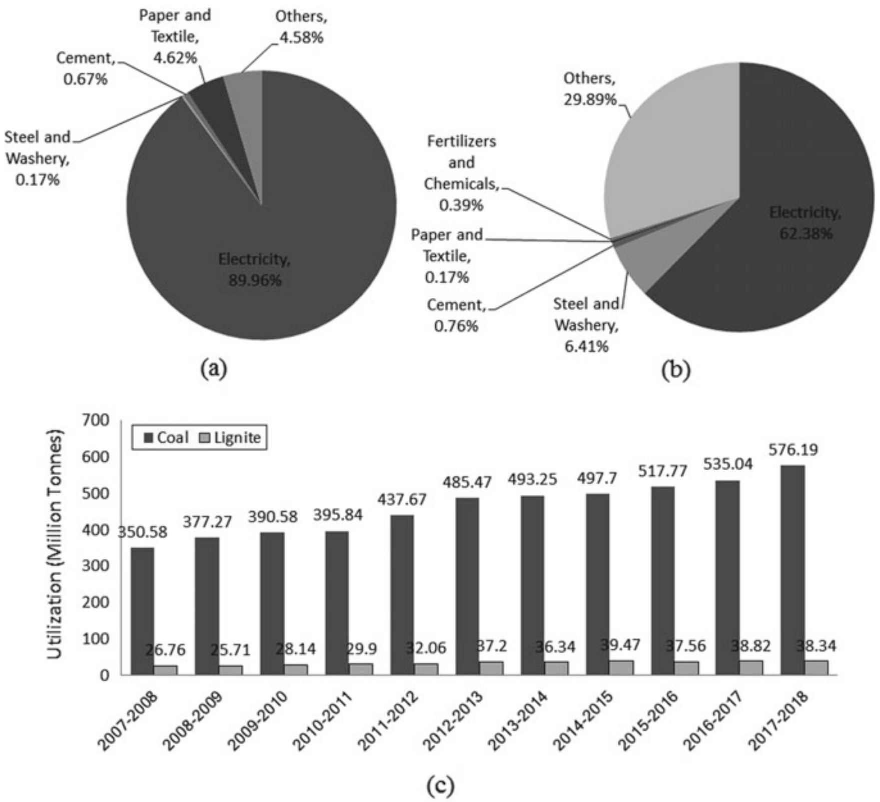


**Fig. 5** Primary fuel utilization [8, 12]. **a** Sector wise utilization of coal. **b** Sector wise utilization of lignite. **c** Utilization over recent years

available in the year 2018 [12]. Tamil Nadu has the maximum share of 80% of total Lignite available in India. From the year 2007 to 2018, the CAGR of production of coal is 3.20% whereas its consumption CAGR is 5.01%. For Lignite, production and consumption CAGR is recorded as 3.62 and 3.70% respectively [8]. The consumption rate of coal in the year 2007–2008 was 9.29% which reduced to 7.06% in the year 2017–2018. The consumption rate of Lignite in the year 2007–2008 was −8.08% which is reduced to 6.16% in the year 2017–2018.

### 2.1.2 Petroleum

India is the 22nd largest producer of oil in the world [11]. The transport sector is the chief customer for oil and petroleum products followed by industries and agriculture. Geographically, Western Offshore of the country indicates maximum reserves of crude oil i.e. around 40% followed by Assam and Gujarat claim 27 and 20% of total reserve respectively. Till March 2018, 594.49 million tonnes of crude oil were recorded. From the year 2007 to 2018, production and consumption CAGR of crude oil is 0.63% and 4.59% respectively. The consumption rate of petroleum in the year 2007–2008 was 3.49% which is increased to 5.95% in the year 2017–2018. Therefore, it is imported from Arab countries. Figure 6 shows the trade wise consumption of oil in the last ten years. High-Speed Diesel Oil (HSDO) is a widely used fuel in transport, industrial and agricultural machinery, and earthmovers; therefore, its consumption rate is a lot higher than other fuels. Aviation Turbine Fuel (ATF), petrol and LPG are also used in transportation purpose and being consumed with great pace in the last decade. Also, the consumption of petroleum products like petroleum coke, lubricants, and fuel oil hits high as they are important for manufacturing firms, power plants, and automotive industries.

### 2.1.3 Natural Gas

India is the 28th largest producer of natural gas in the world [11]. It has wide applications e.g. gas used as an alternative fuel for coal in power generation, LPG for fertilizers, textiles and domestic uses, CNG for transportations, etc. since its carbon emission and flue gas rate is much lower than other fossil fuels. Figure 7 shows the trade-wise application and consumption of natural gas.

As per Indian Geography, eastern and western offshores show maximum reserves of natural gas contributing 61% of the total reserve at the end of March 2018 [9]. Several states like Assam, Jharkhand, Madhya Pradesh, and West Bengal have reserves of natural gas. Around 1339.57 billion cubic meters of natural gas are available across the country as of March 2018 [13]. From the year 2007 to 2018, production and consumption CAGR of Natural gas is −0.06% and 4.82% respectively. The consumption rate of natural gas in the year 2008–2009 was 39.58% which reduced to 4.05% in the year 2017–2018.

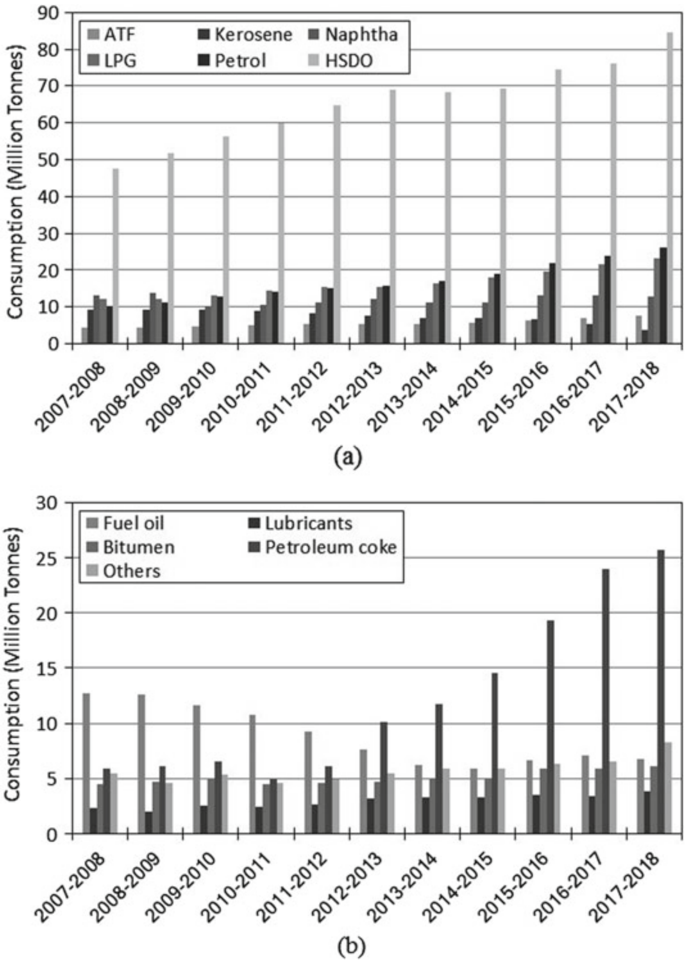


**Fig. 6** Trade wise consumption of oil/ petroleum products in recent years [8, 11]

## *2.2 Non-conventional Energy Sources*

Due to the limited stock of conventional energy sources, India is turning towards non-conventional or renewable energy sources at full pace. GOI has set RE target of 175 GW to be completed by the year 2022 which includes targets of 100 GW of solar energy, 60 GW of wind energy, 10 GW of biomass and bagasse and 5 GW of Small Hydro Power (SHP). Out of that, MNRE has successfully installed a total RE capacity of 84.7 GW in October 2019 [14].

India has a total RE potential of 1096081 MW of renewable energy, which includes maximum shares by solar energy of 748,990 MW and wind energy of 302,251 MW presented in Fig. 8a. Figure 8b shows the total installed capacity of renewable energy

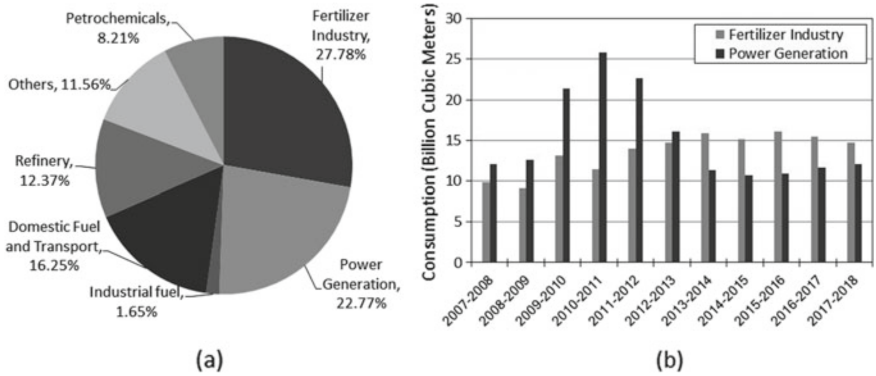


**Fig. 7** Trade-wise application of natural gas over recent years [8, 11, 13]. **a** Potential application areas for natural gas, **b** consumption in major application

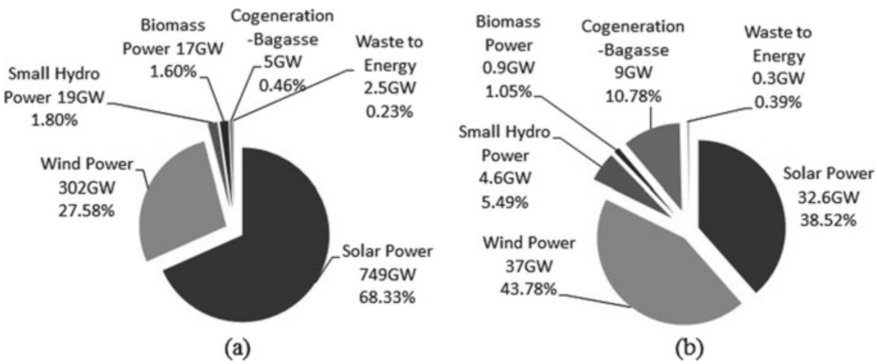


**Fig. 8** Renewable energy scenario of India [8, 14, 15]. **a** Energy potential. **b** Installed capacity on October 2019

sources until October 2019. Rajasthan, Gujarat, Jammu & Kashmir and Maharashtra account 510,780 MW that contributes 46.6% of total renewable energy of the country. India stands 4th in the wind and renewable energy and 5th in solar deployment in the world [15].

### 2.2.1 Solar Energy

Geographically, India is blessed with 300 sunny days and adequate solar flux due to the presence of tropic of cancer, which estimates about 5000 trillion kWh per annum in addition to an indirect form of energy in terms of wind energy, hydropower, ocean energy and bioenergy [16]. Some of the regions receive 4–7 kWh/m$^2$/day which is much useful for energy conversion into industrial applications [17]. Solar energy shares 68% of the total renewable energy sources in India until 2018. In the view of

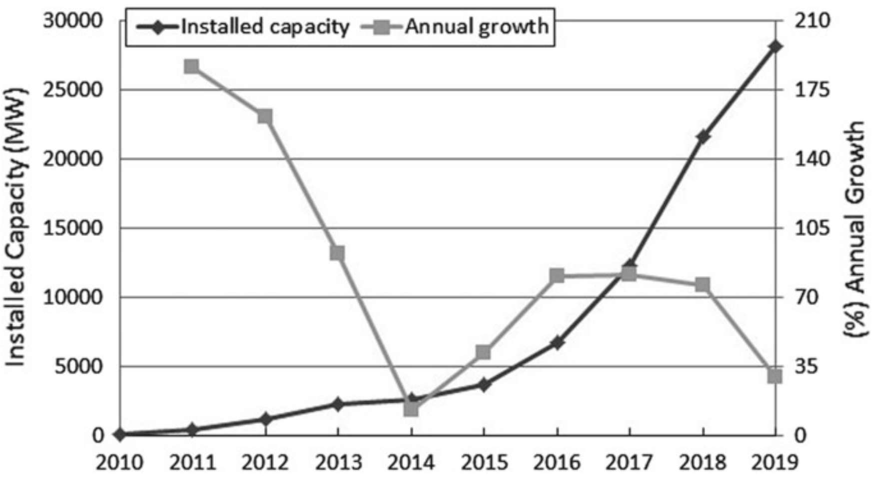


**Fig. 9** Cumulative installed capacity of solar power with annual growth recorded at the March-end per year [6, 8, 14, 15]

solar energy potential and climate change threat, GOI had launched the first National Solar Mission (NSM) called Jawaharlal Nehru National Solar Mission (JNNSM) in January 2010 under policies of National Action Plan on Climate Change (NAPCC). The initial target of the mission was set in 2010 to be achieved capacity of 20 GW by 2020 which was increased by 5 times in 2015 and set a new target as 100 GW to be completed in the same targeted year. MNRE has achieved the first target of 20 GW in the year of 2018, four years before the target year. The installed capacity of solar energy in March 2018 has reached 28.18 GW which was 2.6 GW in April 2014 with a massive increment of around 12.5 GW in the last 1.5 years as shown in Fig. 9.

NSM has implemented several energy schemes like National Thermal Power Corporation (NTPC) state-specific bundling scheme, Solar Park development scheme, Ultra Mega solar power projects, etc. to enhance grid connection for distribution and ease in energy utility. Solar Energy Corporation of India (SECI) Ltd. is a Central Public Sector Undertaking (CPSU) company of MNRE dedicated to solar energy and to facilitate the implementation of NSM and achieved the set target time to time.

Solar energy utilization is broadly categorized as solar Photovoltaic (PV) and solar thermal. Solar PV further classified as Grid-connected PV, Grid-connected rooftop PV, and off-grid PV. Solar thermal is classified as solar thermal application and Concentrated Solar Power (CSP). Till October 2019, MNRE has a total installed working capacity of 29,417.44 MW of Grid-connected PV, 2,278.80 MW of Grid-connected rooftop PV and 936.47 MW of off-grid PV [14]. GOI understands the importance of CSP and turning towards it at a great pace. The installation target of CSP plant was 500 MW in phase-1 (March 2013), 4,000–10,000 MW in phase-2 (March 2017) and 20,000 MW in phase-3 (March 2022). About 228.5 MW capacity of CSP power plant was operational in India at the end of March 2019 as shown in Table 2 along with other CSP power plants.

**Table 2** CSP power plant in India [15, 18, 19]

| Project | Technology type | Capacity (MW) | Location | Generation off-taker | Current status |
|---|---|---|---|---|---|
| ACME Solar Tower | Power tower | 2.5 | Bikaner Rajasthan | ACME group | Operational since February 2014 |
| Godawari Solar Project | Parabolic Trough | 50 | Nokh, Rajasthan | NTPC Vidyut Vyapar Nigam Ltd | Operational since February 2014 |
| National Solar Thermal Power Facility | Parabolic Trough | 1 | Gurgaon India | National grid | Operational since February 2014 |
| Megha Solar Plant | Parabolic Trough | 50 | Anantapur Andhra Pradesh | NTPC Vidyut Vyapar Nigam Ltd | Operational since November 2014 |
| Dhursar | Linear Fresnel reflector | 125 | Dhursar Rajasthan | NTPC Vidyut Vyapar Nigam Ltd | Operational since November 2014 |
| Abhijit solar Project | Parabolic trough | 50 | Phalodi Rajasthan | NTPC Vidyut Vyapar Nigam Ltd | Under construction since July 2015 |
| Dadri ISCC Plant | Linear Fresnel reflector | 14 | Dadri Uttar Pradesh | NTCP | Under construction since November 2016 |
| Diwakar | Parabolic Trough | 100 | Askandra Rajasthan | NTPC Vidyut Vyapar Nigam Ltd | Under Construction since February 2013 |
| Gujarat Solar One | Parabolic Trough | 25 | Kutch Gujarat | Gujarat Urja Vikas Nigam Ltd | Under Construction February 2014 |
| KVK Energy Solar Project | Parabolic Trough | 100 | Askandra Rajasthan | NTPC Vidyut Vyapar Nigam Ltd | Under Construction Since February 2013 |

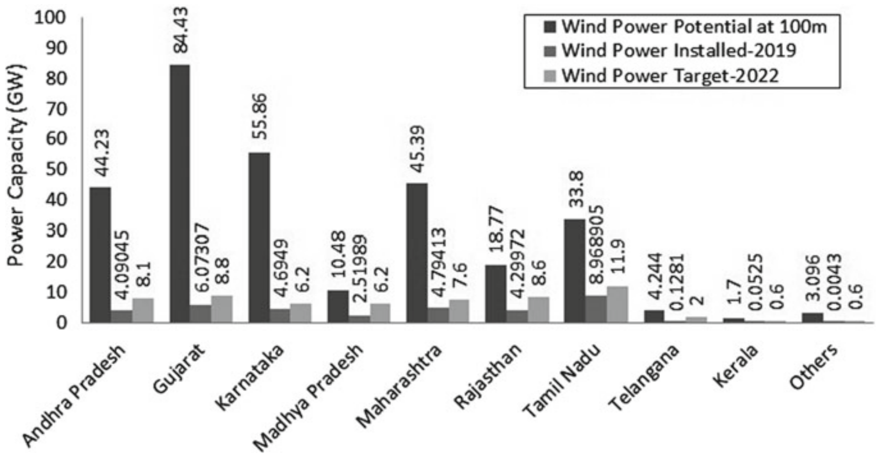


**Fig. 10** State-wise potential, installed capacity and target for wind power [6, 14, 15, 20, 21]

### 2.2.2 Wind Energy

Wind energy is an indirect manifestation of solar energy caused due to heating of the earth's surface and atmosphere that allows the wind to flow. For practical applications, wind energy needs to transform into a useful form of energy i.e. mechanical energy in a sophisticated way. Ancient humans used wind energy for sailing ships by converting it into motion using sail curtains. Over the years, humans produced mechanical or rotary motions using windmills that were used for water pumping, mechanical and agriculture works. Wind turbines are the most developed versions of wind devices and proved to be a useful asset for electricity generation. Due to geographical features, India is endowed with immense wind energy resources. Figure 10 gives information about wind power potential of Indian states with currently installed capacity. At the end of October 2019, India has a total wind energy capacity of 37 GW as given in Fig. 11 and thus stands 4th in the world for the highest deployment of wind energy [14].

### 2.2.3 Hydropower

Hydroelectric or hydropower is well suited for India due to high and low terrain places. Around 12.75% of electricity is generated from hydropower. It is pollution-less but needs a big structure and dams for functioning. India possesses total hydropower potential of 148.7 GW in October 2019 out of which only 40.6 GW i.e. 28% is operational and 10.8 GW (7.45%) is under construction [22]. The hydropower plants with a capacity of less than 25 MW fall under the small hydropower (SHP) category. Figures 12 and 13 shows the installed capacity and annual growth of hydro and SHP respectively. CEA has proposed and permitted the agreement for three

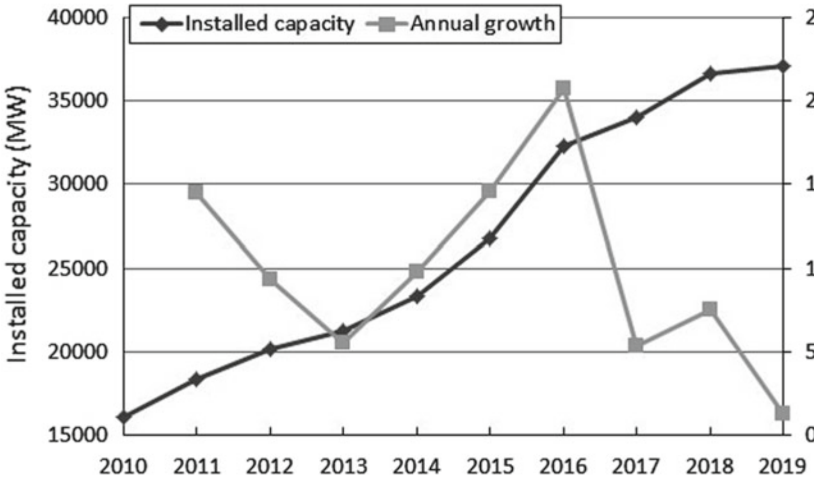


**Fig. 11** Cumulative installed capacity of wind power with annual growth recorded at the March-end per year [6, 8, 14, 15]

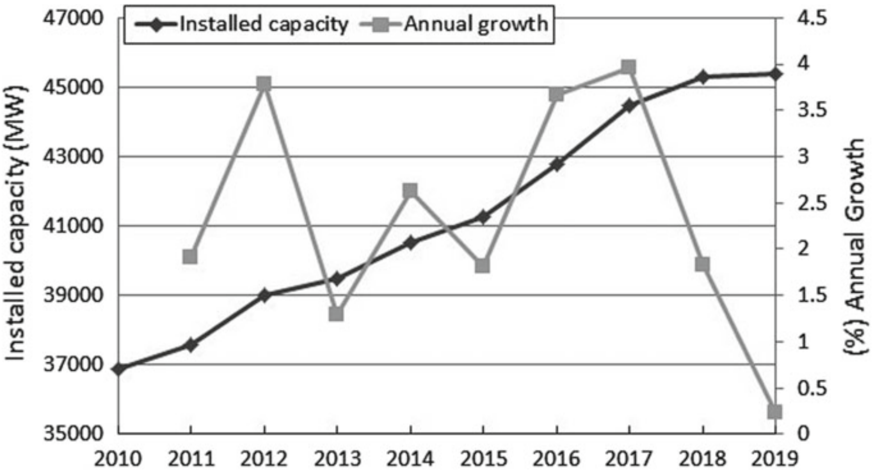


**Fig. 12** Cumulative installed capacity of hydro-electric power with annual growth recorded at the March-end per year [6, 22]

hydro generation schemes aggregating to a capacity of 5531 MW during the year 2017–2018 [9]. In the same year, CEA has rendered four hydro-electric projects of 5110 MW capacity named Punatsangchhu State-I and State-II projects in neighboring country Bhutan. Various power utilities and agencies have been approached for the transmission and other engineering services.

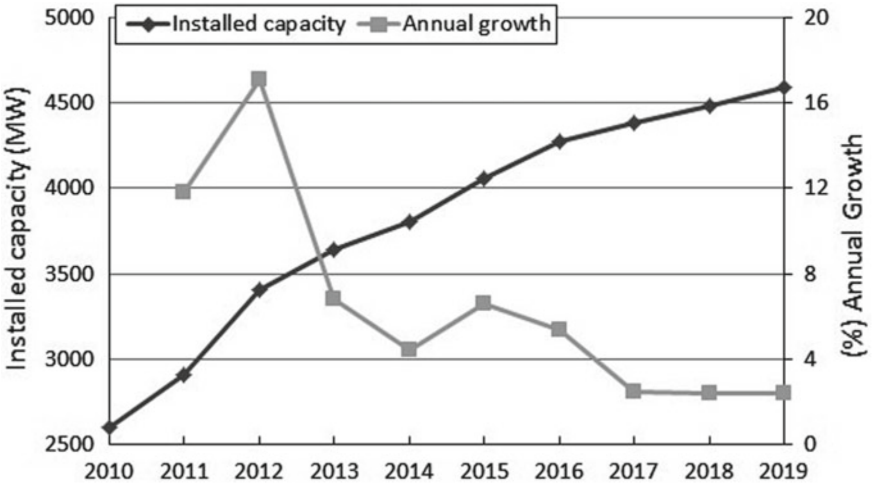


**Fig. 13** Cumulative installed capacity of small hydropower with annual growth recorded at the March-end per year [6, 8, 14, 15]

### 2.2.4 Biomass Power

Biomass and bagasse generation is high in India due to advancements in agriculture and allied businesses. Energy from biomass is a worthy utilization of human and animal wastes. Figure 14 shows the biomass-based power generation since the year 2010. A massive growth was seen in the year 2014 when the awareness from MNRE

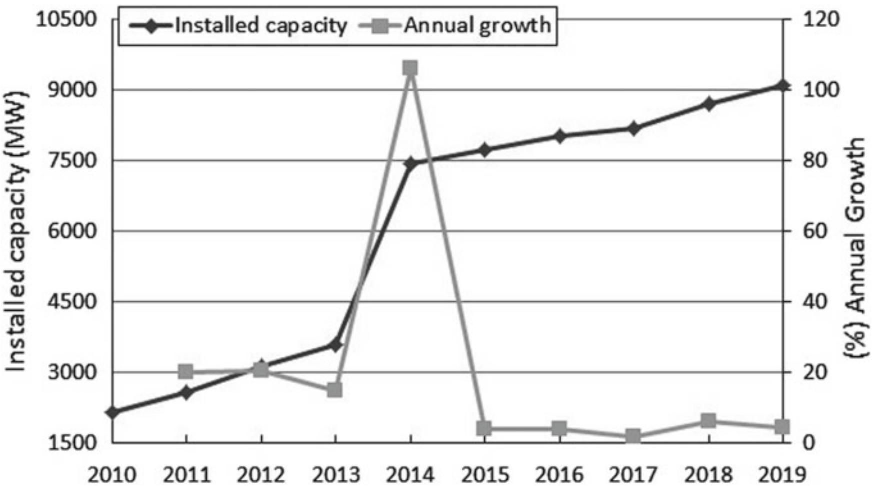


**Fig. 14** Cumulative installed capacity of biomass power with annual growth recorded at the March-end per year [6, 8, 14, 15]

was conducted and biomass plants installed. From this year the utilization of biomass for power generation is increasing continuously but with constant and comparatively low annual growth.

### 2.3 Other Energy Sources

Nuclear energy is very popular to generate a high amount of electricity without generating greenhouse gases and air-polluting elements. In fact, nuclear energy is a renewable energy source but the materials used in a nuclear power plant like Uranium, Plutonium, and Thorium are not renewable. These materials are radioactive and toxic that cause harmful diseases and thus they need careful handling and disposal. Therefore, in India, nuclear power shares only 1.9% of total power plant installed with present capacity of 6780 MW and gross generation of 37,813 GWh at the end of March 2019 [6, 23]. Several under-construction projects governed by Department of Atomic Energy (DAE) like Kakrapar Atomic Power Project (KAPP) unit 3 and 4 with 700 MW capacity, Rajasthan Atomic Power Project (RAPP) units 7 and 8 with 700 MW which will boost nuclear power capacity of India [24].

According to MNRE, India has a huge coastline with a large number of gulfs and estuaries that ensure energy potential of about 12,455 MW by tidal energy, 40,000 MW by wave energy and 180,000 MW by Ocean thermal energy. MNRE is looking forward to utilize such energy sources to tackle energy demands and climate change problems. Currently, these technologies and power plants are at pre-R&D stages and numerous researches and demonstrations are going on under the authority of Ministry of Earth Sciences (MoES), GOI.

As a substitute for fossil fuels and a source of clean and sustainable energy, hydrogen energy is getting huge attention in India. MNRE along with academic and research institutes has been engaged with lots of R&D projects to demonstrate the real-life application of hydrogen energy for electricity generation and transport. National Hydrogen Energy Board has prepared National Hydrogen Energy Road Map [25] under MNRE which highlights the production of hydrogen, supply plans, hydrogen storage and transportation, fuel cell, safety codes and standards of hydrogen application. Similarly, MNRE has been conducting R&D work to extract geothermal energy and looking forward to its actual application to fulfill energy demand.

## 3 Organizations for Energy and Environment

Organizations played the most important role in installing and operating power plants and balance the ecosystems. Due to the large landscape, Indian organizations are categorized as government and private sector to ensure smooth conduct of control and distribution. Further, the government sector is divided into central government and state governments. Although the state governments and private sectors produce a high amount of electricity, central government authority controls them and provides funds, policies, and infrastructures. Besides, various academic and research institutes and organizations like IITs, NITs, CSIR labs, government institutes, and Universities put appreciable contributions in R&D work, demonstrations of projects and prototypes and policy-making initiatives for both energy and environmental aspects. The salient organizations in the area of energy and environment are listed in the following subsections.

### 3.1 Central Government Support

The higher ministries of energy and environment are listed in Tables 6 and 7 respectively.

### 3.2 State Government Support

State Government organizations in the area of the energy sector and environmental control are listed as per the major regions of India in Tables 8, 9, 10, 11, 12.

### 3.3 Private Sectors and NGOs

The energy sector is a big market for investors and industrialists. The private sectors in the energy generation field are emerging with full-throttle as shown in Fig. 15. The installed capacity of the private sector has boosted from the year 2011 and it has crossed central and sector government plant's capacity. At the end of March 2019, the private sector constitutes 46.5% of electricity where central and state government plants have 25 and 28.5% of total share respectively [26]. In the search of huge profit, energy sectors are producing as high as they can but it causes environmental losses since the maximum generated energy is based on fossil fuel combustion. To control such a situation, some private agencies and non-government organizations (NGOs) are working hard to set policies, carbon emission limits and energy utility rules and regulations. Also, the private sectors burst into the RE business to support green energy. NGO's are working in various areas like public health, forests and ecology protection, anti-pollution, RE and Clean India Mission. Their valuable contribution is stepping ahead to preserve the environmental values and status in the country.

**Table 6** Higher ministries of the central government in the energy sector

| Partner | Focus area | Highlights/Objectives |
|---|---|---|
| Bureau of energy efficiency (BEE) | Energy conservation agency under MoP | Energy efficiency, demand side management, energy policies and strategies, implementation of energy conservation acts |
| Central Board of Irrigation and Power (CBIP) | Energy and water resources | Dedicated services of power, renewable energy, and water technology to a professional organization, training, consultancy and database services |
| Central Electricity Authority (CEA) | Electricity authority and control under MoP | Development of electricity plans, plants, policies, control, and records |
| Central Electricity Regulatory Commission (CERC) | Electricity regulation under MoP | Control on electricity generation, a tariff on companies, implementation of energy acts and regulations |
| Central Power Research Institute (CPRI) | R&D institute under MoP | R&D institute of electrical research and technology management |
| Coal India Limited (CIL) | Coal mining and refining under MoC | Production, refining, planning, consulting and distribution coal to state power plants |
| Department of Atomic Energy (DAE) | Nuclear power technology. Nuclear energy research | Application of nuclear radiation technology in agriculture, medicine, industry, and energy sector |
| Directorate General of Hydrocarbons (DGH) | Oil and Natural gas management under (MOP&NG) | Environmental balance, safety, technological and economic aspects of petroleum activity |
| Energy Efficiency Services Ltd (EESL) | Energy Efficiency under MoP | Facilitate energy efficiency, conservation projects, implementation of energy regulatory acts, business, etc |
| Indian Renewable Energy Development Agency (IREDA) | Financial institute under MNRE | Financial activities and control of renewable energy projects and products |
| India Smart Grid Forum (ISGF) | Electricity grid and transportation under MoP | Development and implementation of smart grid technologies and electricity regulation activities |
| Ministry of Coal (MoC) | Coal mining and control | Exploration of coal and lignite, production, supply, distribution, and financial activities |
| Ministry of Micro, Small and Medium Enterprises | Industrial sector | Preparation and support to small and medium enterprises, technical consultants, finance, energy audits, and pollution control activities |
| Ministry of New and Renewable Energy (MNRE) | New and Renewable energy | Develop and deploy renewable energy technology and plant |

(continued)

**Table 6** (continued)

| Partner | Focus area | Highlights/Objectives |
|---|---|---|
| Ministry of Petroleum and Natural Gas (MOP&NG) | Oil and Natural gas management | Exploration, production, distribution, control, import and export of petroleum products and natural gas |
| Ministry of Power (MoP) | Electricity generation, supply, and control | Charge and control the production of electricity in the country, policy formulation, projects, and administrative control |
| National Hydroelectric Power Corporation (NHPC) | Hydropower generation | Plan, develop, organize and promote hydro-electric power plants in the country |
| National Institute of Solar Energy (NISE) | Solar energy institute under MNRE | R&D institute of solar energy deployment, technology management |
| National Thermal Power Corporation Ltd.( NTCP) | Electricity generation business | Generate, regulate, supply and business of electricity to state boards |
| Petroleum Conservation Research Association (PCRA) | Oil and Natural gas conservation under MOP&NG | Promoting energy efficiency, proposing energy policies and strategies for fuel conservations, R&D activities, technology transfer, and public awareness activities |
| Power Grid Corporation of India Ltd. (POWERGRID) | Central transmission utility of India under MoP | Development, coordination, and control of transmission of electricity through the inter-state transmission system |
| Oil and Natural Gas Corporation (ONGC) Ltd | Crude oil and natural gas under (MOP&NG) | Exploration and production of crude oil and natural gas |
| Solar Energy Corporation of India Ltd. (SECI) | Solar energy company under MNRE | Administrative funding. and business for renewable energy plants in the country and implementation of NSM |
| National Institute of Wind Energy (NIWE) | Wind energy institute under MNRE | R&D institute of wind energy deployment, technology management |

# 4 Environmental Challenges and Energy Demand

## *4.1 Carbon Emissions*

Carbon is one of the essential elements for all lives on the planet earth. Nature balances and utilizes its essence for the purpose through the carbon cycle. Humans and animals draw oxygen from the atmosphere and return carbon dioxide ($CO_2$) which is then consumed by plants for photosynthesis process and return in the form

**Table 7** Higher ministries of the central government in the environmental sector

| Partner | Focus area | Type of association |
|---|---|---|
| Central Pollution Control Board (CPCB) | Technical service of pollution under MoEF&CC | Air and water quality status, trends to control pollution, implementation of Prevention and Control of Pollution Act., 1981 |
| Department of Biotechnology (DBT) | Biotechnology | Development and commercialize biotechnical projects, products in areas of agriculture, environment, health care, animals and industries. Funding for state and other institutions |
| Indian Council of Forestry Research and Education (ICFRE) | Ecology and forest | R&D in Ecology and forest studies, technology development and transfer, environmental safety |
| Indian Institute of Remote Sensing (IIRS) | R&D institute for remote sensing under ISRO | Research in the areas of remote sensing, Geo-informatics, GPS technology, information and technology for a weather forecast, natural disaster and environmental changes |
| Indian Institute of Tropical Meteorology (IITM) | R&D institute for meteorology | R&D activity in meteorological observations, tropical Indian Ocean, weather forecast, air-sea interaction, climate monitoring |
| India Meteorological Department (IMD) | Meteorology | Meteorological observations, weather forecast, seismic observations, information supply to agriculture, offshore oil exploration, irrigation, etc. Warn against natural calamities |
| Indira Gandhi National Forest Academy (IGNFA) | Forest and wildlife organization under MoEF&CC | R&D in forest and wildlife, safety, training programs, technology transfer, awareness, and education |
| Ministry of Environment, Forest and Climate Change (MoEF&CC) | Environment and climate change organization | Planning, executing, promoting, and controlling environmental safety activities along with funding, surveying and coordinating with other departments |

(continued)

**Table 7** (continued)

| Partner | Focus area | Type of association |
|---|---|---|
| Ministry of Earth Sciences (MoES) | Earth and Environment | To look after the atmospheric, Ocean and seismic activities, the formation of reports, policies, etc. for the socio-economic benefit to society |
| Ministry of Water Resources (MoWR) | Water resources | Conservation, management, development, presentation of pollution in rivers and other water resources of the country, efficient use of water |
| National Environmental Engineering Research Institute (NEERI), Nagpur | Environmental research institute | R&D in the areas of environment, water supply, sewage disposal, technology transfer, pollution reduction technique, and activities |
| System of Air Quality and Weather Forecasting And Research (SAFAR) | Air quality and pollution | Monitor, record, and forecast the air quality of various regions of the country |

of oxygen and biomass. The amount of carbon is continuously changing while transferring from living things to non-living things and vice-versa. It is available in abundance in inorganic substances like coal, rocks, oil, natural gas, air, etc., which are used as fuel to gain energy. While burning of these substances, a large amount of heat energy releases along with CO, $CO_2$ and other gases. Normally, the carbon is transferring in nature with a specified quantity but over-burning of fuel imbalances its amount liberating in the atmosphere causes air pollution. Due to global competition of industrialization, fossil fuels are over-extracted and overused which imbalances the carbon content in the environment. Also, unlimited cutting of trees and forests reduces air and water quality. As a result, the atmosphere is overburdened with many harmful gases that threaten human and animal life. According to BP [11] report, India has proven 15%, 0.3% and 0.7% of the total global reserves of coal, oil and natural gas respectively. It is equivalent to 266GT of $CO_2$ which is more than seven times higher than the global $CO_2$ emissions from energy sources [27]. In 2018, India became the fourth largest $CO_2$ emitting country with 6.9% shares of total global $CO_2$ emissions after United States, China and the European Union (EU 28) [28]. Since coal and oil are the primary resources of energy in India, they contribute to the highest $CO_2$ emissions. However, India has less $CO_2$ emission per capita per year as compared to the United States, China and EU 28, during the year 2016–2017 the emissions due to fossil fuels are reached up to 2.5 GT of $CO_2$ with annual increment of 3.5% which is a matter of great concern [28].

Figure 16 shows the sector-wise distribution of $CO_2$ emission generation per capita per year. The power sector industries emit the highest $CO_2$ emission since they are

**Table 8** State government bodies for energy and environment control for Northern region

| Partner | Profile | Focus area |
|---|---|---|
| Chandigarh Renewal Energy and Science & Technology Promotion Society (CREST) | Department of Science and Technology, Chandigarh | Solar PV, Rooftop installation and control |
| Haryana Renewable Energy Development Agency (HAREDA) | Government of Haryana | Renewable energy installation and control, Funding agency |
| Haryana Power Generation Corporation (HPGCL) | Government of Haryana | Power generation, control, and utility |
| Dakshin Haryana Bijli Vitran Nigam<br>Uttar Haryana Bijli Vitran Nigam | Government of Haryana | Electricity utility and distribution |
| HIMURJA | Government of Himachal Pradesh | Renewable energy installation and control, Funding agency |
| Jammu & Kashmir Electricity Board | Government of Jammu Kashmir | Power generation, control, and utility |
| Jammu & Kashmir Energy Development Agency (JAKEDA) | Government of Jammu Kashmir | Renewable energy installation and control, Funding agency |
| Punjab Energy Development Agency (PEDA) | Government of Punjab | Renewable energy installation and control, Funding agency |
| Punjab State Power Corporation Limited (PSPCL) | Government of Punjab | Power generation, control, and utility |
| Rajasthan Renewable Energy Corporation Limited (RRECL) | Government of Rajasthan | Renewable energy installation and control, Funding agency |
| Rajasthan Rajya Vidyut Utpadan Nigam (RVUNL) | Government of Rajasthan | Power generation, transmission, control and utility |
| Non-conventional Energy Development Agency (NEDA) | Government of Uttar Pradesh | Renewable energy installation and control, Funding agency |
| Uttar Pradesh Rajya Vidyut Utpadan Nigam (UPRVUNL) | Government of Uttar Pradesh | Power generation, control, and utility |
| Uttarakhand Renewable Energy Development Agency (UREDA) | Government of Uttarakhand | Renewable energy installation and control, Funding agency |
| Uttarakhand Power Corporation Ltd | Government of Uttarakhand | Power generation, transmission, control and utility |
| Delhi Vidyut Board | Government of Delhi | Power generation, control, and utility |

**Table 9** State government bodies for energy and environment control for the Western region

| Partner | Profile | Focus area |
|---|---|---|
| Gujarat Energy Development Agency (GEDA) | Government of Gujarat | Energy efficiency |
| Gujarat Industries Power Company Ltd | Government of Gujarat | Developing action and monitoring plan for reclamation of mine-degraded lands and addressing socio-economic |
| Dakshin Gujarat Vij Company Ltd | Government of Gujarat | Electricity utility and distribution |
| Surat Municipal Corporation | Government of India | Preparation of tender document, technical and financial bid evaluation |
| Maharashtra Energy Development Agency (MEDA) | Government of Maharashtra | Renewable energy, energy efficiency<br>Research Institution |
| Maharashtra State Power Generation Company Limited (MAHAGENCO) | Government of Maharashtra | Power generation, transmission, control and utility |
| Maharashtra State Electricity Transmission Company Limited | Government of Maharashtra | Power transmission, control, and utility |
| Chhattisgarh State Renewable Energy Development Agency (CREDA) | Government of Chhattisgarh | Renewable energy |
| Chhattisgarh State Power Generation Company Limited | Government of Chhattisgarh | Power generation, control, and utility |
| Goa Electricity Board | Government of Goa | Power generation, transmission, control and utility |
| Goa Energy Development Agency (GEDA) | Government of Goa | Renewable energy |
| Gujarat Energy Development Agency (GEDA) | Government of Gujarat | Renewable energy |
| Gujarat Urja Vikas Nigam | Government of Gujarat | Power generation, transmission, control and utility |
| Madhya Gujarat Vij<br>Paschim Gujarat Vij | Government of Gujarat | Electricity utility and distribution |
| Madhya Pradesh Urja Vikas Nigam Ltd | Government of Madhya Pradesh | Renewable energy |
| Madhya Pradesh Paschim Kshetra Vidyut Vitran Co. Ltd<br>M.P. Poorv Kshetra Vidyut Vitran Co<br>M.P.Madhya Kshetra Vidyut Vitran Co | Government of Madhya Pradesh | Electricity utility and distribution |

(continued)

**Table 9** (continued)

| Partner | Profile | Focus area |
|---|---|---|
| Madhya Pradesh Power Generation Company Limited (MPPGCL) | Government of Madhya Pradesh | Power generation, transmission, control and utility |

mainly based on coal combustion. The annual CAGR of $CO_2$ emission by all sectors was 5.28% in the last decade and 7.2% in the year 2017–2018. Out of which annual CAGR observed for the power sector during the last decade was 5.33% which is raised to 8.62% in the year 2017–2018. The power sector and industries altogether share almost 72% of total $CO_2$ emission in India, which shows the intention of high industrial and economic growth of the country. Transportation is going to be another concern for air pollution but it is observed in big cities due to the concentration of population. Out of the 20 most polluted cities in the world 13 cities are in India and only 3 in China [29]. Also, the concentration of industries can be seen near the cities make them more unhealthy places to live.

## *4.2 Global Warming and Climate Change*

Global warming is an impactful aspect of climate change reflected in the rise of the global atmospheric temperature for the long term by natural way or human interventions. It is caused due to rising greenhouse gases like $CO_2$, methane, nitrous oxide, ozone, and water vapor level in the atmosphere which absorb more solar radiation and gets heated. Thus the temperature of the earth's air and surface increases which results in melting polar and sea ice, rising oceans level, the formation of heat waves, extreme vaporization of water resources, and uneven weather conditions. These effects lead to climate change which is a broader aspect generally conveyed as a change in the earth's climate pattern over a specific period or season. Extended summer or winter, the large temperature gradient in a day, uneven and untimely rains, acid rains, etc. are the major signs of climate change. The global atmospheric temperature is increased by 1 °C above the pre-industrial baseline i.e. the year 1850–1900 [31]. According to the recent report by the Intergovernmental Panel on Climate Change (IPCC) [32], there is an increment of $0.93 \pm 0.07$ °C with respect to the baseline of the pre-industrial era. Figure 17 shows the annual average temperature and rainfall in India over the years. It can be seen that from the year 1970 the temperature is continuously increasing indicates growth in industrialization. Agriculture is the most affected field by global warming and climate change as uneven and untimely rains ruin the crop life, quality, and quantity of farm products, infertile farmlands, floods, and droughts [33]. It ultimately affects human and animal life and disturbs the food chain of nature. From the year 1990, the annual average rainfall drops continuously and in the last decade, it shows the second-lowest of the century.

**Table 10** State government bodies for energy and environment control for Southern region

| Partner | Profile | Focus area |
|---|---|---|
| Andhra Pradesh Southern Power Distribution Company Ltd (APSPDCL) | Government of Andhra Pradesh | Solar PV grid integration studies, Demand Side Management (DSM), Energy Efficiency (EE) |
| Bangalore Electricity Supply Company Ltd (BESCOM) | Government of Karnataka | DSM and EE |
| Bengaluru Electricity Supply Co. Ltd | Government of Karnataka | R&D Summit 2018 |
| CESCOM | Government of Karnataka | DSM and EE |
| Gulbarga Electricity Supply Company Ltd (GESCOM) | Government of Karnataka | DSM and EE |
| Karnataka Power Corporation Limited | Government of Karnataka | Power generation, control, and utility |
| Karnataka Power Transmission Corporation Limited (KPTCL) | Government of Karnataka | Electricity utility and distribution |
| Karnataka Renewable Energy Development Ltd | Government of Karnataka | RE installation and control, technology development, Funding |
| Mangalore Electricity Supply Company Limited (MESCOM) Chamundeshwari Electricity Supply Corporation Limited (CESC) | Government of Karnataka | Electricity Transmission, control, and distribution |
| Kerala State Electricity Board Ltd (KSEB) | Government of Kerala | DSM and EE |
| Tamil Nadu Generation and Distribution Corporation Ltd | Government of Tamil Nadu | DSM and EE |
| Non-Conventional Energy Development Corporation of Andhra Pradesh (NEDCAP) Ltd | Government of Andhra Pradesh | Energy conservation, Renewable energy installation, and control, technology development |
| Agency for Non-conventional Energy and Rural Technology (ANERT) | Government of Kerala | Energy conservation, Renewable energy installation, and control, Rural development |
| Tamil Nadu Energy Development Agency(TEDA) | Government of Tamil Nadu | Renewable energy |
| Tamil Nadu Electricity Board (TENB) | Government of Tamil Nadu | Power generation, control, and utility |
| Tamil Nadu Generation and Distribution Corporation Limited Tamil Nadu Transmission Corporation Limited (TANTRANSCO) | Government of Tamil Nadu | Electricity utility and distribution |

(continued)

**Table 10** (continued)

| Partner | Profile | Focus area |
|---|---|---|
| Andhra Pradesh Power Generation Corporation Limited (APGENCO) | Government of Andhra Pradesh | Power generation, control, and utility |
| Eastern Power Distribution Company of A.P. Ltd. (APEPDCL) | Government of Andhra Pradesh | Electricity utility and distribution |
| Telangana Power Generation Corporation (TSGENCO) | Government of Telangana | Power generation, control, and utility |
| Transmission Corporation of Telangana | Government of Telangana | Electricity transmission, utility, and distribution |
| Northern Power Distribution Company of Telangana Limited(TSNPDCL) | Government of Telangana | Electricity utility and distribution |
| Kerala State Electricity Board | Government of Kerala | Electricity utility and distribution |

The root causes of such events are the formation of greenhouse gases, which are either formed by natural calamities like volcanic explosions, forest fires, etc. or by human interferences. In India, volcanic explosions are rare events but forest fire is a matter of great concern. It not only decreases the number of trees but adds smoke and harmful gases in the surrounding air. India's Green House Gas (GHG) emission in the year 2015 reached 3.3 $gtCO_2$ eq./year which was 0.8 and 1.4 $gtCO_2$ eq./year in the years 1970 and 1990 respectively [30]. The hunger for energy encouraged by economic growth leads to environmental crises in India. However, India has 1.93 tonnes of $CO_2$ emission per capita per year and 6.9% shares of total $CO_2$ emission in the year 2018 but the major concern is the neighboring country China which is emitting 11.3 $gtCO_2$ emissions and shared 29.7% of global $CO_2$ emission [28]. China has reported 8 tonnes of $CO_2$ emission per person with a population of 1.4 billion in 2018. It affects the environment of Himalaya, North-Eastern states and nearby areas shared by both the countries. The influence of air pollution and climate change in such places is more severe due to high altitude which results in increased frequencies of natural calamities. Temperature rise is seen in the Himalaya region in past decades causes climate change conditions reflecting in terms of floods, cloudbursts, earthquakes, and landslides which makes this region one of the worst affected regions in the world [34]. The excess coal mining in the North-Eastern states like Assam, Sikkim, Arunachal Pradesh, and Nagaland causes air and soil pollution, and thus causes socio-ecological problems. Coal mining and combustion create many harmful pollutants like carbon, sulfur and overburden materials accompanied by soot, smoke, dust, ash, etc. exerts a long-lasting impact on the ecosystem. The water reservoirs near the coal mines are highly acidic and contaminated which make it unsafe for drinking purpose [35].

**Table 11** State government bodies for energy and environment control for Eastern region

| Partner | Profile | Focus area |
|---|---|---|
| Bihar Renewable Energy Development Agency (BREDA) | Government of Bihar | Renewable energy plant installation and control |
| Jharkhand Renewable Energy Development Agency | Government of Jharkhand | Renewable energy plant installation and control |
| Odisha Renewable Energy Development Agency (OREDA) | Government of Odisha | Renewable energy plant installation and control |
| Odisha Hydro Power Corporation (OHPC) | Government of Odisha | Electricity Generation, control, utility, maintenance and distribution from a hydro and thermal power plant |
| Odisha Power Generation Corporation (OPGC) | Government of Odisha | Electricity Generation, control, utility and distribution |
| Odisha Electricity Regulatory Commission (OREC)<br>Central Electricity Supply Utility of Odisha (CESU) | Government of Odisha | Electricity Transmission, control, and distribution |
| Sikkim Renewable Energy Development Agency (SREDA) | Government of Sikkim | Renewable energy plant installation and control |
| West Bengal Renewable Energy Development Agency (WBREDA) | Government of West Bengal | Renewable energy plant installation and control |
| West Bengal Power Development Corporation Ltd. (WBPDCL) | Government of West Bengal | Power generation, control, and utility |
| West Bengal State Electricity Board | Government of West Bengal | Electricity Transmission, control, and distribution |
| Bihar State Electricity Board | Government of Bihar | Electricity utility and distribution |
| North Bihar Power Distribution Company Ltd<br>South Bihar Power Distribution Company Ltd | Government of Bihar | Electricity Transmission, control, and distribution |
| Damodar Valley Corporation,<br>Jamshedpur Utility and Services Company,<br>Jharkhand State Electricity Board,<br>Bokaro Power Supply Co Pvt. Ltd | Government of Jharkhand | Electricity Generation, control, utility and distribution |

**Table 12** State government bodies for energy and environment control for North-Eastern region

| Partner | Profile | Focus area |
|---|---|---|
| Arunachal Pradesh Electricity Board | Government of Arunachal Pradesh | Electricity Generation, control, utility and distribution |
| Arunachal Pradesh Energy Development Agency (APEDA) | Government of Arunachal Pradesh | Renewable energy installation and control, Energy conservation, funding |
| Central Assam Electricity Distribution Company Ltd<br>Lower Assam Electricity Distribution Company Ltd<br>Upper Assam Electricity Distribution Company Ltd | Government of Assam | Electricity Generation, control, utility and distribution |
| Assam Energy Development Agency (AEDA) | Government of Assam | Non-conventional and Renewable energy –installation and control |
| Electricity Department, Manipur | Government of Manipur | Electricity generation, transmission, and distribution |
| Manipur Renewable Energy Development Agency (MANIREDA) | Government of Manipur | Renewable energy installation and control, Energy conservation, funding |
| Meghalaya Non-conventional & Rural Energy Development Agency (MNREDA) | Government of Meghalaya | Renewable energy installation and control, Energy conservation, funding |
| Zoram Energy Development Agency (ZEDA) | Government of Mizoram | Renewable energy installation and control, Energy conservation, funding |
| Nagaland Renewable Energy Development Agency (NRE) | Government of Nagaland | Renewable energy installation and control, Energy conservation, funding |
| Tripura Renewable Energy Development Agency (TREDA) | Government of Tripura | Renewable energy installation and control, Energy conservation, funding |
| Tripura State Electricity Corporation Ltd | Government of Tripura | Electricity generation, transmission, and distribution |
| Assam State Electricity Board | Government of Assam | Electricity generation, transmission, and distribution |

### *4.3 Impact on the Life*

It is an obvious statement that if the environment is affected, life on the earth gets affected too. Nature always runs in a cycle that is formed with its elements. There is a specific proportion for every element in the environment and all are interrelated and dependent on each other. As being an important part of the food chain, the existence of animals possesses its importance for human life. A small bee is much responsible to keep the balance of nature. We have used energy resources limitlessly for our

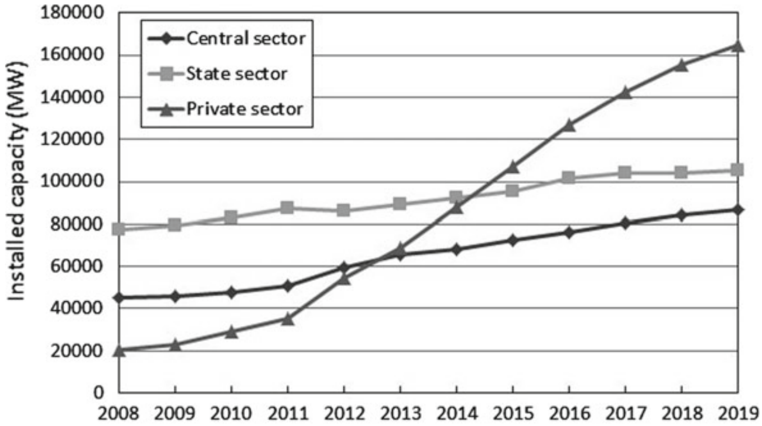


**Fig. 15** Contribution of central, state and private sectors in electricity generation over recent years [6]

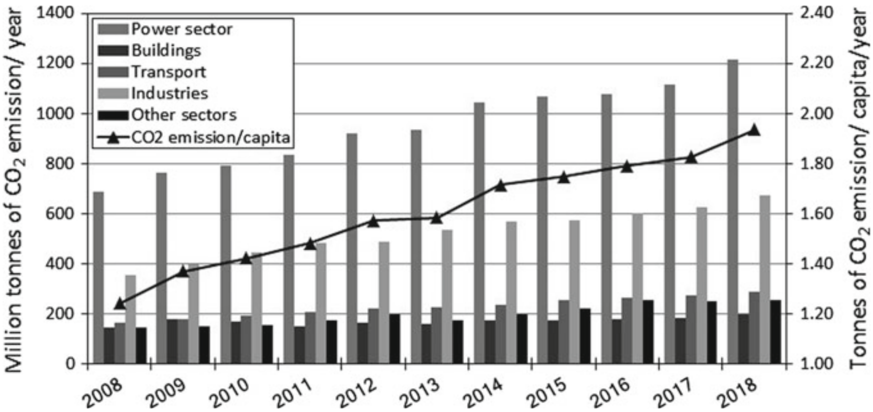


**Fig. 16** Year-wise $CO_2$ emission generation by sectors and per capita [30]

existence and competition among ourselves which costs us in the form of a polluted environment and damaged lifecycles.

Human activities like deforestation, mining, pollution, climate change, and global warming result in major habitat losses and biodiversity problems [36]. As a tropical country, India is blessed with the unique biodiversity that comprises 7–8% of all recorded species in the world on just 2.4% of the world's landscape [37]. Biodiversity plays an important role since it serves almost 70% of the Indian population in the form of food, livelihoods, socio-economic and sustainable development [38]. Out of which 54.6% population purely depends on agriculture and allied sectors [39]. Due to the high population, industrialization and rising economy overburden biodiversity and related services. Also, overhunting, overfishing, deforesting and

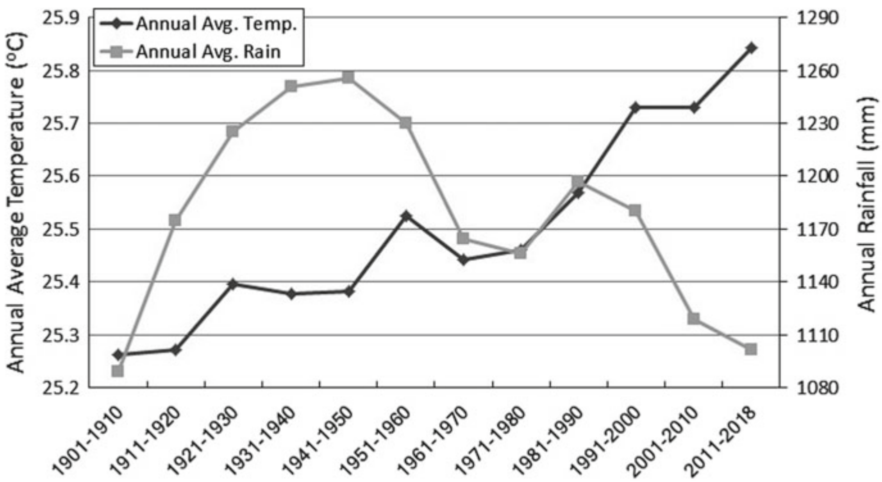


**Fig. 17** Annual average temperature and rainfall in India [5]

urbanization enhanced biodiversity problems to the next level. Ministry of Statistics and Programme Implementation (MoSPI) along with other ministries like MoES and MoEF&CC conducts surveys, gathers information, records, evaluates and sets policies to recover environmental losses in India. According to the recent reports of these ministries, the overuse of fossil fuels put a massive impact on the ecosystem of the country. And if it continues for the next decade, the biodiversity problems will become difficult to recover. Climate change and global warming cause the formation of heat and cold waves which is undesirable for all livings. Figure 18 gives an idea

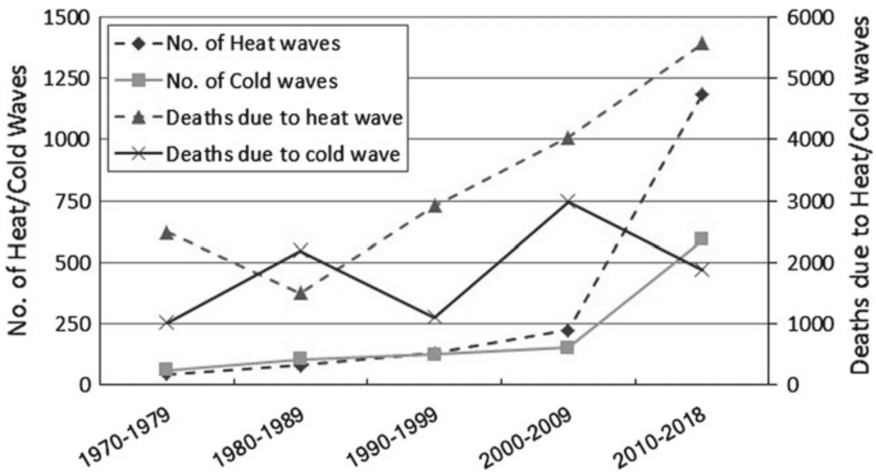


**Fig. 18** Number of deaths due to the occurrence of heat and cold waves in India [5]

about several death cases due to the formation and occurrence of heat and cold waves in India.

India is an agricultural country where the lands and forests preserve most of the ecosystem and become a foundation to born, live, grow, expand and decease. Soil originates supports and structures the terrestrial and amphibious ecosystem and grows plants and trees for serving and providing habitat for living. The quality of soil performs a vital role in farming as it is associated with minerals, carbon contents, metal extracts, moisture and fertility that directly transfer to crops and plants. The extraction process like mining, over-farming and unlimited use of fertilizers weakens the quality of soil affects farming outputs simultaneously. Ministry of Agriculture and Farmer's Welfare, Government of India has conducted soil tests that show the Indian soil is rich in potassium fertility, moderate in phosphorus fertility and less nitrogen fertility except for Jammu and Kashmir and North-eastern states [40]. Therefore, now-days, Indian farmers used a high quantity of nitrogen and phosphate in fertilizers [41]. The lands under forests come to threat due to natural calamities like forest-fire, earthquakes, and floods. Around 35,888 no. of cases of forest-fire have occurred in the year 2017 which is highest in the last decade [5].

Drinkable or clean water has always been one of the biggest problems in India. Water is the most essential part of life on the earth and it is a measure of a rich ecosystem. India holds around 18% of the global population but only possesses 4% of drinkable water in rivers [40]. Contaminated or polluted water yields various diseases in society. On average, one out of five children is facing critical health issues and even death due to diarrhea [42]. Acid rains due to air pollution additionally weaken the water quality and become dangerous man-made disasters. Figure 19 states the number of deaths in India in recent years by harmful diseases that occurred due to air and water pollution.

As being the second largest fish producer, fishing and related sectors are one of the most important businesses in India that serve more than 15 million people

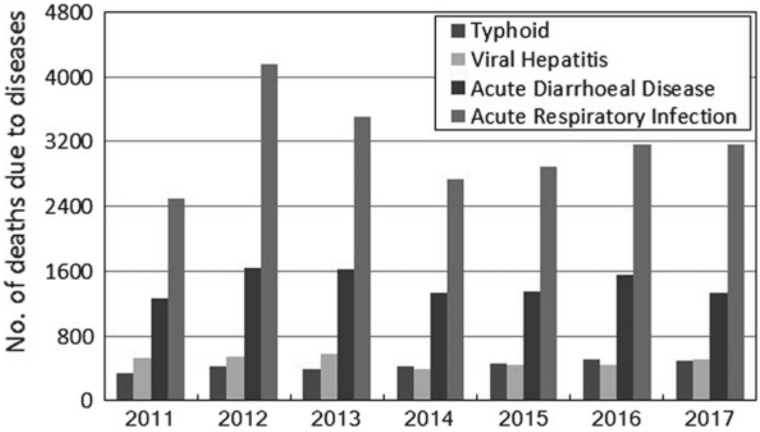


**Fig. 19** No. of deaths due to major diseases occurred due to air and water pollution [5]

directly or indirectly and gather $6 billion foreign currency [40]. India has a long coastline and a large number of islands that shelter around 13.36% of the population. Hunger of high profit, economic growth, and widen businesses overstress the coastal ecosystems. Besides, plastic-pollution, human and industrial wastes, and hazardous extracts weaken the marine water quality. Thus, the assets in the coastal ecosystem deplete gradually, alarming no recovery chances at some places. Oil and natural gas exploration from offshore and its transportation through waterways cause serious issues to marine life. The major concerns like oil leakages, garbage and solid waste, wastewater discharges, sound pollution, tanker accidents, and overexploitation put India on 12th position in the world for creating marine pollution [40].

## 4.4 Impact on Economy and Valuable Assets of the Country

High energy consumption leads to economic growth. As being a developing country, India tries to be in-line with developed nations to get a similar economic status. After the nation's independence in the year 1947, the actual industrial era thus global competition has started for India. Indian economic growth has been encouraged by high energy generation and consumption over the years. The coal-based power plant is the backbone of the Indian economy produces the highest amount of electricity i.e. 74% than any other energy source. But simultaneously, it is the highest contributor of carbon emission than any other fossil fuels. Constrained use of coal for electricity generation drops down the economy and creates a cavity in energy fulfillment. However, this energy demand can be fulfilled by renewable energy sources; it needs decades to get well-established and compete with conventional energy sources as primary energy. Despite the high initial cost of renewable energy set-up, it is essential to use them due to increasing environmental crises. GOI along with private and foreign stockholders has been investing a huge amount of money in installing solar energy parks, concentrated solar thermal power plants, small hydro projects, wind turbines, etc. Even though these investments may not produce an immediate profit, it will boost the economy with less harm to the environment in the future.

Certainly, energy from fossil fuels leads to economic growth but raised pollution damages the environment and economy too. E.g. if we cut the forest to build the industry to raise capital but at the same time we are dropping the profits obtained from forests like wood, fruits, and animals. Apart from environmental harms, pollution does affect the nation's economy and wealth. Biodiversity is the one upon which human civilization is built and developed and get certain benefits for living. It offers food, shelter, fiber, fuel, medicine, raw materials, and whatnot. Biodiversity is the most valuable asset of any nation to safeguards mankind and creatures as well as to raise its social, economic, academic, and cultural growth. India is known for its rich biodiversity properties, contribute lion's share in the socio-economic development in terms of agriculture, fishing, medicine, industries, energy resources, transport, small and medium enterprises, etc. Also, biodiversity stands India's valuable asset in the view of academics, defense, research, and technology. As an agrarian country, farmlands and forests perform significantly role nation's socio-economic developments. Increasing pollution, climate change crises, global warming disturbs ecology inland and marine which lowers its economic profit. Deforestation not only affects forest biodiversity but damages timber business, Ayurvedic medicines, fruits and vegetable trades, and hydrocarbon substances. As a result of climate change crises, uneven and untimely rains disturb crops in farms, underground vegetation, farm storages, spices, and flower businesses. Sometimes whole farms got hunted by floods and cloudburst conditions. On the other side, droughts obtain zero output from thousand-acres of farmland. Thus, people who are associated with agriculture and related professions get financially affected and choose either migration to other places or commit suicide. It is observed that 10,349 Indian farmers/cultivators and agricultural laborers committed suicide in the year 2018 due to financial crises in their profession [43]. Such a loss meant to a matter of great concern to the nation. Pollution in coastal areas reduce fish population and health that ultimately harms fishing trade, tourism business, and travel through waterways. If marine pollution continues with its pace for the next two decades then some of the rare marine species will be on the verge of permanent extinction.

Historical monuments, which are considered as one of the national wealth, are also affected by atmospheric pollution. The stones of monuments are deteriorated by air pollution and acid rains. According to the studies, $SO_2$ in the atmospheric air converts in sulphuric acid and reacts with the marble through acid rains [44]. The other organic acids like citric acid, formic acid, and phosphoric acid not only stains on the marble but cause deterioration in its surface [45]. The atmosphere at Agra City and nearby places of Delhi and NCR is heavily polluted due to increasing vehicles, industries and uncontrolled construction activities [46, 47]. Such polluted climate produces weak acids when it comes in contact with moisture in air results acid rains. Such acids are corrosive and put unwanted effects on paints, stones, and metals that damage the beauty and priceless art of the Taj Mahal. Therefore, reducing pollution near the Taj Mahal is the only way to protect this world heritage monument. Another aspect is controlling the population near such precious monuments. Not only the ancient memorials but the religious and spiritual places in India need to be protected from the concentration of population on certain occasions [48].

## 5 Remedies and Solutions

The utilization of conventional energy sources cannot stop suddenly and implementation of non-conventional energy sources will not establish fully in a short span. These are the gradual processes that need to take place without any massive impact on the economy. The best way to tackle the situation of energy demand and environmental losses is to conserve energy and adopt renewable energy sources in day to day life. Use fossil fuels wisely until the renewable energy sources established to the certain capacity that they can fulfill the energy demand of the whole country. Also, the following protection procedures may be implemented-

### 5.1 Public Awareness

The people are the real strength of any nation. To reduce environmental crises in India, public awareness is the first step towards success. People must be aware of the energy drought, environmental harms due to fossil fuels and remedies to takeover. Traditional thinking needs a new perspective to limit traditional fuels and use new and renewable energy. GOI is leaving no stone unturned in spreading awareness through advertisements, newspapers, and media channels. Also, academic institutes conduct several conferences, workshops, open programs, symposiums, and colloquiums to meet and share research ideas to protect the environment, reduce pollution and develop new technologies. Simple techniques in day to day life may matter a lot like switching-off electrical appliances when not in use, use public transport, use own vehicles wisely, reduce wastages of water and food and so on.

India has great minds that always find a solution over every problem in society. New and innovative ideas must be brought into the light and must be commercialized for daily practice. Many schools and college students present their research projects of energy harvesting, renewable energy technologies, reducing carbon emission, and catalytic converters must be given prime attention and adopted in real applications. National Institute of Solar Energy (NISE), an autonomous research institute of MNRE has initiated the "Suryamitra Skill Development Programme" and "Varun Mitra Yojanain" programs intending to create skills and employment opportunity in the solar energy field for youths of the nation. Under this scheme, basic and advanced training for installation, operation, and maintenance in the solar energy sector is provided and helped them to be an entrepreneur. Similarly, MNRE conducts many short and long term courses and award competitions, exhibitions in the field of new and renewable energy.

### 5.2 Tree Plantation, Growth, and Care

A tree or plant is the most important element to keep a balance of all elements in nature. It holds and serves all species, run carbon cycles, water cycles, and life cycles. Many initiatives from schools, offices, NGOs, are conducting tree plantation programs as a part of social contribution and prime responsibility. In Paris Agreement in the year 2015, GOI has submitted Intended Nationally Determined Contribution (INDC), under which India has committed to reduce carbon emission of 2.5 to 3 billion tonnes of $CO_2$ (Carbon Sink) by additional forest cover and tree plantations till 2030 [49]. Forest Survey of India (FSI) is a national organization working under MoEF&CC for the assessment of forest resources of the country. In addition to forest assessment, FSI is engaged with a tree cover of the country keeping records of inventory data of Trees Outside Forests (TOF). FSI performs forest and tree-cover assessment by satellite data on a biennial basis. From the year 1987 to 2017, 15 cycles of forest assessment have been completed. As per the latest report of MoEF&CC, there is an increment of forest and tree cover of 6,778 and 1,243 km of the country as compared to the year 2015 respectively [50]. During the year 2018, FSI used scenes from remote sensing satellite which is procured from National Remote Sensing Centre (NRSC), Hyderabad. It is beneficial for land mapping with positional accuracy.

The growth and care of trees hold equal importance as that of the plantation. Forest-fire is a critical issue for a forest in India which not only harms forest and animal life but aids air pollution. FSI had initiated the real-time monitoring system for forest-fire in the year 2004 which is revamped in 2017 with a new system i.e. 'Forest Fire Alert System 2.0' [50]. The system is used to predict the forest areas which are more prone to catch fire and take precautionary measures quickly.

### *5.3 Effective Waste Disposal Techniques*

India is promoting waste to wealth conversion achieving dual benefits of effective waste disposal and energy generation. The biodegradable waste is linked with various fertilizers for conversion and obtained market profits. Several Solid Waste Management (SWM) projects have been implemented over the years with USD 397 million grant and public–private partnerships [49]. GOI launched 'Swachh Bharat Abhiyaan' (Clean India Mission) in the year 2014 to clean nearby areas and dispose of waste in a sophisticated manner that it should not harm the environment. The fly-ash generation from a coal-based power plant is continuously monitored and governed by CEA, on behalf of MoP since 1996 by web-monitoring services. In the continuation of this, CEA has developed GIS-based 'ASH TRACK' mobile application for interfacing between fly ash generators and end-users [9]. Therefore, the information and availability of fly ash at nearby thermal power plants are easily tracked and arrangement is done for its effective transportation. Fly-ash utilization has risen to 63.28% of the total in the year 2016–2017.

### *5.4 Government Initiatives and Mandatory Rules*

The world understands the severity of global warming and climate change threat therefore every country is standing up to decrease harmful content in the environment. India has committed to Paris Agreement in climate change under India's INDC to reduce the emission intensity of its GDP by 33–35% by 2030 from 2005 level and install a 40% cumulative electric power plant from renewable energy sources [49]. INDC includes key elements and focused areas like sustainable lifestyle, cleaner economic development, emission reduction through GDP, Non-fossil based electricity, enhancing carbon sink, technology transfer, and capacity building and mobilizing finance. Besides, INDC focused on adaption to climate change by investing development programs in agriculture, health and disaster management especially in Himalaya and coastal regions which are more prone to climate change. In partnership with France, GOI has promoted the establishment of the International Solar Alliance (ISA) in 2015 with an effort to put solar energy on the global agenda and providing clean and sustainable energy for the world.

As a part of Research and Development in the power sector, Bureau of Indian Standards (BIS) committee has issued the report on 'Technical Aspects of Charging Infrastructure for Electric Vehicle' from CEA which focuses on key areas of developed safety and performance standards for energy storage system [9]. MoEF&CC has issued new environmental norms for thermal power stations on 7th December 2015 regarding norms for Suspended Particulate Matter (SPM). Under this norm, the various emissions like SOx, NOx, and Mercury from thermal power stations have been reported along with water consumption for power generation. In addition to the previous norms of $SO_2$ emission, a mandatory action for fitting the Flue Gas Desulphurization (FGD) system in the thermal power plant is taken [9]. MoEF&CC has initiated several plans like High-Level Task Force (HLTF), Comprehensive Air Plan (CAP), etc. to tackle air pollution issues in Delhi and nearby areas in the year 2017. 55 agencies like MoP&NG, Ministry of Road Transport and Highways, Ministry of Housing and Urban Affairs, Transport departments, urban local bodies, Delhi Police, etc. to ensure strict implementation of CAP for prevention, control and mitigation of air pollution [50]. Another initiative called National Clean Air Program (NCAP) launched by MoEF&CC in 2019 which incorporates Central Ministries, State Governments, local bodies, and other stakeholders to prevent, control and comprehensively abate air pollution. Some of the salient actions under this plan are:

- Notification and enforcement of National Ambient Air Quality Standards and emission standards for industries.
- Setting and Monitoring network for air quality assessment for highly polluting industrial sectors.
- Utilization of clean gaseous fuels like LPG, CNG, etc.
- Launching and monitoring the national Air Quality Index (AQI).
- Implementation of BS-IV for vehicles by the year 2017.
- Promoting public transport.
- Mandatory Pollution Under Control (PUC) certificate for vehicles.
- Preventing the open burning of biomass.
- Banned the bursting sound-emitting crackers between 10 pm to 6 am.

The main goal of NACP is to meet the prearranged annual average ambient air quality standards at all 102 locations and targeted 20% to 30% reduction of PM2.5 and PM10 concentration by the year 2024.

### 5.5 *Energy Conservation and Management*

Another and the best way to tackle the energy demand problems is to conserve energy and use it wisely. The energy audit is an inspection survey that gives detailed analysis of energy consumption and losses for a firm, house or any building or sector. Thus, the energy input can be minimized without affecting the output. It sets a platform for energy conservation in industrial and commercial buildings to reduce energy expenses and carbon emissions. Many Government and private agencies offer energy audits publically to spread energy efficiency and conservation awareness and implementation. GOI has established Bureau of Energy Efficiency (BEE) under the provision of the Energy Conservation Act, 2001 with a vision of setting policies and strategies to reduce the energy intensity of the Indian economy. BEE offers several programs like Energy Conservation Building Code (ECBC), Star labeling for electrical appliances, Demand Side Management (DSM), and energy efficiency programs for states and industries [51]. GOI has launched the centralized portal for the Indian power sector named National Power Portal (NPP) on 14th November 2017 to facilitate online information about power generation, transmission and distribution in the country on a daily, monthly and annual basis [9]. The portal was developed by National Informatics Centre, Ministry of Electronics and Information Technology, GOI and it is owned, updated and maintained by CEA, MoP. The valuable updated information of power sectors, their operational capacity, demand, supply and consumption of power is available publically. CEA carried lots of R&D works for improving the efficiency of coal-based generation, identifying thrust areas for future energy, effective energy transportation services, energy storage, DSM programs and accepts research data and information sharing through conferences, seminars, technical workshops, and international congresses as promotional actions for energy harvesting. Another Government agency PCRA under MoP&NG works on promoting energy efficiency programs and environmental protection through the conservation of hydrocarbons in fossil fuels. PCRA has conducted 239 energy audits, 171 fuel oil diagnostic studies, 783 institutional training programs, many seminars and technical sessions throughout the country and serves more than 230 industrial services with more than 233 follow-up studies during 2017–18 [52]. MoP has initiated DSM under Ujwal Distribution companies Assurance Yojana (UDAY) scheme in order to improve operational and financial efficiencies for state distribution companies [9]. Thus the awareness and implementation of energy conservation and management have been spread throughout the country.

## 6 Summary

An overview of the Indian energy scenario is presented with its generation, distribution and utilization structures. The fruitful geographical location makes the country more proficient in energy, economy, and biodiversity. However, an uncontrolled population and rapid industrialization overburden the use of fossil fuels which cost heavily to the Indian ecosystem. The degradation of the ecological condition is elaborated with a timeline and remedies to overcome the energy and environmental crises are presented. The Government initiative is the key point in energy and environmental matter which is illustrated with publically-published Government reports and statistics. High-end technology for renewable energy along with optimized use of conventional fuels would be a great option for the nation to protect the ecosystem with the enriched economy.

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# Energy and Environmental Security Nexus in Pakistan

**Mabroor Hassan, Muhammad Irfan Khan, Muhammad Waseem Mumtaz, and Hamid Mukhtar**

**Abstract** Energy security has evinced a prime role in shaping prospects of economic and social development with its intrinsic relationship with environmental security due to convergence of energy generation and distribution with so many factors like global governance, economic development, affordability, equitable and sustainable energy transitions, environmental protection, environmental politics, water security, air pollution, climate change, conflicts, and environment-induced migrations. Pakistan has energy requirements of more than 75 million tons of oil equivalent (MTOE) in 2019 which is experiencing exponential increase due to growing population and changing lifestyle. The country is currently relying on thermal energy and imported fossil fuels to meet energy requirements. The share of coal in primary energy has been increased in recent years. The construction and operational phase of energy projects have significant threats to environmental security due to soil erosion and compaction, chemical spills and debris disposal, air emissions, noise and wildfire. It also shapes the terrain by damaging vegetation cover, terrestrial ecosystems and wetlands. The impacts further include dislocation of species, disturbance in migratory corridors and changes in breeding areas of wildlife. These projects also affect the water quality and modify drainage patterns causing aesthetic disruption and changes. Archeologically and culturally important sites are also being disturbed on the pretext of improving socio-economic conditions. Furthermore, climate change

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is reshaping the nexus of energy with environmental security in Pakistan. Resultantly, there may be a paradigm shift due to energy insecurity, geopolitical conflicts in the region, consumer's access to affordable energy, environmental injustice and insecurity. Pakistan already lacks renewable energy but inefficient use, line losses, energy-inefficient infrastructure and technologies challenge the government to meet the targets of Sustainable Development Goals (SDG 7), pillar 4 (Water, energy and food security) of the Pakistan Vision 2025. Hence, Pakistan has to establish a good framework of governance for thermal power sector, upgrade its existing energy infrastructure, diversify energy recourses, introduce energy-efficient technologies, develop minimum standards for power generation, explore renewable and competitive energy market, identify low carbon power generation methods, subsidize alternative and renewable energy (ARE) technologies, balance energy mix, improve fuel efficiency, manage energy demand, invest on research and development, aware the people and regulate consumer's behavior and practices to achieve optimum energy security and environmental security.

**Keywords** Energy · Environment · Human · Security · Systems · Renewables · Climate change · Nexus · Pakistan

## 1 Introduction to Energy and Environmental Security

### *1.1 Energy Security*

Access to sustainable energy is considered as a fundamental human right and cardinal policy discourse of every government across the world. Meanwhile, the goal 7 of United Nations (UN) agenda of sustainable development for 2030 stresses on member states to provide access to affordable, reliable, sustainable and modern energy for all. However, the requirement of energy is considerably increasing in both developed and developing countries with the growing population, changing lifestyle and rapid economic growth. In this scenario, the procurement of sustainable energy to all is part of the global commitment of every government. At the same time, energy security is among the top priority agendas of political governments. But the definition of energy security varies across the world due to diverse geopolitical and socio-economic circumstances. However, the Asia Pacific Research Center defines energy security as "the ability of an economy to ensure the availability and timely access to energy resource supply in sustainable manners at an affordable cost without adversely affecting the economic performance of the economy [1]. Winzer (2011) describes energy security as the continuous transitions of energy relative to energy demand [2]. According to Sovacool (2011), energy security has multi-dimensions such as availability of energy resources, diversification, dependency, trade, innovation, decentralization, investment, affordability, price stability, production, transparency, good governance, literacy of society, efficiency, reliability and environmental factors (adequate land use, resilience against climate change, water use, pollution, and greenhouse gas emissions) [3]. The states have to consider all dimensions to ensure energy security and environmental sustainability.

### *1.2 Environmental Security*

Environmental challenges have threatened the survival of humanity worldwide. The concept of environmental security has emerged as an integral part of both national and foreign policies of the governments in recent years. The prospects of environmental security have been broaden from adequate availability, access and equitable supply of natural resources (water, energy, minerals, oils, food, and use of marine passages, etc.), environmental pollutions, illegal transboundary movement of hazardous waste and transboundary river pollution to human security (environmental refugees and social upheavals caused by natural resource scarcity and environmental disasters), national security and foreign policy discourse. Recent challenges like exploitation and unequal distributions of resources, environmental migrations, energy insecurity, water crises and climate change have disturbed patterns of human, environmental and national security in recent decades. Hence, survival of humanity, inclusive economic growth and stability of the state are entwined with environmental security in the recent time.

## 2 Energy-Environmental-Human Security Nexus

Sovacool (2013) has established the view, "*if the 20th century was about energy, then the 21st century would be about energy governance and climate change*" [4]. Meanwhile, the UN Sustainable Development Goal (SDG) 7 is set to ensure access to affordable, reliable, sustainable, and modern clean energy for all by 2030. However, the conditions are divesting in developing countries because of increasing demand, overwhelming population growth and intermitting supply. Developing countries are relying on interim sources of power generation like thermal power plants to meet energy requirements which have the potential to endure environmental degradation, air pollution resulting climate change, human ill-health, environmental conflicts and threatened environmental and human security.

The triad of energy-environment-human security nexus have a complex relationship in developing countries as mega projects for energy generation including dams or power plants require land, which is usually acquired from communities. Communities are not only inhabiting that land but also dependent for livelihood on that land for subsistence (food, fuel, and livestock). At the same time, the land may be a habitat for many species in that ecosystem. The distinct topography and landscape also contribute to supporting ecosystems and biodiversity. However, land requirement, clearance and use for construction of power generation projects need resettlement of communities, impact on livelihood, topographic and landscape changes and disturbed biodiversity. Dislocation and resettlement of communities surrounding the projects have potential to threat human security by social disruption, conflicts, pressure on urban areas, changing means and ways of livelihood, management of livestock, exploitation of natural resources for income and shift in ways to availability and access to food, fuel, education and health. Such conditions may be worse in developing countries because of thick population density and dependence of communities on agriculture and livestock for livelihood. In developing countries like Pakistan, governments or investors usually pay the price of land on acquisition and rarely consider resettlement and subsistence to some extend. But overall dimensions of human security are rarely considered or consulted with communities. Similarly, the land use for construction of energy projects has eminent threats to environmental security. The removal of top soil may cause soil erosion, dust, contamination of soil, loss of nutrients, removal of vegetation cover decreases the ability of carbon sequestration and migration of wildlife species. These energy generation systems require water, materials, chemicals, whereas, machine operations and vehicular transportation during construction phase cause dust, exposure to chemicals, noise, waste and air pollution. Meanwhile, the energy projects may also affect nearby protected forests, national parks, archeological site or environmentally sensitive areas.

Alike construction phase, energy security has a genuine relationship with human and environmental security during the operation phase of the energy project. The human security might be adversely affected by air pollution, noise, poor standards of occupational safety and health as well as occupational accidents. The air pollution from the thermal power plants and noise from the hydropower and wind project can lead to public health issues. Contemporary, the functioning of energy projects have a positive impact on human security. They create employment opportunities for the local communities which improve the income, meliorate livelihood of people, and reduce the poverty. The energy projects are usually planned in remote areas in developing countries like Pakistan which have poor road infrastructure and accessibility. The commencement of energy projects improves the road infrastructure, build schools and health units. They enhance the accessibility to urban markets. Some energy companies are providing education, health facility, skill development training and opportunities for women empowerment under their corporate social responsibility e.g. Engro Energy Pakistan (a subsidiary Engro Corporation Pakistan). Engro Energy Pakistan in collaboration with the Engro Foundation has established 26 schools in Sindh where more than 1300 out of school children were accommodated to peruse education. They have established a clinic at Daharki, trained 7690 farmers in better livestock management and developed the skills in hundreds of women to improve livelihood [5].

The operation of energy systems has significant impacts on environmental security. The functioning of energy systems may affect the land through fossil fuel exploration, material extraction, transportation, processing, refining, manufacturing, use, waste, and disposal. At the same time, energy generation from thermal power plants is releasing greenhouse gases, toxic air contaminants, and particulate matter. Air pollution from energy generation leads to serious public health concerns. The public health concerns include respiratory inflammation, chronic respiratory infection particularly in children, lung cancer, bronchitis, heart diseases, asthma, adverse health effects on the fetus, reduced life expectancy, and premature mortality. Air pollution can also cause acid rain, damage to buildings and degradation to biodiversity. Moreover, greenhouse gases are contributing to global warming and climate change which are enduring illustrious threats to environmental and human security. The developing counties are facing massive floods, frequent droughts, abrupt rains, an outbreak of infectious diseases, flash flooding, sea-level rise, and glacier melting due to climate change. It has divesting impacts on agriculture, food security, livestock, tourism, livelihood, infrastructure, water security, and economic development. Besides air pollution, energy generation requires water for both hydropower and thermal power (heating and cooling system). Therefore, energy security has a distinct relationship with water security which may affect or affected by the availability, access, and use of water. The mega-dam projects increase the water logging in the surrounding areas and affect the agriculture, livestock, and livelihood of the communities. The energy generation from hydropower, thermal and wind produce the noise which has direct or indirect effects on the communities. The noise has serious public health concerns from temporary hearing loss, poor concentration, stress, reverberation, loss of productivity, sleeping issues, fatigue, cardiovascular diseases, tinnitus, to permanent hearing loss. While, it has also significant impacts on the environment including the loss of biodiversity, migration of birds and wildlife species, behavioral changes in birds and land animal species, and causes the loss of communication among the birds and animal species. The noise from geothermal energy and offshore exploration of oil and gas has posed adverse effects to marine species. These adverse effects include problems in communication, stress, confusion, hearing problems, difficulties in the detection of acoustic information which may cause the problem in migration, hunting, food and detection of threats around them, and physical trauma. The marine species migrate in deep waters which may affect their reproduction and population.

Although, it is a mandatory obligations to conduct environmental assessments like Initial Environmental Examination (IEE) or Environmental Impact Assessment (EIA) or Strategic Environmental Assessment (SEA) before the commencement of energy projects by law in Pakistan and most of developing countries. These assessments must have to identify the issues caused by the pre-construction, construction and operation phases of energy projects which may endure adverse impacts on the environmental and human security as well as propose mitigation measures to reduce their adverse effects. Unfortunately, the proponents of the projects pretermit the environmental management and resettlement plans due to poor monitoring of the Environmental Protection Agencies (EPAs). Perhaps, the EPAs have low human resource capacity, financial constraints, lack of availability of technical resources, low institutional capacity, fragile governance, and weak legal framework which have considerably reduced their effectiveness of monitoring systems. Hence in the context of energy-environmental-human security nexus, there is a dire need to rationalize this nexus to ensure judicious informed decision making and policies to provide the affordable, reliable, sustainable, and modern clean energy for all, human and environmental security.

## 3 Current Energy Scenario of Pakistan and the Contribution of Renewables

Pakistan has distinct and immense energy resources. Pakistan has about proven 185 billion tons of coal, 19 trillion cubic feet of gas reserves since 2017, and 350,632 million barrels of oil reserves (Fig. 1). It has also monumental alternative and renewable energy (ARE) resources. According to the Government of Pakistan, it has ARE potential of about identified 45,000 MW from hydropower, estimated 346,000 MW from wind power (60,000–70,000 MW is technically exploitable), about 1000,000 MW from solar power (irradiation of more than 5–6 kWh/m$^2$/day in most areas of the country), 2,000 MW from geothermal energy, 4,000 MW from solid waste, annual 50 million tons biofuels from 34 million hectares marginal land, and 225,000 tons of crop biomass for bioenergy [6] (Fig. 2).

The Economic Survey of Pakistan 2019 had demonstrated that the energy requirements of Pakistan have been increased from 64.5 million tons of oil equivalent (MTOE) (2010–11) MTOE (2015–16) to more than 75 MTOE in 2019. The energy demand is increasing day by day due to the increasing population and change in lifestyle. It has been projected that the energy demand of Pakistan will be more than 131 MTOE by 2030 [7].

Pakistan has enhanced the electricity installed capacity to 34,282 MW in 2019 at the growth rate of 2.5% as compared to the previous fiscal year. According to the Economic Survey of Pakistan 2019, the contribution of different energy resources in electricity generation was hydropower (25.8%), thermal (62.1), nuclear (8.2), and

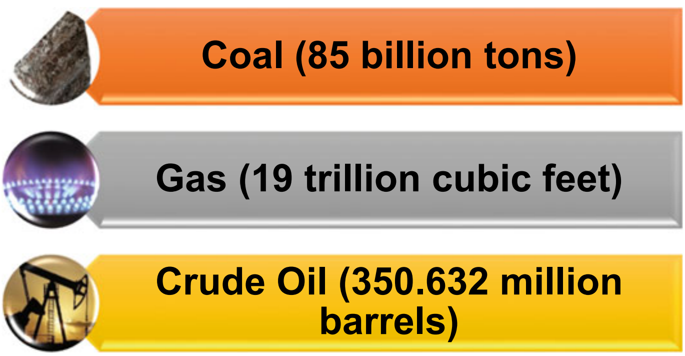


**Fig. 1** Non-renewable energy potential of Pakistan

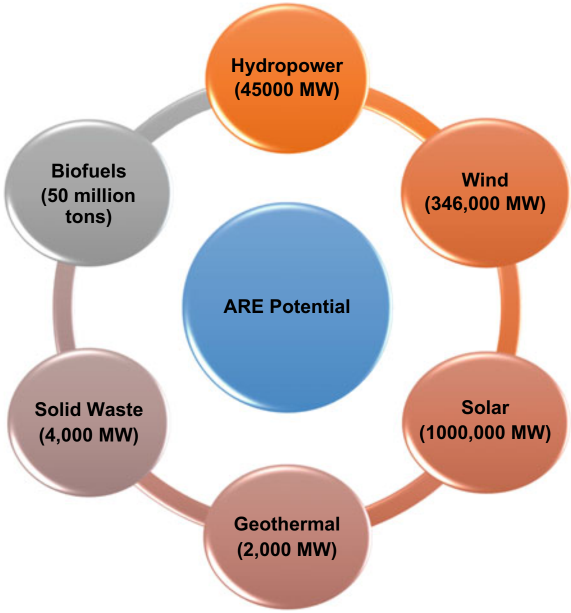


**Fig. 2** ARE potential in Pakistan

renewables (3.9%) in 2019. In the context of the primary energy mix, the oil has contributed 32.2% in 2018 as compared to 43.5% in 2001. The gas has contributed a 34.6% share (2018) in the overall energy mix as compared to 50.4% in 2006. The share of coal in the energy mix was increased to the highest of 12.7% (2018) in the history of the country. Similarly, the share of liquefied natural gas was recorded to 8.7% in 2018 with an increase of 0.7% as compared to share in 2015. A steady increase of 2.7% share (2018) of nuclear energy in overall energy has been observed as compared to a 0.2% share in 1997. However, the hydropower and renewables have contributed to the overall energy mix at the share of 8.1% and 1% respectively in 2019 [8] (Fig. 3).

## 4 Energy Generation and Environmental Security in Pakistan

It is evident from the recent data of the energy of Pakistan that energy security in the country has an established relationship with environmental security in assorted dimensions. The country is intemperately relying on thermal energy or fossil fuels to meet the energy requirement. The contribution of interim energy resources like coal has been increased in the overall energy mix of the country. According to the Private Power and Infrastructure Board (PPIB), 12 projects of power generation having the capacity of 11,000 MW are under construction currently. But the 9 projects of them

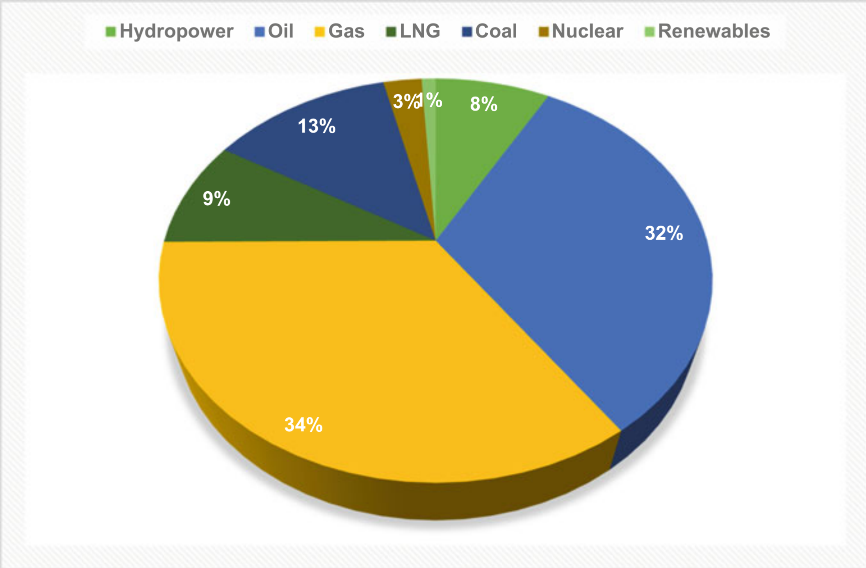


**Fig. 3** Overall energy mix of Pakistan in 2018–2019

having the generation capacity of 8,220 MW are coal-powered thermal plants while 3 projects are hydropower (2,714 MW). The PPIB plans both non-renewable and renewable mega independent power projects of more than 100 MW. It seems that the contribution of thermal energy generated by coal power will be increased in the primary energy mix in future years. The construction of coal power plants may threaten environmental security.

Alternative and renewable energy is contributing a 1% share in the overall primary energy mix. The government of Pakistan has set the target of a 5% alternative and renewable energy share in the primary energy mix by 2030. The Alternative Energy Development Board (AEDB) (deal with ARE projects of less than 100 MW) is focusing on alternative and renewable energy in collaboration with independent power producers to reduce the share of non-renewable energy in primary energy mix and combat with the adverse impacts of climate change. The AEDB has completed the 5 wind energy projects of 256 MW capacity and 1 solar power project (Quaid-e-Azam Solar Park) of 100 MW capacity. However, 8 wind projects and 3 solar power projects of energy generating capacity of 450.8 MW and 300 MW respectively are under construction across Pakistan. The AEDB has planned further planned 6 wind power projects of 300 MW capacity and 8 solar power projects of 345 MW across Pakistan.

According to International Union of Conservation for Nature and Natural Resources [9], the soil erosion, compaction, spills of chemicals, disposal of debris, terrain shaping, impacts on water quality, modification in drainage patterns, damage to vegetation of cover, air emissions, noise, and aesthetic disruption are significant environmental impacts from power plant's construction in Pakistan during pre-construction and construction phase. Alike, impact on terrestrial ecosystems including flora and fauna, habitat loss, wildfire, dislocation of species, disturbance of migratory corridors, changes in breeding area of wildlife, destruction of wetlands and plastics may reduce the number of species and habitats which eventually placed them in the list of endangered or extinct species and endure adverse impacts on environmental security. Additionally, there might be changes in archeological, cultural and socio-economic conditions. However, the operational phase of the energy projects has multifaceted risks to environmental security in Pakistan. The operation of power plants requires a dam for cooling which affect the communities due to the dam failure, and water quality. The cooling system requires water which is likely to affect the water availability and security of communities. The heat discharges from the cooling tower may alter the surrounding temperature, habitat, and biodiversity. At the same time, the use of on-site equipment (turbines, generators, cooling towers, fans or boilers) may generate noise and affect the terrestrial fauna (migration, breeding, spawning, calving areas, and nests). The transportation of coal or oil to power plants also contributes to greenhouse gas emissions. The coal washing and preparation contaminates the soil, releases dust from pulverizes, water pollution from waste residues and affects biodiversity. The solid waste generated by power plants and workers may attract pests or vector diseases, smell, aesthetic pollutions as well as impair water quality by leachate. The fuel and chemical may spill or leak during handling and storage which can contaminate soil and water. Although the construction of thermal power plants will generate employment opportunities for communities and positively affect their livelihood. There are also occupational safety and health concerns at thermal power plants in Pakistan. The burning of fossil fuels has the potential to contaminate soil from ash, sludge, and downwind deposition of air contaminants. The disposal of ash and sludge from combustion towers can cause water pollution. The exhaust and stack emission can deteriorate the air quality surrounding areas. The burning of fossil fuels has adverse impacts on public health and conduces to climate change. According to the World Air Quality Index 2019, the two cities (Lahore and Karachi) are among the polluted cities of the world. It has significant adverse health impacts on public health particularly children. The communities are suffering from respiratory, mental and cardiovascular diseases due to air pollution in Pakistan. The contaminated air may affect the pediatric and early childhood development among children in Pakistan. The urban centers of Pakistan are also suffering from the problem of smog in September and October every year from the last 3 three years. The smog increases the severity of health effects caused by air pollution. Furthermore, Pakistan is already among the most vulnerable counties to the impacts of climate change. The burning of fossil fuels may foster the phenomenon of climate change and environmental insecurity in Pakistan. However, the adverse environmental impacts from thermal power generation can be minimized or avoided by strong policy measures, planning, and environmental management. The PPIB has planned most of the thermal power plants in the remote areas of Sindh like Thar Desert and Baluchistan. Although, non-renewable energy has eminent environmental impacts but the government of

Pakistan has overcome the yawning energy crises, load shedding, and shortfall by utilizing these energy resources. The un-interrupted energy supply may have positive impacts on the growth of agriculture and industry particularly small and medium units which will ultimately improve the livelihood of people and inclusive economic growth. However, the appropriate practices for environmental management, rationale both non-renewable and renewable energy share in the primary energy mix adequate policy measures and good energy governance are still obligatory to ensure environmental security.

## 5 Renewable Energy and Environmental Security

Wind, solar and hydropower are the sources of renewable energy in Pakistan. Pakistan has added renewable energy in the national grid from solar and wind after 2015. However, Pakistan is generating the cheapest and clean energy from hydropower for the last six decades. But the recent Economic Survey of Pakistan has reported that hydropower contribution in electricity generation has been reduced from 70% in 1970, 37.8% in 2005–06 to 25.8% in 2018–19. Similarly, the share of hydropower has been decreased from about 14% (2006) to 8% (2019) in the overall primary energy mix. The thermal power has replaced the hydropower contribution which has threatened environmental security in Pakistan.

Renewable energy generation has both positive and negative impacts on environmental security in Pakistan. Although, the wind energy requires less land area per kilowatt-hour (kWh) energy generation than any other energy source and no water for cooling systems but it produces noise which may adversely affect the communities and bird biodiversity. The birds may be trapped into the moving and stationary blades of the wind turbine which may affect the distribution lines and crash into the tower. It can stress ecosystems by changing wind speed during large scale generation. These impacts can be avoided or minimized by planning wind projects in remote arrears and modern design. Pakistan has planned to install the wind turbines in remote and least populated coastal zones of Sindh and Baluchistan. Meanwhile, modern designs have significantly reduced the noise level and increased the protection of wind turbines. The modern, least noisy and protected wind turbines have insignificant impacts on communities, environment, and bird biodiversity.

The solar power projects require the land which maybe agriculture. The proposed solar projects in Pakistan are located in the Punjab which may affect the agricultural land. Besides agriculture, the construction of large scale solar power projects may affect topography, landscape, habitats, biodiversity, soil, air quality, vegetation cover, water quality, fragmentation in biodiversity, albedo, ecosystems, and agriculture. Similarly, the operational phase of solar power projects requires water for the cleaning of solar panels. The solar panels may have toxic materials used in their manufacturing. Meanwhile, the disposal of waste solar panels or modules is also a challenge and may affect the environmental conditions. Contemporary, solar power projects have benefits and positive environmental effects. The solar power projects utilize a low quantity of water which is only for the cleaning of solar panels. They did not emit greenhouse gases and mitigate climate change. The environmental impacts from land can be avoided by using degraded, barren or desert land and use the solar panels as a decentralized energy system. The decentralized solar energy provides the opportunity to electrify the remote areas of Sindh and Baluchistan where the electricity distribution and transmission line costs are very high due to nomadic lifestyle and scattered population. The AEDB has introduced the net metering policy for the individual decentralized consumer which will not only reduce the load on the national grid but an individual consumer can also avail financial benefits by selling extra energy to the government. At the same time, the AEDB has planned to electrify the 7,875 villages through decentralized solar energy in the remote areas of Sindh of Baluchistan. There are no transmission line losses in case of decentralized energy. Additionally, the utilization of solar energy has created many job opportunities and economic activities in Pakistan. Modern solar energy technologies have long life therefore solar power projects have a long life span and more payback as compared to coal power plants. Agriculture is considered as a backbone of the economy of Pakistan. The agriculture land is being irrigated by the thousands of diesel-driven tube wells in the rural areas of Pakistan which are among the largest consumers of diesel and releasing air emissions. The shifting of tube wells from diesel to solar energy has the potential to cut the use and import of diesel, economic benefits, and reduce air emissions. Hence, solar technologies may be preferable renewable energy sources by individual consumers and government in the future due to their distinct economic and environmental benefits.

Hydropower is the largest contributor to renewable energy in the primary energy mix of Pakistan. The utilization of hydropower also offers both positive and negative environmental impacts on Pakistan. The hydropower turbines are installed on the river flow or dams. There are numerous adverse environmental impacts from dam construction. The communities in the project area have to dislocation. The decrease in river flow or environmental flow to low riparian has been recorded particularly in dry seasons to maintain flow which is required to generate hydropower. The construction of the dam also results in the cutting of trees, biodiversity and habitat loss in the dam area, migration of species, air emissions from transportation of material and changes in area terrain. Meanwhile, the changes in the migratory patterns of river animal-like trout have also been observed due to the construction of dams. The dams limit the flow of land fertility-enhancing sediments in the dam area which results in silting of reservoirs, reduces their capacity and reduced the fertility of low riparian. It can affect the downstream temperature of the river, the humidity of the surrounding environment, waterlogging in the vicinity, and salt level of water. The dam may be a source vector disease because it provides an appropriate environment for the breeding and growth of mosquitos and snails. The large water reservoir can cause the fragmentation of the river ecosystem by restricting migration, changes in the breeding areas, flooding of wetlands, change food patterns, loss of local species, and habitat loss. The greenhouse gases may also be released from dams due to different environmental conditions of water columns, flooded soils, and eutrophication. There are also failure hazards due to poor construction, negative environmental impacts, terrorism, and induced seismicity. Furthermore, there are several issues and conflicts on water allocation, distribution, taxes, and royalty among provinces in Pakistan which is also a distinct barrier in the construction of new dams. Climate change has also affected water availability particularly in dry seasons which is fostering conflict among the provinces, enduring adverse impact on livelihood and leading to water scarcity and environmental insecurity.

Besides adverse impacts, the hydropower generation has diverse positive impacts on the environment, agriculture growth, agriculture expansion, livelihood improvement, poverty alleviation, and economic development in the context of Pakistan. Pakistan has generated clean energy from hydropower at the lowest price for decades. The cost will be further reduced if it will be produced from large dams which are the most practical and environment-friendly solution to energy crises. It has contributed as a major energy source for many decades. The government of Pakistan has procured the sustainable, clean and affordable energy transactions through hydropower. It has neither contributed to greenhouse gas emissions nor in the climate change but fosters environmental security. Meanwhile, Pakistan has built large water reservoirs or dams like the Mangla and Tarbela dam for the installation of hydropower turbines and generation of energy. The dams are supporting the largest canal system of Pakistan, agriculture and terrestrial ecosystem of Indus of the valley. They are contributing to sustaining livelihood support systems of communities, gross domestic products (GDP) and economic development of Pakistan. At the same time, per capita availability of water is drastically decreasing in Pakistan which has endangered the water and environmental security in Pakistan. The large water reservoirs are attuning the floods in rainy seasons, providing the water in dry seasons and contributing to ensuring water security. The ecosystem or environmental services include food, water, shelter, herbal medicines, biodiversity, living environment, soil for agriculture, recreation, aesthetic value, water purification waste management, pollination, pest control, and climatic regulation, etc. Pakistan has faced hottest May recently and heatwaves in many parts of the country due to variations in climatic regulations particularly relative humidity. The relative is directly associated with the evaporation of water. The water reservoirs and surface water have a core role in the evaporation potential, eventually in sustaining the relative humidity, water cycle, and rain. The government of Pakistan has planned to reduce the social and environmental impacts from hydropower and dam by adopting integrated water and environmental resource management. The seldom disputes between communities and government have been observed in recent mega hydropower projects e.g. Diamir Bhasha Dam and Karur Hydropower projects due to adequate consultation with communities, consideration of their views and resettlement plans. Furthermore, the construction of decentralized independent small hydropower units on runoff of streams has been increased in Northern Areas and mountainous Khyber Pakhtunkhwa. The small hydropower units neither require large land areas, dislocation of people, and infrastructure nor restrict the water flow. They have very low adverse impacts on the environment and ecosystems. However, there are numerous further requirements including comprehensive policy for hydropower generation, diverse resettlement policy, modern design, consideration of corridors for migration of aquatic species, getter governance in dam management, transparency in cost–benefit (economic, social, environmental, technical and technical), use of innovative modern technologies, optimization of operational phase, silt management, resilience against climate change, adequate institutional capacity and good governance standards to transform future hydropower generation into sustainable and eco-friendly energy for Pakistan.

## 6 Energy-Climate Change and Environmental Security Paradigm for Pakistan

Energy security, climate change, and environmental security have an established paradigm for Pakistan. Climate change has shaped a complex multivariate and diverse paradigm in terms of energy security, regional geopolitical rift, affordability of consumer, energy access for all, energy requirement, ecological impacts, environmental justice and environmental security (Fig. 4). According to Germanwatch Report 2020, Pakistan is 5th most vulnerable country to the impacts of climate change in the Global Climate Change Risk Index. It has eminent threats to environmental and energy security in Pakistan. The recent climate data of Pakistan have demonstrated that the 0.6 °C increase in average temperature has been recorded as compared to the increase in the global average temperature [10]. Additionally, climate change has induced about 150 freak weather incidents including flash floods, glacier melting in the Hindu Kush-Himalaya region, smog, forest fires in summer, landslides, heatwaves, dislocation of people, and severs droughts like a drought in Thar Desert in the last two decades.

Environmental security in Pakistan is at significant risk due to climate change-induced adverse impacts on water availability and ecosystems. The variability in snowfall patterns may reduce the permafrost of the Hindu Kush-Himalaya region and flash floods as the weather turns to hot which will drastically affect the ecosystems and cause biodiversity loss. Similarly, the changes in rainfall patterns have radically affected the recharging of groundwater in Pakistan and water availability. A substantial decrease in water availability per capita, temperature rise, and more frequent and massive floods have observed in recent years which have challenged environmental security in terms habitat loss, damage to agriculture, biodiversity loss, reduction in the food availability, decrease in water availability, adverse impacts on livelihood of communities, infrastructure damage, catastrophe to archeological sites and national parks, destruction of energy system, endemic morbidity and mortality, sea-level rise, loss coastal reefs, marine biodiversity loss, human causalities, and economic loss. According to the Germanwatch report, Pakistan has suffered 3.8 billion dollars economic loss, and 9,989 human deaths due to the 152 extreme weather events during 1998–2018. Additionally, climate change may cause social and environmental injustice through the unequal distribution of natural resources, social inequality, instability, conflict among the communities, and climate change-induced migration.

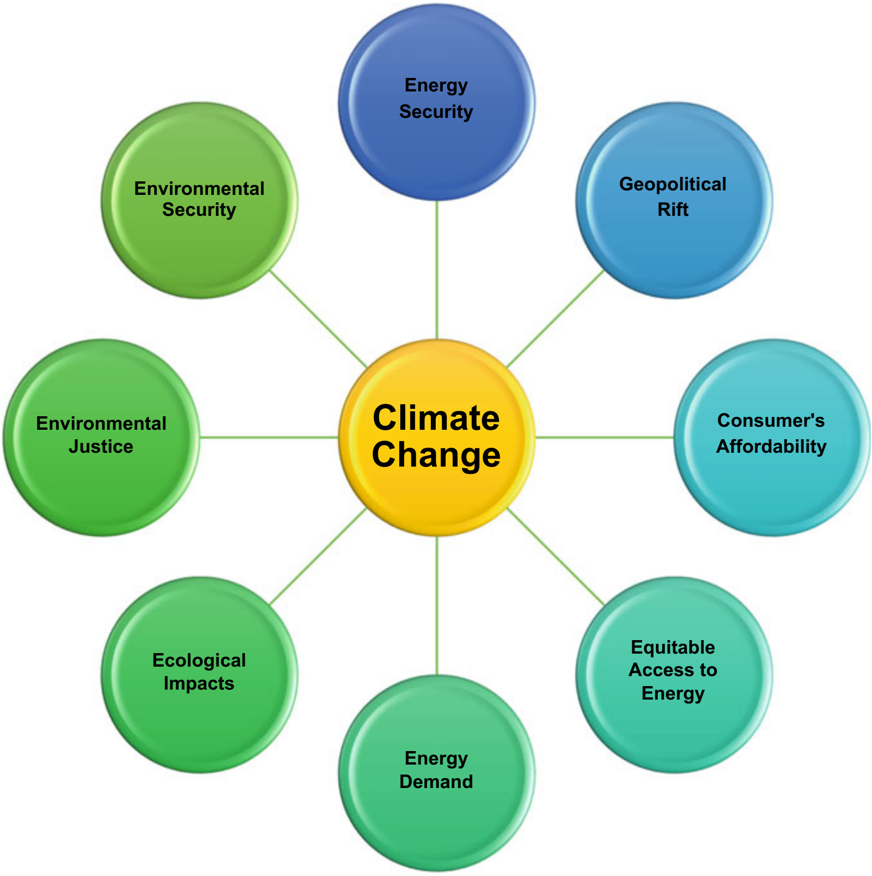


**Fig. 4** Energy-climate change and environmental security paradigm for Pakistan

Pakistan is depending on the Transboundary Rivers for water and generation of energy. The country has continuous conflicts on water distribution with neighboring countries particularly India besides geopolitical rift. Climate change has the potential to affect the Hindu Kush-Himalaya glaciers and water availability in the region. It may not only lead the region to water scarcity and insecurity but also volatilizes the geopolitical rift between India and Pakistan which may agitate regional and environmental insecurity.

In the current energy security-climate change-environmental security paradigm, climate change may reshape energy security discourse in Pakistan. The temperature rise, abrupt rains and climatic variation in Pakistan may affect the efficiency of future renewable energy like solar energy by affecting the irradiation. The abrupt rains and floods may also damage the transmission and infrastructure of solar power projects. Similarly, the wind turbines and transmission lines are also at the risk of impacts of change such as frequent storms, temperature rise, abrupt rains, and floods. The conventional energy systems of Pakistan like hydropower, nuclear, and thermal require the water for cooling or hydropower generation. Climate change is affecting water availability and security through changes in rain patterns, extreme weather events, variability in recharging of groundwater, glacier melting, and adverse impacts on permafrost. The water availability in Pakistan is decreasing due to the huge population, over-abstraction, inefficient use of water, the use of less water and energy-efficient technologies, and climate change. Pakistan is geographically located in the region which is the most vulnerable climate change which is supporting the phenomenon of the water-stressed country to water-scarce country. Therefore, the energy generation is at a noteworthy risk due to climate change in Pakistan. Climate change is threatening energy access, affordability and demand in the context of Pakistan. A decrease in energy generation will increase the demand and supply gap which will lead to the energy shortfall. According to the Economic Survey of Pakistan 2019, the major reason for the decline in hydropower share in electricity generation and the primary energy mix is the decrease in water availability in Pakistan. The government will introduce the load shedding and energy supply management strategy in which some consumer is preferred on others which affects the equitable access to energy for all. Pakistan has preferred the commercial urban centers and industries over the domestic consumers to sustain GDP in recent energy shortfall from 2005 to 2016. Meanwhile, the governments rely on costly, interim and non-renewable energy sources to overcome shortfall which affects the affordability and environmental security. Pakistan has relied upon thermal power generation from oil and coal to overcome the shortfall. It has not only increased the share of thermal energy in the primary energy mix but also enhances both generation and overall energy cost in Pakistan.

Alike generation, climate change endure adverse impacts on the energy infrastructure and distribution in Pakistan. The electricity is distributed across Pakistan through a centralized national energy grid. The national grid comprises of the overhead tower located across Pakistan. The extreme weather events including thunderstorms, abrupt rain, and floods can damage the national grid and interrupt the power supply which can affect the access of consumers to energy. Furthermore, the dams or hydropower turbines are situated on the river runoff and the flash floods can damage or fail the infrastructure of dams or hydropower turbines. The dam failure has divesting impact on ecosystems, agriculture, infrastructure, industries, livelihood, communities, transmission lines, and environmental security due to the massive flood. The Shadi Kaur Dam (Baluchistan) failure had killed more than 100 people and washed away many villages in 2005. Similarly, many thermal power projects in Pakistan are located in the areas which may affect from the floods. The operation of some projects may remain close and face infrastructure damage during the flood. Hence, the damage to infrastructure and interruption in supply may affect the access, demand, payback time of projects, operational cost, affordability of consumers, energy and environmental security in Pakistan.

Overall, Pakistan has limited capacity and financial resources. Therefore, it should have the water-smart energy systems, energy-smart water system, adequate design of power projects, and implementation of Climate Change Policy of Pakistan and framework, climate change resilient infrastructure of power projects, utilization of renewable energy, human capacity building, stakeholder engagement, decarbonization of economy, enhance energy efficiency, and diversify energy sources to secure energy and environment in the context of climate change.

## 7 Energy and Environmental Security of Pakistan in the Context of SDGs

The United Nations has introduced the 2030 Agenda for Sustainable Development in 2015 and adopted by member states. It comprises 17 goals and commonly known as Sustainable Development Goals (SDGs). The SDGs offer a shared global framework and policy guidelines for the prosperity of people, peace and sustainable future of the planet. The SDGs require urgent actions by the all member states in global partnership to alleviate poverty and hunger, reduce inequalities, decent economic growth, providing good standards of health and education, access to clean energy for all, access to clean water and sanitation, innovative industrial growth, sustainable consumption, mitigation of climate change, marine and land biodiversity conservation, and peace. Pakistan has not only signed and ratified the SDGs but adopted them as national development goals in the Pakistan Vision 2025 [11]. It is a detailed policy document which visualized an aspiration destination to development, future strategies, planning, reforms, and national goals. Pakistan is attempting to meet its global commitment and the targets of SDGs.

In the context of the energy and environmental security of Pakistan, a strong partnership is required among SDGs to achieve their targets (Table 1). The SDG 6 (Clean water and sanitation), SDG 7 (Access to clean and affordable modern energy for all), SDG 8 (Decent work and economic growth), SDG 9 (Innovation in industry and infrastructure), SDG 11 (Sustainable cities and communities), SDG 12 (Responsible consumption and production), SDG 13 (Actions on climate change), SDG 14 (Life below water), SDG 15 (Life on land), and SDG 16 (Peace, justice and strong institutions) are directly related to energy and environmental security nexus, coalesce, and necessitate understanding and partners to ensure energy and environmental security.

Pakistan is heading towards a water-scarce country from the water-stressed country due to a consistent per capita decrease in water availability due to inefficient use, poor management, transboundary conflicts, and climate change. Meanwhile, water pollution is also increasing which is decreasing the quality of water. The decrease in water availability has adversely affected both energy and environmental security. Therefore, vibrant policy, judicious legal framework, strong institutions, integrated water resource management, water cooperation on Transboundary Rivers, community engagement, efficient use, and water-smart technologies are urgent measures required to meet the targets of SDG 6.

**Table 1** SDGs and their target related to energy and environmental security

| SDG | Target related to energy and environmental security |
|---|---|
| Clean water and sanitation (SDG 6) | • Reduce water pollution and improve quality<br>• Enhance water use efficiency among all consumers<br>• Improve water availability to reduce scarcity<br>• Adopt integrated water resource management<br>• Improve water cooperation on transboundary rivers<br>• Engage the local communities |
| Access to clean and affordable modern energy for all (SDG 7) | • Ensure access to clean and affordable modern energy for all<br>• Improve the share of renewable energy<br>• Improve the energy efficiency at double rate<br>• Support the developing countries in renewable energy production and research<br>• Invest in energy-efficient infrastructure and technology |
| Decent work and economic growth (SDG 8) | • Diversify technology and innovation to achieve a higher level of economic growth<br>• Improve global resource efficiency (energy and environment) in both consumption and production |
| Innovation in industry and infrastructure (SDG 9) | • Develop quality, climate change resilient, and sustainable infrastructure<br>• Reduce carbon dioxide per unit of value-added<br>• Improve resource efficiency (energy and environment)<br>• Use sustainable, clean, efficient and environmentally sound technology |
| Reduce Inequalities (SDG 10) | • Reduce all types of inequalities and inclusion of all without any discrimination<br>• Ensure the representation of all stakeholder in decision-making |
| Sustainable cities and communities (SDG 11) | • Provide access to affordable, safe and sustainable transport<br>• Improve inclusive and sustainable urbanization<br>• Minimize per capita adverse environmental impacts of cities<br>• Integrate social, economic and environmental benefits<br>Enhance resource efficiency, energy efficiency to mitigate climate change and disasters |

(continued)

**Table 1** (continued)

| SDG | Target related to energy and environmental security |
|---|---|
| Responsible consumption and production (SDG 12) | • Implement road map sustainable production and consumption<br>• Improve the management and efficient use of natural resources<br>• Achieve sound and sustainable environmental management<br>• Reduce and manage the waste<br>• Support the lifestyle compatible with sustainable development and nature<br>• Cut fossil fuels to reduce environmental impacts<br>• Improve energy efficiency, and use of renewable energy |
| Actions on climate change (SDG 13) | • Strengthen adaptive capacity and resilience against climate change<br>• Improve awareness, the capacity of institutions, and integration of climate change in national policies<br>• Provide financial support to developing countries |
| Life below water (SDG 14) | • Prevent and reduce marine pollution<br>• Protection and sustainable management of coastal and marine ecosystems<br>• Regulate overfishing and illegal destruction of marine biodiversity<br>• Improve research, conservation, and sustainable use of oceans |
| Life on land (SDG 15) | • Ensure restoration, conservation, sustainable use, and management of land and mountain ecosystems<br>• Restore the degraded land and combat desertification<br>• Act to reduce habitat loss and extinction of biodiversity urgently<br>• Stop the trafficking and illegal trade of flora and fauna<br>• Take actions to prevent the impacts of invasive alien species<br>• Integrate the value of biodiversity with national strategies |
| Peace, justice and strong institutions (SDG 16) | • Develop the transparency and equal representation of all stakeholders at all levels and decision-making<br>• Promote non-discriminatory laws |
| Partnership for the goals (SDG 17) | • Strengthen and develop a partnership for finance, technology, trade, capacity building and systematic issues to achieve SDGs |

According to Pakistan's Implementation of the 2030 Agenda for Sustainable Development Report 2019, the country has improved 8% points access to electricity in the last ten years and 3.9% ARE in the primary energy mix from 2015–19 [12]. Currently, the country is about 93% electrified without any discrimination and relying on non-renewable energy while the contribution is 11% in the total final energy consumption. The prices of electricity and fuels are also increasing. The government has planned to electrify less populated remote areas, schools and public sector buildings with decentralized solar energy. The AEDB is working on the development of domestic ARE technologies. Meanwhile, the National Energy Conservation Authority (NECA) of Pakistan is working on energy efficiency in collaboration with the United Nations but its improvement pace is too draggy. The NECA has replaced the tube lights and energy savers with energy-efficient light-emitting-diode (LED) bulbs in the local market. The NECA has assisted the local fan and air conditioner industry and significantly improved the energy efficiency of fans and air conditioners after a change in design and technology. Despite numerous efforts, Pakistan is still dependent on the non-renewable sources energy sources, lacking renewable energy, bear inefficient use, line losses, energy-inefficient infrastructure, and technologies which hampers evident threats to meet the targets of SDG 7, pillar 4 (Water, energy and food security) of the Pakistan Vision 2025, energy, and environmental security.

The pillar 2 (Achieving sustained, indigenous, and inclusive growth) of Pakistan Vision 2025, SDG 8, and SDG 12 have emphasized on decent economic growth, modern industrializing, sustainable consumption, and production through innovation, diversifying technology, recourse efficiency, and quality and climate change resilient infrastructure to ensure climate change mitigation, energy and environmental security in Pakistan. The economic growth of Pakistan is recorded to be steady in recent years. The most prominent contributors in economic growth were agriculture and manufacturing but both are using non-renewable energy, energy inefficient and traditional technologies. The diesel-driven tube well engine, tractors, and harvesters are being used in the agriculture sector. Similarly, the manufacturing sector is also using traditional and resource inefficient technologies that consume extra raw material and energy and deliver low production at high product cost, pollution, and extra waste. Meanwhile, unskilled labor, traditional working procedures, inadequate practices, and inefficient process worsens the condition. The waste is also promptly increasing due to a huge population and poor management. Meanwhile, the lifestyle of Pakistani people is also energy inefficient, consumes extra resources, and less compatible with the modern norms of environmental sustainability. Besides lifestyle, Pakistan is wretched in cutting fossil fuels. The contribution of fossil fuels is increasing in the primary energy mix. Perhaps, Pakistan has been dispensed low points in SDG 8 and 12 in 2019 due to these reasons. The current scenario, practices, and inefficient use of resources in leading contributors to GDP are lagging behind the targets of SDG 8 and 12 and threatening energy and environmental security.

The SDG 9 (Innovation in industry and infrastructure), SDG 11 (Sustainable cities and communities), and pillar 3 (Modernizing transportation, infrastructure, and greater region connectivity) of Pakistan Vision 2025 have focused on sustainable infrastructure (quality, and climate change resilient), low carbon dioxide, resource efficiency, eco-friendly urbanization, sustainable transport and use of sustainable, clean, efficient and environmentally sound technology to ensure and environmental security. Although, Pakistan has improved the infrastructure, building design, and included energy efficiency in building codes of Pakistan. But rapid urbanization, horizontal housing and individual construction without prior design are overlooking building codes and parameters for energy efficiency. The horizontal housing requires more land, destruct biodiversity, extra resources, adversely affect food security and energy as compared to vertical construction. Pakistan has significantly improved the transport infrastructure and introduces mass transit projects. However, the transport sector is among the largest consumer of fossil fuels (Compressed Natural Gas, petrol, and diesel) in Pakistan which is releasing greenhouse gases. The hybrid cars are also getting popularity and increasing in Pakistan. The government of Pakistan has recently introduced the electric vehicle policy and intended to cut fossil fuel to improve energy and environmental security.

Pakistan has established climate change governance and integrate the climate change in national policies to meet the targets of SDG 13. However, the country is still striving to develop adaptive capacity and resilience against climate change. The energy sector is the most leading contributor to greenhouse emissions (51%) and followed by agriculture and livestock (39%). Pakistan has planned and started the renewable projects to cut fossil fuels and mitigate climate change. Pakistan is encountering the glacial outburst floods (GLOF) by 37 million dollars funding under Green Climate Fund. The SDG 14 (Life below water) accentuated the prevention of marine pollution, protection, conservation, regulate the fishing, prevent the illegal biodiversity loss, sustainable use, and management of coastal and marine ecosystems. But the marine and coast biodiversity are at the risk of loss due to marine pollution, and industrial and commercial activities in the coastal areas of Pakistan. The SDG 15 (Life on land) marked reduction in habitat loss, prevent extinction, restore degraded land, combat desertification, stop illegal trade of biodiversity, prevent the impacts of invasive alien species, and restoration, conservation, sustainable use, and management of land and mountain ecosystems as the distinct targets. Pakistan has faced a 2.1% increase in deforestation from 2001–2005. However, the Billion Tree Tsunami Project has been completed on 350,000 hectors of land in 2014 to restore the depleted forests. A large number of trees and shrubs are still used as fuel to meet the energy requirement in rural and mountainous areas of Pakistan due to interruption in electricity and gas supply in winter. The development of energy projects may also affect terrestrial ecosystems.

Overall, transparency, justice, representation of all stakeholders in decision-making, and strong institution capacity (SDG16) through productive partnerships for finance, technology, trade, capacity building, and systematic issues are cardinal for mechanisms to achieve SDGs in the context of energy and environmental security of Pakistan.

# 8 Conclusion and Policy Implications to Ensure Energy and Environmental Security in Pakistan

Energy security has an intrinsic link with human and environmental security in Pakistan due to an established relationship of energy generation and distribution systems with global governance, economic development, affordability, equitable sustainable energy transitions, environmental protection, environmental politics, water security, air pollution, climate change, conflicts, and environmental migrations. The energy policy discourse and decision-making are being perplexed by environmental security and climate change in the recent era. More informed and sensible decision-making is indispensable to ensure sustainable energy transitions, energy security, and environmental sustainability. Access to energy is conceived as a fundamental human right worldwide and the core priority of every government for economic development. Meanwhile, energy sector decisions are crucial for economic development, environmental sustainability, and decision-making of other sectors like industry, production, mining, and residential. It determines the discourse of the economic growth of every country. The informed and sensible decision-making for energy security should reflect practical knowledge, indigenous needs, future expectations, and clear vision. Pakistan is still struggling to meet the unremitting energy demand and ensure energy security. The country anticipates clear energy vision and sensible decision-making to rational energy and environmental security nexus. The vibrant policy implications (Fig. 5) can unriddle the complexity of decision-making for energy security in the context of the environmental security of Pakistan.

## *8.1 Good Energy Governance*

Good energy governance comprises vibrant energy policies, a legal framework (regulating the energy sources, prices, efficiency, infrastructure, climate change, and environmental aspects), strong institutions, and all stakeholder representation and engagement in the decision-making process. Energy policy should be judicious and coherent with indigenous needs, stakeholder expectations, clear vision, policy objectives, energy demands, climate change, agriculture, development, external relations, and environment. Pakistan has established and implemented the ARE Policy 2011, National Power Policy 2013, and Power Generation Policy 2015. Hassan et al. (2019) critically analyzed the energy policies in Pakistan in terms of technical, economic, social and environmental aspects [13]. The study identified that several gaps in ARE Policy including low compatibility with industrial growth, disregard environmental aspects (land use and water security), neglect the integration of ARE technologies, pretermit domestic manufacturing of ARE technologies, omit biofuel portfolio standards, and high interconnection cost. It was observed that the National Power Policy 2013 was lacking the projection of future energy demand, compatibility with industrial growth, employment opportunities, and environmental aspects (Greenhouse gas

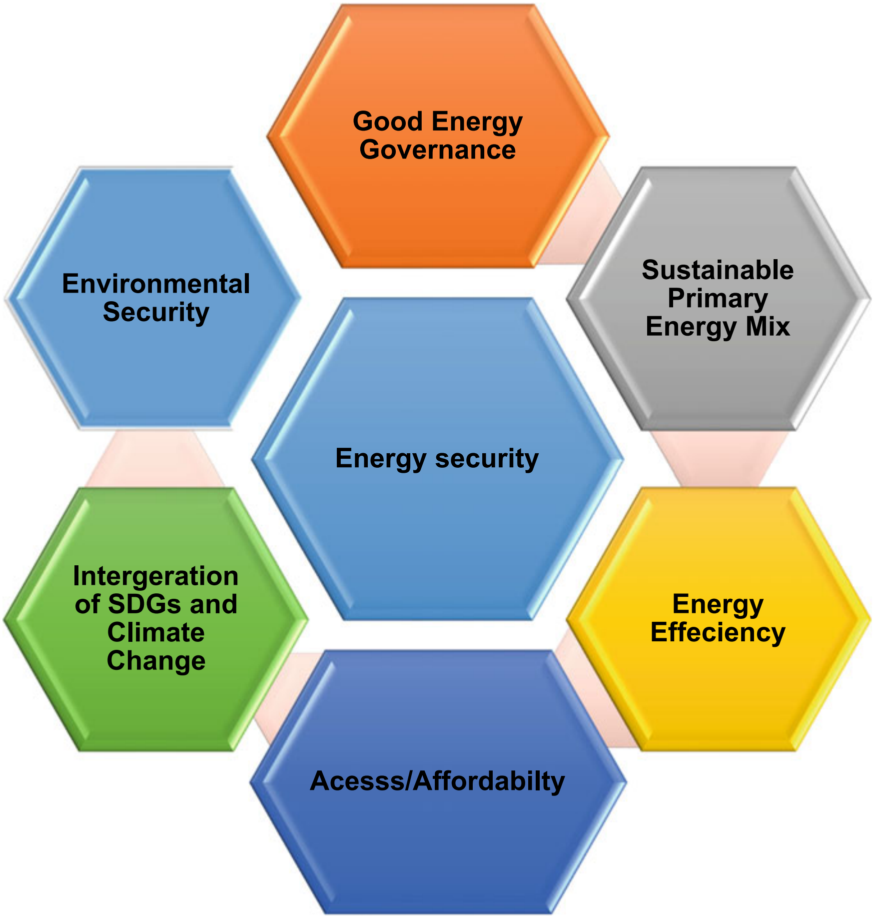


**Fig. 5** Policy implications to ensure energy and environmental security in Pakistan

emissions, noise, land use, climate change, and water security). Power Generation Policy 2015 has also snubbed the future energy demand, energy potential, fuel cost, compatibility with industrial growth, and environmental aspects (Greenhouse gas emissions, noise, land use, climate change, and water security). The government of Pakistan should revisit energy policies to ensure energy and environmental security. Although, Pakistan has established a legal and institutional framework in the energy sector. There is a need to implement laws, provide resources, ensure transparency, remove system errors, and mobilize the institutions. However, the stakeholder representation and engagement in the decision-making process is still least considered in Pakistan. There is an urgent need to enhance stakeholder representation and engagement in the decision-making process through participatory approach mechanisms.

### 8.2 Sustainable Primary Energy Mix

Pakistan is still relying on non-renewable sources for energy generation. The government should identify the exact potential of renewable energy in Pakistan and indigenous needs. It should devise a comprehensive strategy to phase out energy-inefficient technologies, optimum utilization of renewable energy, cut the use of fossil fuels, and balance the energy mix to ensure sustainable energy production, energy, and environmental security.

### 8.3 Energy Efficiency

The national energy policies in Pakistan reflected energy efficiency in terms of transparency, tariff efficiency, fuel allocation, merit in contracts, optimization of line losses, and procurement of clean efficient ARE technologies. Pakistan has successfully reduced the line loss due to maintenance and replacement of the national grid but it has least prioritized the procurement of clean efficient ARE technologies. Energy efficiency can improve the efficient use of natural resources, and reduce the energy cost. Pakistan has upgraded the electric appliances, introduces LED lights, provide custom duty relaxation on the import of ARE technologies, offered soft loans for ARE, and implemented the Pakistan Energy Conservation and Efficiency Act 2015. However, it should restructure the thermal power plants, upgrade existing energy infrastructure, diversify energy recourses, introduce energy-efficient technologies, develop minimum standards for energy generation, explore renewable and competitive energy market, identify low carbon energy generation methods, subsidize ARE technologies, balance energy mix, improve fuel efficiency, manage energy demand and regulate the people behavior and practices to achieve optimum energy efficiency and environmental security.

### 8.4 Equitable Access to Affordable Energy

The government of Pakistan considers equitable access to affordable energy for all as a basic human right. Pakistan is about 93% electrified and attempting to ensure equitable access to energy. Pakistan has also introduced a net metering policy to promote centralized solar energy and environmental sustainability. Furthermore, Pakistan has planned to electrify the remaining 7% through decentralized ARE. However, the uninterrupted supply and price are the major concerns of the consumers. The electricity supply interruption increases in summer due to the increase in demand. Meanwhile, both electricity and fuel prices are also increasing in Pakistan due to oil price volatility and dependence on thermal energy. The energy prices affect the socio-economic benefits of energy and the hardships of low-income families. Pakistan can reduce the price of energy through efficient use, exploration of indigenous resources, increasing the share renewable energy particularly hydropower, use of modern clean and energy-efficient technologies, decentralization of energy supply in remote areas, developing domestic ARE technologies, capacity building, regional energy trade, sustainable infrastructure, energy conservation, demand–supply management and increasing the role of community in energy efficiency and conservation.

## *8.5 Integration of SDGs and Climate Change with Energy Policies and Generation*

The energy generation and security may be affected by climate change in Pakistan. The energy sector should meet the requirement of economic, social, environmental sustainability. It should be efficient, low carbon releasing, and not contribute to the global warming. The climate change should be addressed in goals and integrated with energy policy. Although, Pakistan has an established climate change governance but it is addressed only in ARE policy. Meanwhile, the energy sector of Pakistan is relying on non-renewable sources. Therefore, it is urgent to mediate climate change in energy policies, balance energy mix, cut fossil fuels, utilize indigenous renewable energy resources, foster energy efficiency, and establish effective climate change governance to combat the adverse impacts of climate change. The energy policies in Pakistan were implemented before the SDGs but Pakistan has adopted them as national development goals. But the SDGs should be integrated with energy policies and development of the energy sector in Pakistan.

## *8.6 Environmental Security*

The energy policies in Pakistan have least considered the environmental aspects like land use, emissions, biodiversity, noise, water security, and climate change but Pakistan has established environmental governance to regulate pollution and conduct environmental assessments to assess environmental impacts of projects before commencement. There is a need to comply with the environmental policy, acts, and regulations during the commencement of energy projects and energy generation, reduce greenhouse gas emissions, use of clean technologies, integrate energy governance with environmental governance, and cooperate on transboundary natural resources to ensure environmental security.

### 8.7 Awareness and Education

The education and awareness are requisite to individual behavior and lifestyle changes to reduce carbon emissions, efficiently use energy, foster sustainable consumption, and wise use of natural resources to ensure energy and environmental security in Pakistan. The government should raise awareness of the consequences of energy and environmental insecurity, include them in the school curriculum, educate the children, and regulate public behavior with effective legislation.

### 8.8 Research and Development

The research and development are critical to reduce the price of energy, upgrade existing systems, and provide solutions to the future energy problems of Pakistan. Pakistan has experienced low investment in research and development in energy sectors and still imported both non-renewable and renewable technologies. The government of Pakistan should invest on research and development in energy sector to create new knowledge, manage the data (Outlooks, and reports), understand the problems, project future energy demand, set the goals, project the required resources, manage demand–supply, upgrade existing technologies, develop domestic ARE technologies, achieve sustainable consumption and production, informed decision-making, and futuristic planning to ensure energy and environmental security.

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# Sustainable Energy Infrastructure Planning Framework: Transition to a Sustainable Electricity Generation System in Bangladesh

**Imran Khan**

**Abstract** Globally, governments are planning for a sustainable energy infrastructure to deal with negative climate change and to ensure a low-carbon future. In the developed world, energy generation expansion plans are designed so that the infrastructure can be adaptable to new technologies, reliable, affordable, and sustainable. In contrast, the developing world is trying to keep up with their anticipated levels of GDP growth, and to accommodate these needs energy has the utmost priority. Consequently, these nations are planning for long- and short-term energy generation infrastructures. Most often, these future generation expansion plans are not effective from a sustainable point of view, as they do not explicitly consider the existing resources. This is due to the absence of an appropriate sustainable energy infrastructure planning framework (SEIPF). There are thus two objectives of this chapter: first, to propose an SEIPF and second, to apply this SEIPF to an assessment of the future power generation expansion plan of Bangladesh as a case study. This proposed framework would be suitable to (i) assess and minimize the overall costs along with cascading impact mitigation, (ii) identify environmentally sound technologies, (iii) explore resource options to ensure sustainable development, (iv) warrant reliable and affordable electricity generation, and (v) identify an optimized sustainable electricity generation system. The proposed framework would be helpful for developing countries, in particular, in designing a sustainable electricity generation system, where plans are at the initial stage or under development.

**Keywords** Sustainability · Electricity · Power generation expansion plan · Sustainable development · Sustainable transition · Sustainable technology · Energy planning framework · Optimized energy plan · Developing economies · Bangladesh

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## 1 Introduction

Globally, the energy sector, particularly the electricity sector, is experiencing a drastic transition in the way electricity is generated, distributed, and consumed. Specifically, generation is increasing exponentially in the developing world due to industrialization and the need to ensure access to electricity for its total population [1]. Thus, the grid expansion plan must consider the key factors for a sustainable electricity sector development: securing energy supply, limiting negative climate change, grid adaptability to new technologies, and economic feasibility.

Despite increasing access to electricity in the developing countries, about 840 million people still lack access [2]. The electrification rate was about 89% in 2017, which is an increase of 6% from 2010. One of the reasons of this increase was the renewable energy boom particularly in developing Asia through solar energy [3]. Figure 1 depicts region-specific installed renewable capacity from 2010 to 2018. Clearly, the nature of renewable growth in Asia was exponential and drastic over this period. Although not as far-reaching, similar exponential growth was also observed for north and south America. Growth was linear for Europe, Eurasia, and Africa, while modest linear growth was found in Oceania. On the other hand, there was almost no growth in renewable capacity in central America, the Caribbean, and the Middle East.

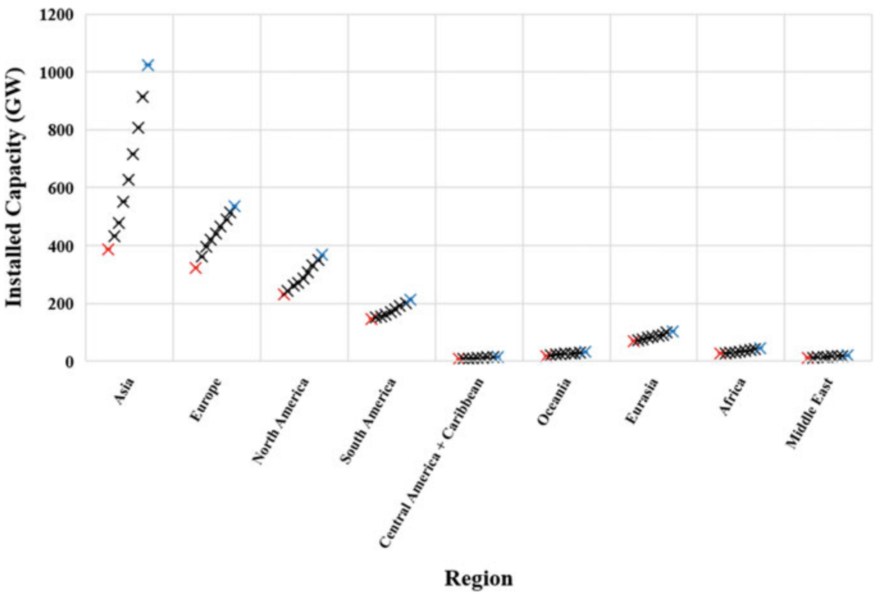



**Fig. 1** Trends in renewable energy by region: installed capacity for the period of 2010–2018. Each cross represents capacity for that specific year. Bottom (or left) and top (or right) crosses indicate the capacities for the year of 2010 and 2018, respectively (*Data source* [4])

Although energy is essential to economic development, energy generation, transmission, and use have unavoidable social and environmental impacts. To ensure the long-lasting economic, social, and environmental success of electricity generation, technologies that are less carbon intensive to minimize negative environmental impacts, economic, and widely accepted in the society need to be selected. A new framework is proposed to assess these criteria in order to ensure long-term success.

Although renewable growth in the electricity sector is a sustainable solution, this growth was predominantly off-grid. For example, in Bangladesh, a south Asian country, the electrification rate was increased due to the adoption of off-grid solar home systems to acquire basic access to electricity [5]. Integration of this off-grid with the national grid remains a great challenge. This implies that the electricity infrastructure planning was not sustainable. This is a very common problem for the developing world transitioning to a sustainable electricity generation system. This chapter thus focuses on how this problem can be minimized by adopting a sustainable energy infrastructure planning framework. Generally, a framework is either conceptual, in the form of a system of rules, ideas, or beliefs, or real structure, which is used to plan, guide or support the building of something useful to achieve a defined goal. Here, the word 'framework' is chosen because 'it is pitched at an interdisciplinary level' [6].

A single electricity generation technology, either renewable or non-renewable, is not sufficient for a complete sustainable transition of any electricity generation sector. Moreover, any new technology deployment in the electricity system must be accepted by the society (e.g., waste to energy plant) and needs to be economically viable, and environmentally friendly. Proper economic, environmental, and social impact assessment should therefore be conducted for each new power project [7, 8]. Thus, a framework that can assess the sustainability of an electricity system by considering the three issues is a crucial requirement. To assess any new plan, this type of framework is important for several reasons: first, sustainability assessment is an essential component of any project to avoid deterioration in social, economic, and environmental issues. Second, the framework might reveal new opportunities for development. Finally, it is able to provide a number of benefits in the long run, such as efficiency improvement of the system, cost reduction, and risk minimization through assessment.

In Bangladesh, as is common in developing countries, inefficient and unsustainable grid expansion plans are hampering the government's targets towards sustainable development. Thus, the purpose of this chapter is to present a conceptual framework that utilizes a sustainability index and levelized cost of electricity to assist in understanding the electricity grid expansion plan and to assess its overall sustainability. In light of this rationale, the framework will incorporate insights from the literature on sustainability issues with the aim of better understanding the proposed electricity grid transition plan and its related sustainability status.

The rest of the chapter is organized as follows: Section 2 sheds light on available energy planning or analysis frameworks or models in the literature. Section 3 explains the proposed framework. Section 4 presents the case study of Bangladesh, considering the proposed framework and the results are compared with that of New

Zealand to show the generic application of the framework. Section 5 discusses the findings and the final section concludes the chapter.

## 2 Energy Planning Frameworks or Models in the Literature

Numerous studies in the literature have reported many energy planning frameworks and models. It was found that energy planning frameworks for developed countries vary significantly from those of the developing nations. For instance, in [9], the authors "*identified five key distinctions between the energy transition contexts of developed and developing countries, namely: (i) fulfilled versus unmet power market; (ii) large-scale versus small scale; (iii) fossil versus renewable; (iv) time aspect – slow or fast; and (v) diminishing return versus niche opportunities*" (Reprinted by permission of the publisher). For instance, a multi-period stochastic optimization model was developed for long-term power generation planning using mixed-integer linear programming for developing countries [10]. Under budget constraints, the model is able to produce an optimized generation mix and size along with the timing of generations.

There are many energy planning tools available for future energy planning and analysis in the literature [11]. At the same time, many studies have attempted to explain different energy planning frameworks or models. For example, in [12], the authors proposed a theoretical framework for strategic energy planning, which involves four basic steps, along with two supporting steps. The first step defines the level of planning, that is, at national, regional, municipal or city level for which the planning will be conducted. The second step considers all the possible elements required for the planning, such as security of supply, energy savings, and reliability. In the third step, strategic plan is prepared with the help of available tools and methods such as computer models and scenario analysis. The final step implements the plan with the help of implementation tools. For further details, see [12].

In [9], for unmet electricity markets, an energy transition framework was proposed, which has the following key characteristics: "(i) considers traditional technology; (ii) has defunct deceleration; (iii) consists of a niche technology curve; (iv) landscape support for niches; and (v) new regime condensation (emergence)" (Reprinted by permission of the publisher).

An optimized model for sustainable district energy planning was proposed in [13]. The model provides optimized decisions based on the following variables: the amount of power exchanged with the public grid, the number and type of cogeneration plants, wind turbines, and size of the photovoltaic fields. Similarly, an energy planning model was developed in [14], which is able to consider seasonal variations in electricity demand and plan accordingly over hourly and daily timeframes. A multi-objective model for future power generation expansion was presented in [15]. This model was able to consider the three main objectives in designing a future power generation plan with high renewable penetration. These objectives are total cost minimization, ensuring maximum generation at peak load, and maximization of renewable generation, particularly from non-hydro sources. In Malaysia, ‘a Computable General Equilibrium (CGE) model to examine the potential impacts of gas subsidy reform in the power sector’ was proposed in [16]. “*The model evaluates and compares the impacts of two methods of providing funds for encouraging the development of renewable energy production, reallocating revenues from gas subsidy removal, and remunerating the FiT mechanism*” [16] (Reprinted by permission of the publisher).

Apart from these, ‘dynamic reliability-based model for distributed energy resources (DER) planning’ was proposed in [17]. The authors claimed that the “*planning model can be directly implemented in real life distribution networks which face load uncertainty and consist of a mixture of voltage-dependent loads, rather than constant loads*” [17], (Reprinted by permission of the publisher). However, the main limitation of this study is that it only considers distributed renewable resources. On the other hand, Abdin and Zio considered the intermittent renewable energy sources in the power planning framework they have developed [18]. The main purpose of this framework was to assess the operational flexibility in power system planning. The proposed framework is able to design an integrated power generation expansion plan [18]. In Germany, a modeling framework for multi-modal energy system planning was reported [19]. The proposed framework offers a number of benefits claimed by the authors: it offers optimal plan for future investments, shows a detailed energy transition pathway, and it considers politically defined climate goals for the country.

Another framework that received particular focus in different sectors of energy such as electricity, transport is the ‘energy cultures framework’ (ECF) [6]. The ECF was proposed to explain energy behavior of people, particularly at residences. “*The Energy Cultures framework suggests that consumer energy behavior can be understood at its most fundamental level by examining the interactions between cognitive norms (e.g. beliefs, understandings), material culture (e.g. technologies, building form) and energy practices (e.g. activities, processes)*” [6], (Reprinted by permission of the publisher).

“*Each of these three core concepts can itself be understood as an interacting system* (as shown in Fig. 2). *The material culture of a household or an industry can be understood as a technical system in its own right; energy practices can be systemically understood the interactions between individual, social and institutional behaviors and cognitive norms can be understood as an attitude/value/belief system. As a whole, these are co-constitutive of behavioral outcomes*” [6], (Reprinted by permission of the publisher). In recent studies, in-house energy-use dynamics and behavior was also explained in [20, 21], which are in line with the energy cultures framework.

A study in the Philippines proposed an alternative framework for renewable energy planning [22]. The authors discussed the effectiveness of energy planning using renewable sources with respect to sustainability. The effectiveness was divided into four quadrants as illustrated in Fig. 3.

The first quadrant indicates the renewable sources that can be used for energy generation, which is highly developmental and ensures high energy delivery such as

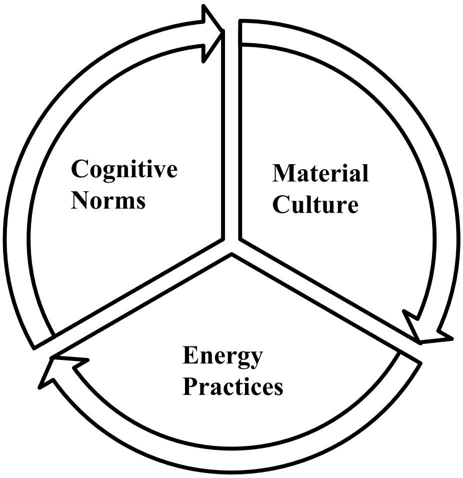



**Fig. 2** Concept of energy cultures framework [6]

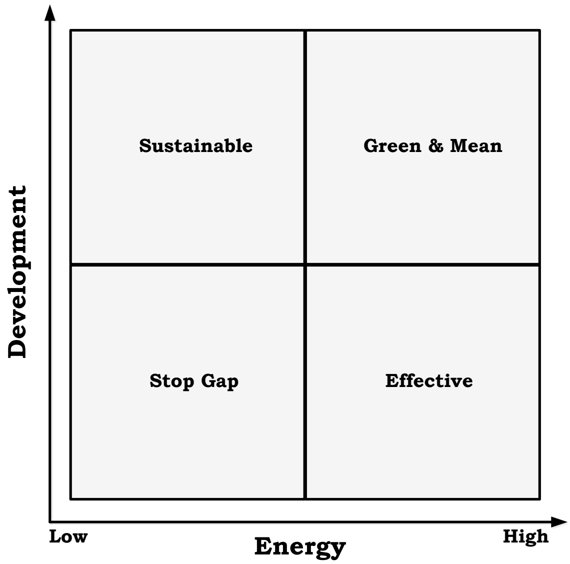



**Fig. 3** Effectiveness of sustainable energy planning using renewable sources (*Source* [22], reproduced with permission)

off-grid biomass and waste to energy options. The second quadrant-sustainable is effective in achieving developmental goals but not in energy delivery. These renewable sources include off-grid solar and wind. The ‘stop gap’ quadrant is neither developmental nor high energy deliverable, such as grid connected wind. On the other hand, quadrant four shows low development but high energy delivery. Impounding hydro and grid-connected solar fall in this category. Further detail can be found in [22]. Similarly, for the identification of an optimal hybrid renewable solution in metropolitan areas, a systematic framework was proposed in [23].

In [24], the authors proposed a future power generation planning framework for Iran to assess the sustainability of a different generation fuel mix in the electricity sector. The framework consists of a four step evaluation procedure to measure the sustainable electricity generation scenarios [24]. These four steps were (i) defining generation scenarios, (ii) energy supply optimization through available model, (iii) sustainability assessment with respect to environmental, social, and techno-economic indicators, and (iv) ranking of scenarios using multi-criteria decision analysis. However, the study did not check the relation between sustainability and affordability towards the transition to a low-carbon future.

## 3 The Proposed Framework and Its Objectives

To engage in any future energy planning a framework is indispensable in guiding the analysis, setting the strategies and implementing the plans. A framework that helps in achieving a sustainable electricity infrastructure is referred to as Sustainable Energy Infrastructure Planning Framework (SEIPF). The objective of an effective SEIPF is to ensure a healthy balance between planning principles and sustainability dimensions—social, economic, and environmental. To be effective, the SEIPF must promulgate a sustainable vision coordinated with a predictable and clear regulatory procedure that encourages the involved entities to be confident to invest and take probable risks associated with the planned power projects.

A similar energy planning tool known as 'strategic energy planning' is closely associated with an energy planning framework, which "*shall secure a future energy system that is both energy efficient and flexible. Strategic energy planning includes all possible elements of municipalities'* (or country's) *energy plans, and coordination with municipal plans, security of supply strategies and climate strategies. The municipalities* (country) *should conduct energy planning to create an optimal interplay between the energy demands and energy supplies (heating, cooling and electricity) in such a way that the energy resources are optimally used*" [12], (Reprinted by permission of the publisher). This strategic energy planning underpins the overall energy planning process by involving the private, public, and social community sectors of a country.

The objectives of an SEIPF is to provide a guideline for the policymakers, electricity authority of the country, researchers, and engineers to understand the sustainable electricity generation infrastructures, which will underpin the sustainable energy planning. Some specific objectives of SEIPF are as follows:

(i) To help in prioritizing the issues that are more crucial for sustainable energy infrastructure planning.
(ii) To support identifying different energy infrastructure planning sustainability status.
(iii) To help identify the sustainable indicators and criteria that are necessary in accordance with the sustainable development goals.

(iv) To facilitate national sustainable energy infrastructure planning.
(v) To help in assessing data requirements for the planning.
(vi) To help in strengthening sustainable capacity building strategy and action plan for the energy planning.
(vii) To underpin the linking between the national sustainable energy plan and global sustainable development goals.

The proposed sustainable energy infrastructure planning framework (SEIPF) is illustrated in Fig. 4. The SEIP framework comprises two axes: the y-axis indicates the sustainability status of the plan and the x-axis presents the affordability of the plan. Based on these two criteria, any energy planning can be placed in one of four categories. These are explained in this section.

**First Quadrant—SEIP**: If the energy infrastructure plan falls in this quadrant, it can be said that the plan is sustainable and will be effective towards a sustainable energy transition. This implies that the plan would be sustainable and affordable at the same time, which is always a desired outcome.

**Second Quadrant—Cost driven SEIP**: If the energy expansion plan falls in this quadrant, the plan would be sustainable. However, it will involve a huge cost for its implementation. The cost includes capital, operational, maintenance expenses, among others.

**Third Quadrant—Costly and not SEIP**: This is the worst plan that might occur if not planned properly considering different sustainable issues. The energy expansion plan that will fall in this quadrant will not only be costly but also unsustainable.

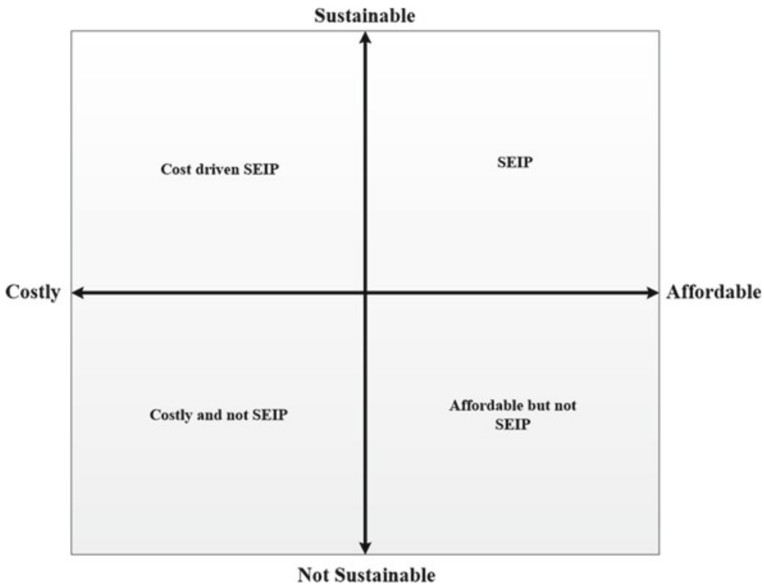



**Fig. 4** Proposed sustainable energy infrastructure planning (SEIP) framework

**Fourth Quadrant—Affordable but not SEIP**: In this quadrant, the plan would be affordable but not sustainable. That is, the overall cost might be affordable, but the technology transition will not be a sustainable one.

In addition, this proposed framework can also be used to assess sustainability status of electricity generation technologies.

To obtain a specific position for an energy expansion plan in any of the quadrants of the proposed framework, it is essential to define values for these two axes. In doing so, sustainability index [25] and levelized cost of electricity (LCOE) generation [26] can be used for the sustainability [x-axis] and cost [y-axis] axes, respectively. Thus, prior to the SEIP assessment through the proposed framework, it is necessary to assess the sustainability status of that plan through the sustainability framework [27]. The sustainability framework comprises many indicators under the three major criteria: social, economic, and environmental.

## 3.1 Levelized Cost of Electricity

"*Levelized cost of electricity (LCOE) represents the average revenue per unit of electricity generated that would be required to recover the costs of building and operating a generating plant during an assumed financial life and duty cycle..... Key inputs to calculating LCOE include capital costs, fuel costs, fixed and variable operations and maintenance (O&M) costs, financing costs, and an assumed utilization rate for each plant type*" [26]. The concept of LCOE is illustrated in Fig. 5.

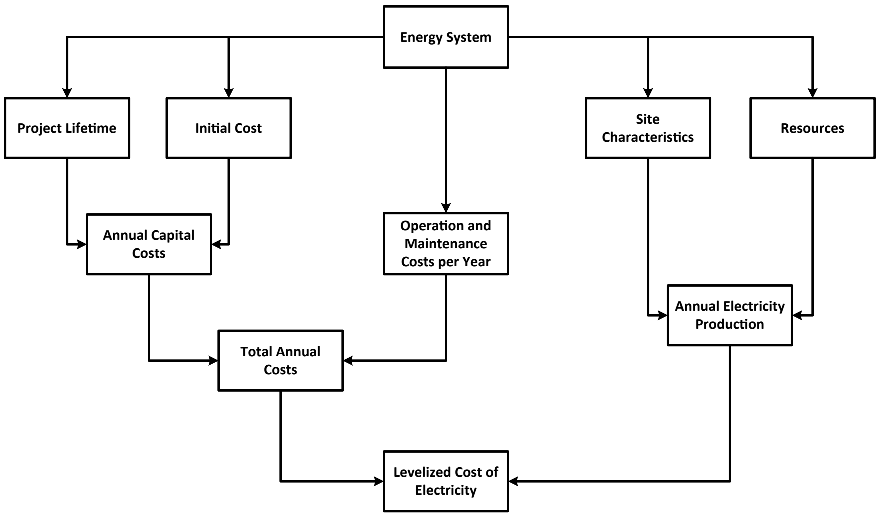



**Fig. 5** Concept of levelized cost of electricity [28]

In terms of cost of the electricity generation technologies, LCOE has become a practical method of cost estimation and comparison. This cost estimation method is internationally recognized as it offers a number of benefits. First, it is able to assess the economic viability of an individual electricity generation technology. Second, it can evaluate electricity generation projects involving available generation technologies. Third, it reflects the significant factors associated with the production cost throughout the lifetime of the electricity generation unit. Fourth, it evaluates the factors that are crucial for economic evaluation of the power plant or project. Finally, as LCOE is just a numeric value, it reduces complexity and allows easy and quick comparison between different options. In addition, LCOE not only offers high levels of transparency but also ensures clarity, and is thus accepted internationally. Although LCOE is advantageous for economic analysis, it has a few limitations such as uncertainties. As LCOE considers calculations over the lifetime of the power generation unit, some values might have to be predicted, and consequently produce uncertainty. Moreover, due to a narrow viewpoint, misinterpretation might occur, resulting in an undesirable decision.

The calculation of LCOE can be conducted in two ways [29]: (a) net present value (NPV) method, and (b) annuity method.

(a) For a new power plant, the following formula (Eq. (1)) is used for NPV calculation

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^t}} \tag{1}$$

where

LCOE Levelized Cost of Electricity.
$I_0$ Investment expenditure.
$A_t$ Annual total cost per year t (includes fixed and variable costs for the operation of the plant, maintenance, servicing, repairs and insurance payments).

Therefore, $Annual\ total\ costs,\ A_t = Fixed\ operating\ costs + Variable\ operating\ costs + Residual\ value\ or\ disposal\ of\ the\ plant\ (if\ applicable)$

$E_t$ Produced amount of electricity in kWh per year.
$i$ Real interest rate in %.
n Economic lifetime in years.
t Year of lifetime (1, 2, … n).

(b) Annuity method, defined as (Eq. (2))

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+r)^t} \times ANF}{\frac{\sum_{t=1}^{n} E_t}{n}} \tag{2}$$

where

LCOE Levelized Cost of Electricity.
$I_0$ Investment expenditure.
$A_t$ Annual total cost per year t (includes fixed and variable costs for the operation of the plant, maintenance, servicing, repairs and insurance payments).

Therefore, $Annual\ total\ costs,\ A_t = Fixed\ operating\ costs + Variable\ operating\ costs + Residual\ value\ or\ disposal\ of\ the\ plant\ (if\ applicable)$

$$The\ annuity\ factor,\ ANF_{t,i} = \frac{i \times (1+i)^t}{(1+i)^t - 1}$$

$E_t$ Produced amount of electricity in kWh per year.
$i$ Real interest rate in %.
$r$ Discount rate in %.
n Economic lifetime in years.
t Year of lifetime (1, 2, … n).

The LCOE can also be written in a simplified form as (Eq. (3))

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{3}$$

where

$I_t$ Investment expenditures in year t (including financing).
$M_t$ Operations and maintenance expenditures in year t.
$F_t$ Fuel expenditures in year t.
$E_t$ Electricity generation in year t.
r Discount rate.
n Lifetime of the system.

## *3.2 Sustainable Development and Sustainability*

Sustainable development is defined as meeting "*the* [human] *needs of the present without compromising the ability of future generations to meet their own needs.*" Therefore, sustainable development must entail: "*a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are made consistent with future as well as present needs*" [30]. Renn et al. set four principles of sustainable development [31], (Reprinted by permission of the publisher):

(i) *Acknowledgment of absolute limits with respect to the carrying capacity of the earth principle.*

(ii) *Acknowledgment of the limits of substitution between natural and artificial capital.*
(iii) *Focus on the resilience of anthropogenic ecosystems.*
(iv) *Incorporation of social values in man's relationship to the environment and nature.*

Overall, sustainable development is a combination of a conceptual framework and a process with an end goal. The conceptual framework assesses any change through a holistic view by maintaining a proper balance between the different elements. The process ensures application of the principles of integration across time and space to all related decision-making, and the end goal involves identifying and solving specific problems [32].

There are three elements of sustainability: environment, economy, and society. Environment deals with biodiversity, biophysical interactions, energy, and materials. This ensures healthy and recoverable resources for present and future generations. Economy considers money and capital, investment, employment, market forces, and technological growth, and should confirm economic growth overall. This growth must be less material and energy intensive, along with equitable impacts. On the other hand, society takes into account human diversity such as culture, language uses, equity, quality of life, political issues, and institutional and organizational structures, all of which in turn underpin social progress [33].

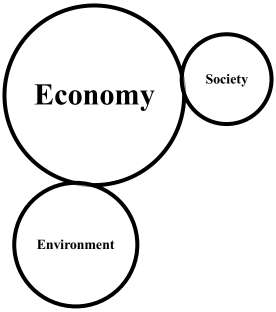
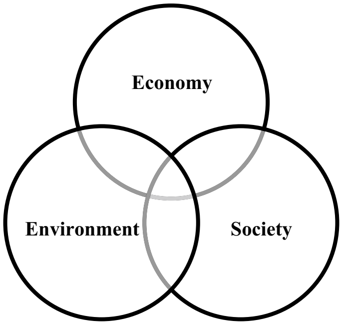
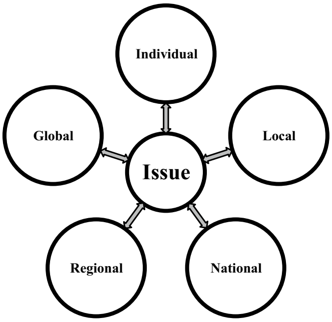
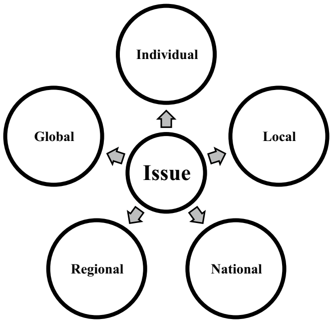
Generally, sustainability is essential for several reasons: first, to reduce depletion of resources such as fossil fuels. Second, to challenge the inadequate use of renewable sources. Third, to mitigate pollution of air, water, and soil through the overuse of resources. Fourth, to counter inequality in economic, gender, political, and social issues. Finally, to deal with losses of endangered species and habitats. In the developing economies, however, there are two main factors impeding sustainable development: fragmented decision making and lack of accountability. For instance, the former involves existing jurisdictional rigidity, narrow mandates, and lack of coordination and communication between different sectors.

In the developing world, most decision making at the policy level is in the traditional form, which is unable to coordinate the three main elements of sustainability. A comparison between traditional and sustainable decision making is illustrated in Table 1.

Decision making can be divided into three major types: reactive, anticipatory, and radical decision making. The first considers 'end of pipe' problem and their solution considering any one element of sustainability. Anticipatory decision-making deals with planning for change, which might include any two elements of sustainability. In contrast, radical decision making takes into account all the fundamental root causes, and thus involves all three elements of sustainability. Traditional decision making is mostly of the reactive kind, and is often anticipatory. On the other hand, sustainable decision making is radical, so that the root cause can be minimized through proper planning and coordination between the three sustainability elements.

In assessing the sustainability of any system, it is necessary to establish a measuring scale, referring to physical, geographical, ecological or jurisdictional

**Table 1** Comparison between traditional and sustainable decision making

| Traditional decision making | Sustainable decision making |
|---|---|
| Fragmented and need-based | Integrated and a well-coordinated |
| Any one sustainability element might gain priority over the other two based on necessity or vice-versa | All three elements have equal priority |
| Non-participatory decision-making process | Participatory decision-making process |
| <br>Priority: Economy > Environment > Society | <br>Priority: Economy = Environment = Society |
| <br>Fragmented and bidirectional decision making | <br>Integrated and central unidirectional decision making |

areas. A physical scale could include ranking-based, dimensional or geographical subunits. The ecological scale involves individual, community or population-related measures, while the jurisdictional scale considers local, municipal, regional or global measures. "*However, no single number tells us whether or not a process is sustainable; instead, a set of values can be obtained and then compared to standards and thresholds*" [34], (Reprinted by permission of the publisher). Thus, different types of indicators can be used to measure the sustainability of any process or system. In general, there are four types of indicators: qualitative, quantitative, warning, and state indicators [34]. In sustainability assessment, the first two are frequently used. Qualitative indicators, such as social status, are difficult to measure. On the other hand, quantitative indicators can be represented by numerical values and are thus easy to measure.

All the indicators can be selected by either the top-down or the bottom-up approach. In the top-down approach, indicators are preselected in accordance with the goal, whereas in the bottom-up approach, indicators define the goal. In sustainability assessment, the bottom-up approach is preferable [34].

In general, "*decision-making is the study of identifying and choosing alternatives to find the best solution based on different factors and considering the decision-makers' expectations*" [35], (Reprinted by permission of the publisher). Different multicriteria decision analysis/making (MCDA/M) methods are available to assess different indicators and evaluate the overall sustainability of any system or process. The most common MCDA methods are (i) Analytic Hierarchy Process [AHP], (ii) Weighted Sum Method [WSM], (iii) Weighted Product Method [WPM], (iv) Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE), (v) Elimination Et Choix Traduisant la REalité (ELECTRE), (vi) Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS), (vii) VlseKriterijumska Optimizcija I Kaompromisno Resenje [in Serbian] (VIKOR), (viii) Choquet Integral, and (ix) COmplex PRoportional ASsessment (COPRAS). Details of these methods can be found in [36]. Based on MCDA, preferences can be elicited at different stages in the decision-making process: before or after the identification of alternatives or iteratively, both before and after the identification of the alternatives. However, the results obtained from can vary from one MCDA to another [25].

Sustainable solutions include cyclical material use, safe and reliable energy, and life-based interests through proper involvement of the three sustainability elements, that is, environment, economy, and society. Any sustainable development-related decision making must account for future and present needs regarding social, political, and institutional changes, energy use, resource utilization, technological development, and direction of investment. However, sustainable development sets limits to growth, both quantitative and qualitative limits based on the elements of sustainability. These limits are not predefined or absolute, but rather imposed by different elements. For example, the absorption ability of the biosphere in response to human activities, political and social organizations' adaptability to different changes, and limits imposed by the technology, that is, economic factors.

Transition from traditional to sustainable decision making requires a three step procedure to be followed, depicted in Fig. 6. The first step is to set principles for

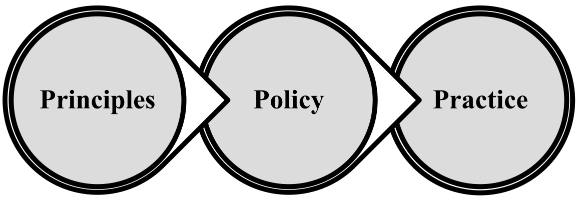



**Fig. 6** Sustainable decision-making procedure

sustainable decision making. These principles should be that it is easy to understand, transferrable between different sectors, adaptable across different scales, applicable from fundamental issues to applied policy and practice, and able to detect changes for each element of sustainability over a period of time under consideration. The policy should be designed in accordance with the principles. For policymaking, the environment needs to be considered as the basis of sustainable development; in achieving sustainable development, the economy needs to be considered as a tool; the target of sustainable development would be an improved quality of life for all. In the final step, the practice needs to be ensured by proper regulations which should be imposed by governments.

### 3.2.1 Methodology for Sustainability Assessment

To assess the sustainability of any system it is necessary to follow a systematic approach and apply relevant methods. In assessing sustainability, some general steps need to be followed as illustrated in Fig. 7. In the first step, the relevance and scoping of a sustainability assessment need to be analyzed with respect to the system under consideration. If a framework for sustainability assessment is not in place, a conceptual framework must be developed in the second step. Selection of criteria and related indicators need to be sorted in the third step. It is also necessary to decide a minimum number of indicators such as capital cost (economic), GHG emission

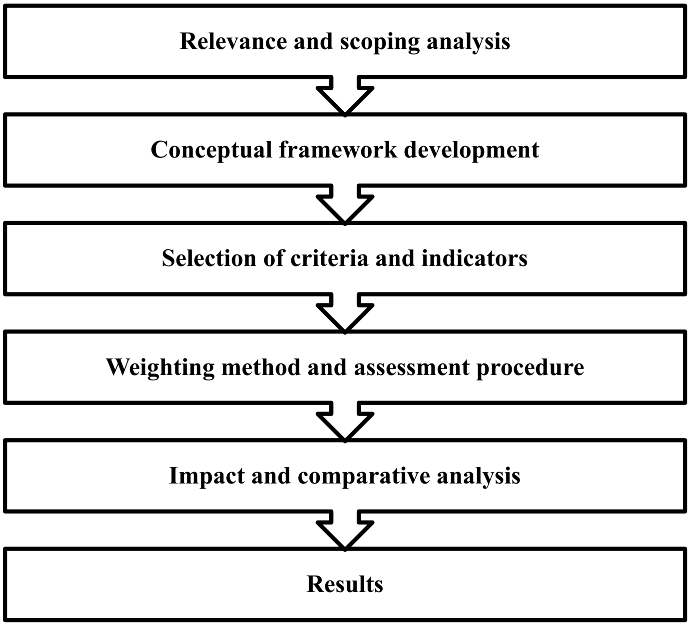



**Fig. 7** Sustainability assessment basic steps

(environmental), people displacement (social) to conduct the assessment. For a list of different indicators see [34]. For this indicator selection, the bottom-up approach would be a good choice. In the fourth step, suitable MCDA methods such as AHP, TOPSIS should be selected. Research shows that at least two MCDA approaches should be used to obtain an optimized result [25]. In the fifth step, impact analysis should be evaluated with respect to the results obtained from the MCDAs. These impacts must be compared with national standard impact analysis results. These analyses should consider the economic, environmental, and social impact assessments. In the final step, the analyzed result would be obtained. For further detail with specific examples in relation to sustainability assessment considering all the mentioned steps see [25, 37, 27].

Although the basic steps to conduct sustainability assessment have been outlined, there are some difficulties that need to be addressed.

(i) Giving equal consideration to the three criteria (economic, social, and environmental) of sustainability.
(ii) Sustainability assessment for the longer term (e.g., more than 20 years).
(iii) Weight assignment to qualitative indicators such as quality of life and social status.
(iv) Identifying the optimized option for the three sustainability criteria.
(v) Consideration of positive and negative social impacts.

Therefore, to check any energy infrastructure plan using the proposed framework, it is necessary to follow a step-by-step procedure as depicted in Fig. 8. The first step checks the reliability and affordability of the planned electricity generation. This step is crucial, as it ensures reliable and affordable electricity for the population, particularly people without access to electricity in developing Asia and Africa.

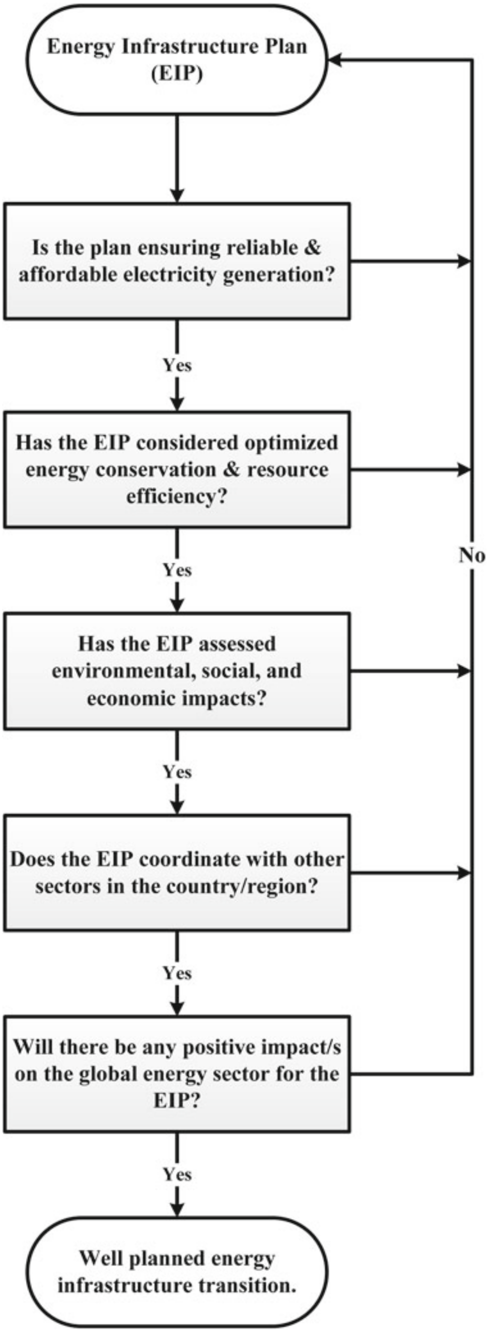
The second step ensures optimization between existing and planned infrastructures through related measures, for example, energy conservation and increasing resource efficiency. Energy conservation is one of the effective ways to reduce energy consumption, predominantly at residences, for instance, energy-saving behavior at residences [21]. Similarly, efficiency improvement can also reduce energy consumption.

The third step explicitly considers the sustainability assessment of the proposed plan with respect to the three dimensions of sustainability: social, economic, and environmental. Each of these impacts needs to be evaluated by considering many different indicators from each of these dimensions. This is critical, as the sustainability index that will be obtained from this step will be used directly in the proposed SEIP framework.

In the next step, it must be checked that the plan has good coordination with other sectors within the country or region towards sustainable development. This coordination is important, as sustainable development in one sector does not ensure the country's overall sustainable development.

In the last step, it is necessary to check if the plan cam make any contribution to the regional or global energy sector's sustainable development. This is important because any one country's sustainability status is linked with regional sustainability.

**Fig. 8** Sustainable energy infrastructure planning steps



For example, in a recent study, Khan [38] showed that the electricity generation sector's sustainability status of the south Asia growth quadrangle region depends on individual countries' sustainability status [25].

Overall, if any one step does not fulfill its criteria, the plan must be adopted from its first step.

## 4 Case Study: Bangladesh

Electricity demand is increasing at a very fast rate in Bangladesh, predominantly due to increased economic activities. The annual average growth rate of electricity demand is about 10%, which will increase in the coming years [39]. This growth rate is dominated by fossil fuels. The total installed capacity was 15,953 MW and 18,961 MW for the fiscal years 2017–18 and 2018–19, respectively [39, 40]. Fuel-specific installed capacity is illustrated in Fig. 9 for these fiscal years.

It is clear from Fig. 9 that generation from furnace oil and solar increased from the previous fiscal year by 3.58% and 0.14%, respectively. Importantly, solar generation capacity increased from 3 MW in the previous year to 30 MW in 2018–19. At the same time, 1.98% more power was imported from India. On the other hand, major capacity reduction was observed for gas, which reduced to 57.36% in 2018–19. Bangladesh's power sector is dominated by fossil fueled generation, yet the technologies used to generate electricity are not all up to date. For instance, about 12.36 and 8.48% generations come from steam and gas turbine and their efficiency level varies between 16.14 and 56.13% [39].

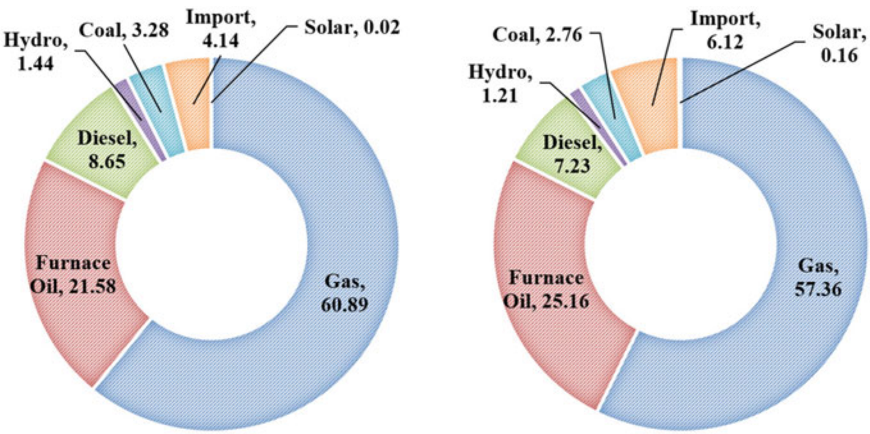



**Fig. 9** Installed electricity generation capacity (in %) of Bangladesh for the fiscal year 2017–18 (left) and 2018–19 (right) (*Source* [39, 40])

Recently, Bangladesh has developed its long-term power system master plan (PSMP) up to 2041 [41]. The PSMP considered different electricity generation technologies along with different generation mix combinations in 2041. These combinations are listed in Table 2. The sustainability assessment of these technologies and scenarios was investigated in [27]. Therefore, the sustainability index values and LCOE were considered from [25, 27].

The sustainability index and LCOE values were plotted in the SEIPF and the results are shown in Figs. 10 and 11. It can be seen from Fig. 10 that only energy

**Table 2** Different electricity generation plan (scenarios) of Bangladesh in 2041

| Scenarios | Import (%) | Oil/Hydro/Others (%) | Nuclear (%) | Renewable (%) (except hydro) | Coal (%) | Gas (%) |
|---|---|---|---|---|---|---|
| P1 | 15 | 5 | 10 | 0 | 55 | 15 |
| P2 | 15 | 5 | 10 | 0 | 45 | 25 |
| P3 | 15 | 5 | 10 | 0 | 35 | 35 |
| P3/RE10 | 15 | 5 | 10 | 10 | 25 | 35 |
| P3/RE20 | 15 | 5 | 10 | 20 | 25 | 25 |
| P4 | 15 | 5 | 10 | 0 | 25 | 45 |
| P5 | 15 | 5 | 10 | 0 | 15 | 55 |

*Source* Government of Bangladesh [41]
*Note* P3/RE10 and P3/RE20 indicate P3 scenario with 10% and 20% renewable generation, respectively

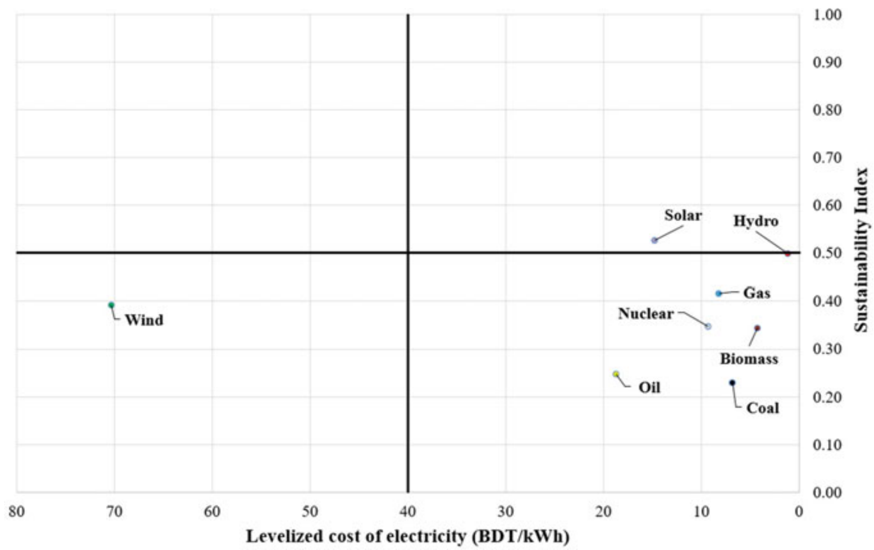



**Fig. 10** Different electricity generation technologies in Bangladesh assessed through the SEIPF

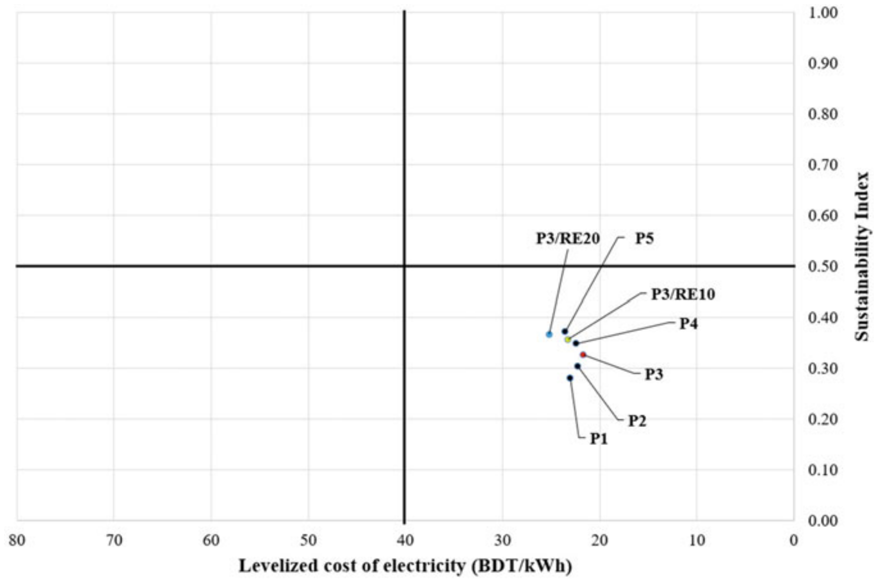



**Fig. 11** Different electricity generation scenarios of Bangladesh in 2041 assessed through the SEIPF

generation from solar falls in the first quadrant. This means that if the energy expansion plan is dominated by solar technology it might be a sustainable energy transition, although the position of the solar technology is very close to the borderline of sustainable status. Biomass falls in the fourth quadrant. Although biomass is more affordable than other renewable technology except hydro, it is not sufficiently sustainable at present. Wind falls in the third quadrant, that is, it is a costly technology at present in Bangladesh. On the other hand, the LCOE generation for hydro was found lower than any other available technology in the country. At the same time, the sustainability of hydro technology falls on the borderline (see Fig. 10). In contrast, all the fossil fuel technologies fall in the fourth quadrant, that is, these are affordable but not sustainable technologies to plan future electricity generation. Towards sustainable development in the power generation sector of Bangladesh, the government made a power system master plan (PSMP) in 2016, which considers 10–20% renewable generation predominantly from hydro and solar [41]. However, 25% share of the total generation was represented by coal (see Table 2, scenarios: P3/RE10 and P3/RE20). Clearly, coal technology falls in the fourth quadrant and at the bottom of all technologies under consideration (Fig. 10). Among all the fossil fuel generation technologies, gas is comparatively more sustainable than others.

It is therefore recommended to use a combination of different technologies to plan future power generation using the available technologies. The PSMP considers different power generation scenarios in 2041, as listed in Table 2. Unfortunately, none of the combinations are found to be sustainable enough to be considered a sustainable future energy plan in Bangladesh as depicted in Fig. 11. All the combinations are affordable but not sustainable. This is because the electricity sector in Bangladesh is dominated by fossil fuels and their combinations would not provide a sustainable solution. Although there is no share of renewable generation in the P5 scenario except for a small element of hydro, it is comparatively better than any other fuel mix in 2041, as the percentage of coal is reduced to 15%. Another reason was the share of gas which increased to 55% for this P5 scenario, and it was found that gas is a comparatively more sustainable technology than other fossil fueled generation (Fig. 10).

To check the versatility of the SEIPF, it was applied for the generation technologies for New Zealand and depicted in Fig. 12. For New Zealand, the sustainability index for specific technologies was considered from [42] and LCOE were taken into account from [26]. LCOE values were used with the following conditions: coal with 30% carbon capture and sequestration, conventional combined cycle for gas, onshore wind, it was assumed that 'hydroelectric generation' has seasonal storage so that it can be dispatched within a season, but overall operation is limited by the resources available by site and season [43]. Levelized costs for non-dispatchable technologies can vary significantly by region. The capacity factor ranges for these technologies were 37–46% for onshore wind, 22–34% for solar PV, and 76% for hydroelectric. The LCOE might also be affected by regional variations in construction labor rates and capital costs as well as resource availability' [26].

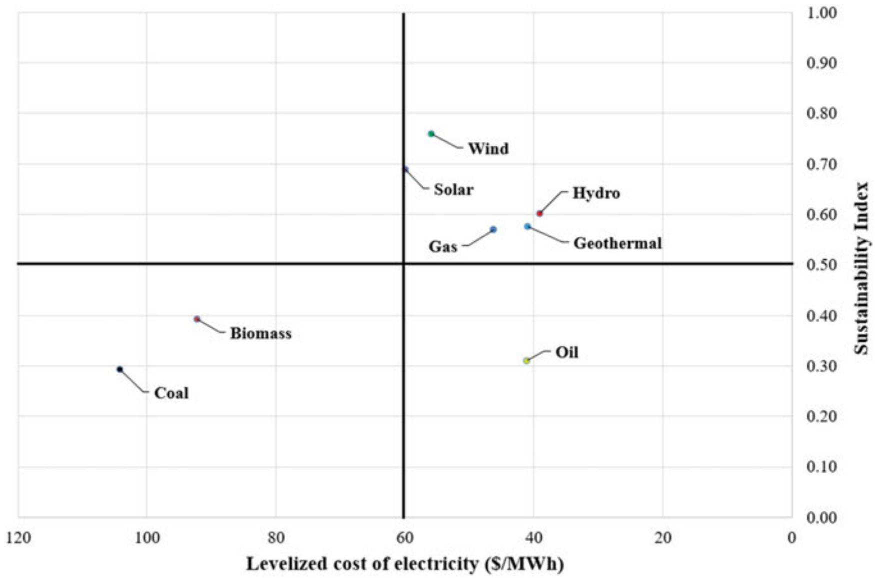



**Fig. 12** Different electricity generation technologies in New Zealand assessed through the SEIPF (*Data sources* [26, 42])

Figure 12 depicts the sustainability status of the electricity generation technologies in New Zealand. A clear difference exists between the sustainability statuses of different generation technologies in New Zealand and Bangladesh. For instance, electricity generation from solar is costly in New Zealand, but less costly in Bangladesh due to government subsidies. On the other hand, electricity generation from wind is costly in Bangladesh and not suitable due to wind speed, whereas in New Zealand wind speed is sufficient to generate electricity and the overall cost of generation is comparatively lower. In addition, within quadrant one, wind occupies the top position in sustainability status. Interestingly, gas was found to be a sustainable technology in the New Zealand context. Transition planning involving coal and biomass was found to be 'costly and not SEIP' (Fig. 12).

## 5 Discussion

In recent years, significant progress has been observed in renewable energy generation technologies. However, developing a sustainable energy generation system is not only a slow process but also depends on proper planning. In addition, a sustainable transition will only be possible if sustainable technologies are accepted and adopted by the population. At the same time, such a transition must meet economic and environmental sustainability criteria. Society plays a crucial role in sustainable electricity transition. If a renewable energy generation technology meets both economic and environmental criteria but is unable to satisfy people's needs, the transition might not be a successful one. Often, in the developed world, electricity generation projects from wind have been seen unsuccessful due to aesthetic concerns. Similarly, in the developing world, waste to energy generation plants are often opposed due to environmental issues.[1]

For a sustainable electricity transition, "*a set of five relevant characteristics is identified in the broader areas of geography, population and economy, and flexibility,…….country-specific geographical and socio-economic characteristics may determine the starting point, speed and scale of power system transformation process*" [44]. These characteristics are:

(i) *Availability and potential of dispatchable renewable energy sources*
As can be seen from Fig. 9, the electricity sector of Bangladesh is dominated by fossil fueled generation, in particular, gas fired power plants. Due to the location of Bangladesh, hydro is not a potential source for electricity generation. Similarly, wind speed is very limited, and is thus not suitable to generate electricity, whereas solar has potential. However, there are a number of social and technical factors that might affect local conditions and renewable outcomes.

(ii) *Patterns of renewable resources in time*

[1] https://e360.yale.edu/features/as-china-pushes-waste-to-energy-incinerators-protests-are-mounting (accessed 13-Dec-2019).

Patterns of renewable source availability vary from one season to another. For example, although solar has the potential to generate electricity in Bangladesh, during the monsoon season the generation could be lower due to lower amounts of sunlight. Similarly, hydroelectricity generation varies significantly from one season to another in New Zealand due to variable rainfall [45].

(iii) *Trend of demand growth*
Both in developed and developing countries, demand for electricity is increasing. In the former case, this is due to the adoption of new technology such as electric vehicles, whereas demand is increasing almost exponentially in the latter case due to industrialization and increased numbers of electrical appliances in households [21, 46]. Therefore, countries with increasing demand may favor grid expansion by integrating more renewable options. This might be true for developed countries with renewable potential such as wind, for example, in New Zealand [38], but not so for countries like Bangladesh, where renewable resources are limited.

(iv) *Density and distribution of population*
This is a crucial parameter to be taken into account during renewable energy planning. For example, a densely populated area is not suitable for a large renewable energy generation plant such as a solar power plant. Thus, the Bangladesh *government is looking to use the rooftops of factories and public agencies to generate about 300 MW of clean electricity through solar photovoltaics.*[2] In contrast, sparsely populated areas are suitable for renewable energy generation technologies such as wind farms.

(v) *Interconnection to directly neighboring countries*
"*Interconnections allow the exchange of power with neighboring systems, helping a country to balance the system in case of oversupply (through power export) or a supply deficit (through power import)*" [44]. "*For instance, during the period April-June, demand is high in Bangladesh but low in the north-east of India, Nepal, and Bhutan grids. Hence, surplus power can be transmitted from those three countries to Bangladesh*" [25], (Reprinted by permission of the publisher).

Due to these distinct characteristics, transition to sustainability in the electricity generation sector varies significantly from one nation to another. Sustainable energy transition plans must be checked through a framework as proposed in this chapter. Thus, wind technology was found to be 'costly and not SEIP' for Bangladesh (Fig. 10). In contrast, electricity generation from wind was found to be in the first quadrant, that is, a sustainable energy infrastructure for New Zealand (Fig. 12).

[2] https://www.thedailystar.net/business/government-eyes-300mw-rooftop-solar-power-1801123 (accessed 13-Dec-2019).

## 6 Conclusion

Existing energy generation systems are considered by stability and lock-in, thus, transition to a more sustainable energy system is difficult with existing traditional generation expansion planning. This is a very common scenario in infrastructure systems in the electricity sector. Typically, the primary investments in electricity generation plants or distribution networks slow down the transition to a new sustainable system. Although sustainable transition is taking place in the developed world, it is rarely seen in the developing world. This is predominantly due to the lack of a proper sustainable energy infrastructure planning framework for energy-related policymaking. Therefore, a framework is proposed in this chapter that could serve sustainable energy planning in the electricity generation sector for the developing economies.

Overall, the proposed sustainable energy planning framework inculcates the required confidence of the entity, who is responsible for planning and implementing the future energy generation expansion plan. The framework also assists in achieving government goals in the energy sector, and helps to avoid any market bias or dominance, such as the fossil fuel dominated electricity market to make maximum profit. Sustainability assessment related framework is complex, shaped by many economic, social, and environmental factors, some of which are essential to the given context (e.g., location), whereas others are influential but optional. The sustainable energy infrastructure planning framework is proposed to deal with these different factors and their influences in an integrated multidisciplinary way. The sustainable energy infrastructure planning framework is proposed in part to support policymaking and form proper regulations to achieve sustainable energy infrastructure planning in the electricity sector.

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# Sustainable Energy Transition in Sub-Saharan Africa

**Charles Adulugba**

**Abstract** There are little or no records of regions in Sub-Saharan Africa involved in key energy transition programs. Nearly all the countries in the sub-Saharan African region and developing countries rely on fossil fuels and low-efficiency hydro systems for energy generation. With a global shift towards more sustainable, cleaner, and renewable forms of energy generation, these countries must seek new ways to transition from their reliance on old methods to more modern and efficient means of energy generation. In addition, there is a severely negative impact from the generation of energy using these inefficient and environmentally harmful methods. The consequences are far-reaching as the health and economic life of the inhabitants of the region are negatively affected. Furthermore, the theft and vandalism of energy generation and transmission infrastructure and social insecurity in the region has led to very low efficiencies in capacity leading to huge wastes of natural and human resources. This chapter explores the feasibility and necessity of energy transition in the Sub-Saharan African region. It also analysis both the prospects and challenges that are faced by the people and the governments in the region while proffering solutions. Analysis of the situation is made through empirical evidence from studies and previous research works. The findings indicate that sustainable energy transition in Sub-Saharan Africa is achievable but is intricately woven with several pertinent environmental factors and that the general progress and development of nearly all facets of the environment relies heavily on the energy transition of the region which must be made timely.

**Keywords** Renewable energy · Energy transition · Sub-Saharan Africa · Carbon footprint · Energy crisis · Energy security · Electricity generation · Fossil fuel · Solar energy · Biomass

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## 1 Introduction

Forty-eight of Africa's fifty-four countries which make up Sub-Saharan Africa (SSA) is home to nearly 1 billion people, but it remains one of the poorest regions of the world as regards electricity. About 600 million people within the region currently lack access to electricity and 80% of those with electricity access are connected to unreliable grids that supply insufficient energy with negative economic and health implications [1]. The access rate to electricity of countries within the region is estimated to be a little above 40% with the annual average electricity consumption per capita recorded to be around 185 kilowatt-hours (kWh), which is about 15% when compared to the 3,000 kWh per capita global average. The total generation capacity of Africa as of 2018 was about 245 GW which compares to a quarter of the capacity installed in European countries. The picture is even worse as South Africa and North African countries, account for around 165 GW of this installed capacity [1], without accounting for other factors that reduce the overall capacity. The International Energy Agency (IEA) forecasts the total demand for electricity in Africa to increase at an average rate of 4% a year through 2040 but also projects that about half a billion people will still lack electricity access due to population growth. Full electricity access is expected to be achieved in 2080. Wealth inequality and the cost of available electricity makes electricity unaffordable even for some with access to the grid, this situation gives rise to other problems such as poor health, lack of proper educational facilities and, slow economic growth [1, 2]. There is also a lack of proper grid infrastructure and overdependence on fossil fuel which also has negative effects on the health of the people and the environment. Technical, financial, and policy issues also plague the energy sector of the region, but a proper collaboration of public-private partnerships can provide solutions to a smooth and successful energy transition for the region [3].

The problem of electricity in sub-Saharan Africa (SSA) is a complex one, the region is in desperate need of technological advancement and development, and this largely hinges on the availability of reliable energy [3]. With the present global push for net-zero emissions and cuts in carbon emission, most countries in the region find themselves caught in between the dilemma of either having to go after sufficient and reliable energy for their ever-increasing population or focusing on reducing emissions as a result of energy generation [1, 4, 5]. The temptation to ignore the negative impact of greenhouse gas emissions in pursuit of adequate electricity irrespective of the environmental impact is hard to overcome since leaders in the region have realized the link between energy and poverty alleviation. But the governments of sub-Saharan Africa do not have much of a choice since energy transition is inevitable with the current global push for clean energy and it guarantees sufficient, reliable, and sustainable energy. More so, there has not been any concrete proof that there is a relationship between poverty alleviation and the increase of $CO_2$ emissions—as some studies have suggested; although findings have shown that sustainable energy transition can reduce both poverty and the carbon footprint [6].

There is a huge energy crisis in SSA, and despite its renewable energy potential, a large portion of the funds invested in tackling the energy crisis has been used to procure alternative energy that is inefficient, expensive, and in most cases dangerous to the health of the people and the environment. From records of previous years, it can be deduced that at least 32 TWh Energy demand was met using backup generators in 2019 alone, but this has severe impacts on the environment and the health of the people of the region. The fast-growing population of SSA makes the energy situation even more difficult to solve as projections suggest the energy demand of the region will double by 2030 [7]. A radical and effective approach must be put in place to address all these issues by the regional governments with consideration for current global trends. If success will be recorded in transitioning to more reliable and clean energy from the current energy generation methods, renewable energy must play a very central role in the process.

With the population projected to increase in SSA between now and 2050, energy demand will implicitly increase in the region as well. The United Nations' goal of global electrification by 2030 means that at least 84 million people must be provided with electricity annually. This is a difficult task as currently, over 1.06 billion people in the world have no access to electricity with well over 630 million of that number living in SSA [8]. The situation gets more complex since most of the population of SSA reside in rural areas where access to grid electricity is absent, the most practical means of providing electricity to those areas will therefore be through stand-alone infrastructure. This again poses a new challenge as huge sums will be required to be invested to achieve this goal. Financial constraints have been one of the problems that have plagued the energy sector like many other sectors over the years and this problem has remained until now. Corruption, theft, and vandalism of energy assets have dealt huge blows to the successful achievement of adequate and reliable energy in the region. Among other technical and environmental factors, this social vice must be tackled as well to record a successful transition.

## 2 Energy and Environment in Sub-Saharan Africa

Sub-Saharan Africa is home to almost 50 developing countries, most of which struggle to provide enough energy that will lead to the development of their regions. With only 7 countries in the Sub-Saharan African (SSA) Region having over 50% access to electricity, the region is in dire need of a reliable energy supply but the conventional methods of energy generation and centralized grid systems cannot meet the required demand [7]. This has been the perennial pursuit for most of these countries and the problem has become more difficult to handle with the increasing population and subsequent increase in demand for electricity. The problem is not only about sufficient energy generation but also the efficiency of the methods of generation and transmission and consideration for the carbon footprints which most of these energy generation methods leave behind. Stakeholders, policymakers, and investors have unanimously agreed that they must take multiple pathways to solve the energy crisis and achieving the required energy goal of SSA. High level, transparent and detailed scenarios have been drawn up to present a clear picture to stakeholders of all the work that is required in the energy sector of SSA to meet the energy targets by 2030.

Statistical projections from experiments and forecasts have shown that installed generation capacity will grow up to 3 times by 2030, but analysts have suggested that at least 10 times the present generation will be needed to meet the required demand which represents a 13% annual growth rate [1, 9]. These figures seem discouraging, but they tell the disparate tale of the energy crises of the region. Foreign investors, private firms and, Public-Private Partnerships agreements will need to be made for this huge challenge to be conquered. The private sector is particularly key in this project as it has proven to be the best option for successful projects but with a daily per capita income of only about $2, most of the rural inhabitants of SSA are simply unable to contribute to this transition and have to continue relying on crude sources of energy such as coal fires and firewood. The government has to play a role in encouraging the involvement of the private sector. The cost of connection to the grid for a domestic home is around $400 which is largely beyond the reach of many homes in the rural communities; this is as a result of comparatively high costs of energy generation in SSA compared with other parts of the world. Southern African Power Pool (SAPP) was $72.3/MWh in 2016–2017 compared with NordPool, the largest electricity market in Europe, which was $34.6/MWh in 2017. This high cost is linked to many factors such as poor grid maintenance and operation, low efficiencies in energy generation and transmission, illegal connection and, electricity theft among many other factors [8].

Energy transition is essential not only in the sub-Saharan African region but globally, this transition is important especially at this helps in tackling the problems of global warming and to solve the climate change problem, and to guarantee energy security. Barasa [7] stated that energy generation accounts for over two-thirds of the anthropogenic greenhouse gas emissions, this figure may be higher in the sub-Saharan African region even though it is not as industrialized as some of the more advanced countries like China and the United States. The heavy dependence on fossils for energy generation with very little strides made in the area of Renewable Energy (RE) is responsible for this situation. Currently, IEA studies indicate that the combined generated energy from all RE schemes except for solar will reach 12GW by 2040 which will be only 15% of the total generated energy. 26% will be generated by hydro to make up for the 1540TWh projected and this indicates that SSA is projected to be about 60% dependent on fossil fuels even by 2050. The prospects for any region with this forecast are not promising as it suggests that a large portion of SSA will lack access to clean and reliable energy well into the future.

The quality of life and the level of the general development of the people within the region will improve as more of them begin to get access to reliable and sufficient energy. The governments in the region have not shown any real commitment to other forms of energy generation aside from fossil fuels. Biomass especially has been seen as a retrogressive source of energy and wrongly believed to be harmful to the environment hence there has not been any drive to improve energy generation from biomass. The governments in Africa need to realize, that biomass is capable of generating revenue flow from the urban to the rural areas, create employment, and increase the level of energy security of the region and not focus solely on foils for energy reliability and generation [1, 10]. At least 1000 TWh can be saved if the energy standards in the region become efficient and employ advanced technologies to improve industrial and commercial process heating, cooking, and air conditioning [7]. This is an area where biomass can play a very crucial role.

## 3 Feasibility of Energy Transition

Research has shown a huge energy potential in the region with several renewable sources, less than 10% of the hydroelectric potential has been harnessed, and not up 1% of its geothermal potential is currently used [11]. As of 2011, only 60 MW of the estimated geothermal capacity of 14,000 MW had been tapped [12]. The African Energy Policy Research Network has submitted that the electrical needs of the 16 southeastern countries in SSA can be met from agricultural waste in the form of biomass with bagasse-based cogeneration. Also, it has been estimated that South African coal power can be replaced by the use of hydroelectric from the Democratic Republic of the Congo which could cut down carbon dioxide emissions by up to 40 million tons annually [12]. 25% of Mauritius' energy is produced through the use of by-product cogeneration from the sugar industry, and it is projected to be capable of producing up to 13 times more with widespread rollout cogeneration technology and process optimization [11]. Karekezi, [13] as far back as 2003, outlined the potential of SSA as vast in energy production from fossils as well as RE sighting Africa's huge RE potentials especially in solar and bioenergy; but not much has been done since to harness it. The current electricity generation mix of the SSA region is shown in Fig. 1, as indicated, biomass, wind, and solar remain largely untapped, a successful

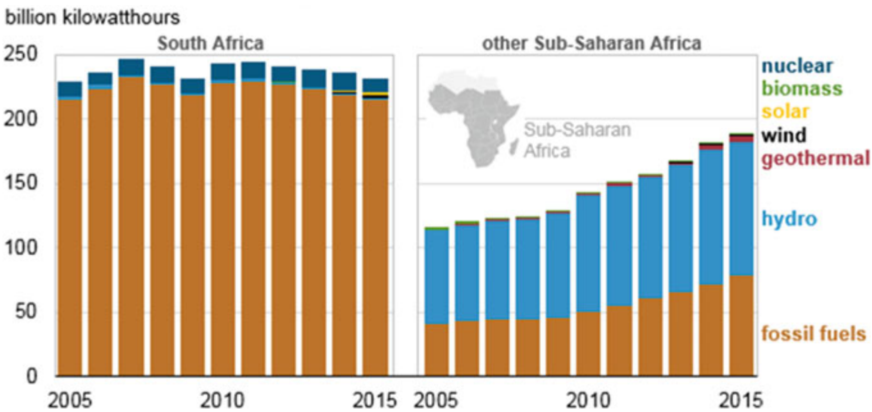


**Fig. 1** Sub-Saharan Africa electricity generation mix (2005–2015) [36]

energy transition for the region will require the exploration of all possible energy generation methods.

The decision of the most viable RE resource in any given area is not always a very obvious one to make; extensive investigation needs to be done before selecting a renewable resource for energy generation. The cost of implementation and running the energy source, the pollution and disruption to the immediate environment, and the ability for the energy source to be expanded and relied upon are some areas that will determine the feasibility of any energy resource that will be used in energy transition [1, 5]. Some researchers suggested that renewable energy could as well be the least cost electricity solution for the sub-Saharan African region with studies indicating that RE is sufficient to cover 866.4 TWh estimated electricity demand by the year 2030, and solar PV and High Voltage Direct Current (HVDC) grids have been analyzed to be one of the most reliable sources [7]. Figure 2 shows PV as the most tapped RE resource followed by onshore wind and run-off hydro. While the best choice of RE to be used is determined by the actual geographical location in

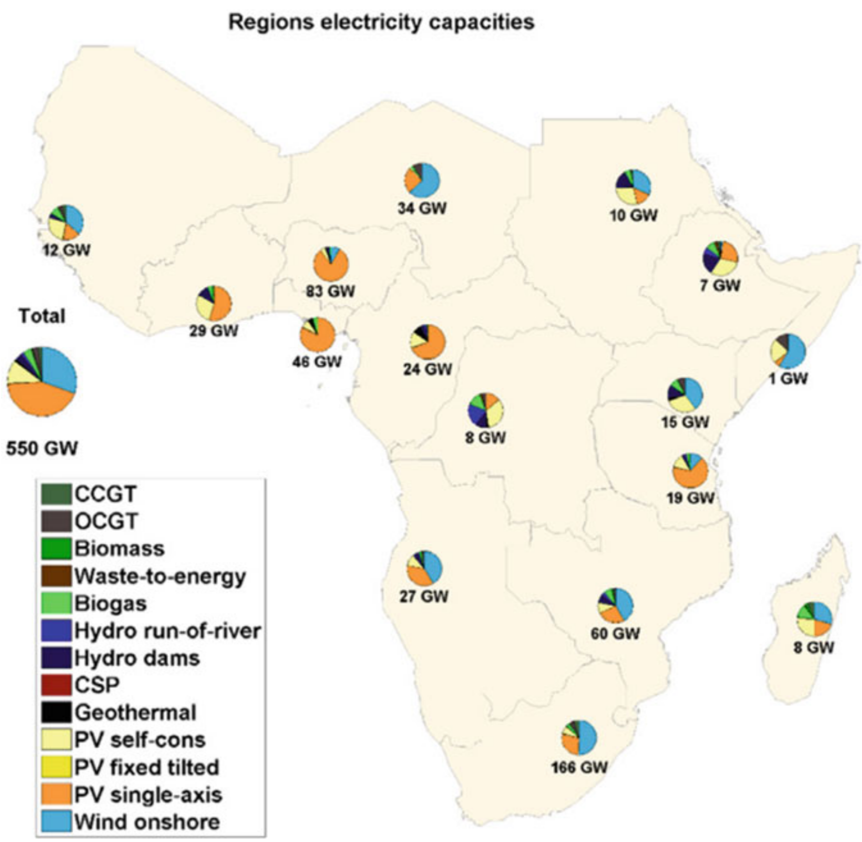


**Fig. 2** Installed capacity of integrated RE schemes [7]

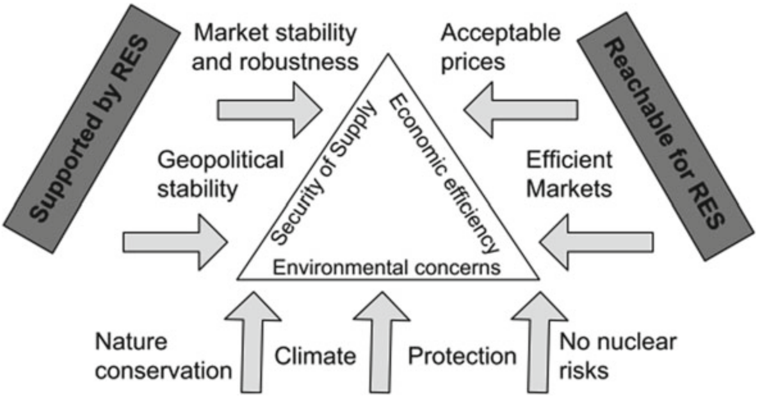


**Fig. 3** Energy triangle showing the essential requirements for a sustainable energy supply system [5]

Africa, many other RE schemes can also be harnessed if properly investigated, and effective and innovative solutions employed.

There are large quantities of renewable energy sources in most of the African countries of sub-Saharan Africa [5, 7], solar, hydro, biomass, biogas, wind, tides and waves, hydrogen and geothermal being some of the most abundant renewable energy resources in the region. However, the integration of RE sources to the existing structure in the region for the expansion of energy is not always straight forward as many factors come into play to determine how well the system can perform. The market stability and robustness of the resource and the scheme, the availability of the resource, and the impact on the environment are some of the areas that will determine how well the RE scheme will perform. Figure 3 is an energy triangle that shows the essential requirements of a sustainable energy system, this model can be borrowed to investigate the most effective RE energy system for any particular are with SSA.

Energy transition can be approached in a flexible manner. Hybrid systems can be employed to complement each other depending on the season or the location in which they are installed and for the purposes for which the are intended. PV and wind energy have been seen to complement each other well, biomass can be integrated with hydro plants to boost the backup and installed capacity up to 15%. It has been predicted that one-third of the renewable energy required to meet 50% demand of SSA can come from hydropower while the remainder from solar PV, Concentrated Solar Plants (CSP) and, wind energy [7]. Renewable Energy systems can be set up using business models, most of the conventional models are too expensive for rural communities, Vanadzina [8] presents four solutions for rural electrification;

i. Nano-scale such as Solar Home Systems (SHS) with a capacity between 10–80 W, which basically are used for powering lights or/and small household appliances.

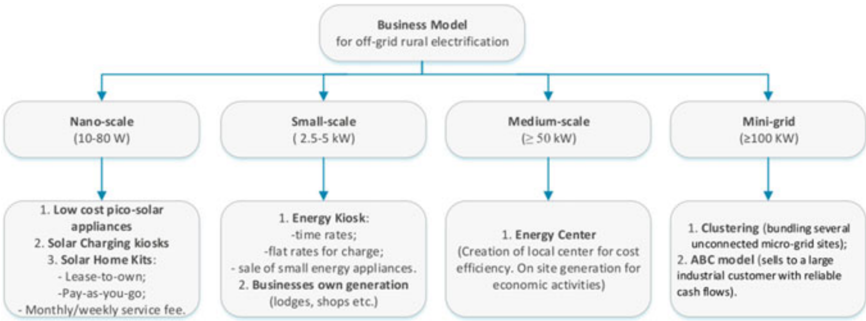


**Fig. 4** Business model schematic for off-grid rural electrification in SSA [8]

ii. Micro-scale power installations which are intended to supply one entrepreneurial point or public institutions (such as school, police station, clinic, etc.) of up to 5 KW.
iii. Micro-scale power installations which are intended to supply one entrepreneurial point or public institutions (such as school, police station, clinic, etc.) of up to 5 KW.
iv. Mini-grid with capacity of more than 100 kW, consisting of a base station and distribution grid extensions to the consumers.

The business model in Fig. 4 presents an ideal approach for governments of the SSA region to use especially in tackling rural electrification.

These energy system models can be used as a means of predicting energy pathways for small households and large businesses, which will in turn help in the formulation of policies for the energy sector. Analysis of the energy demand of various settlements shows that urban households' energy consumption will increase significantly by 2050 and cooking is the most energy-intensive end-use. Transitioning from fuelwood to LPG cooking gas (Liquefied Petroleum Gas) for cooking increases $CO_2$ emissions but reduces the indoor pollution of the households. It has been seen that the energy models indicate that biogas and electricity are the more economically friendly option for cooking in SSA but more useful and effective policies need to ensure sustainable energy transition for the domestic energy sector [14].

## *3.1 Generation*

Different approaches have been taken to propose the most feasible and cost-efficient generation strategies to meet the ever-growing energy needs on the African continent. There are several inefficiencies and losses in the energy system of the region and these losses are present not only at generation but also during transmission. The transitioning from fossil-based generation which is commonplace in SSA to cleaner and more efficient and sustainable methods is a task that currently burdens the governments of the region. Until recently, only hydropower had been explored as a renewable energy source. Fuelwood has only been used largely only for heating and cooking in rural areas, but no major strides have been taken in the processing and transitioning to biomass. Wind energy has not been harnessed as much as hydro and, solar; this is partly because the wind energy potential is not as promising and abundant as that of solar PV and hydro. Coastal countries in the north of Africa, South Africa, and a few countries in the east of Africa such as Ethiopia and Kenya where there is relatively good wind resource have seen relatively fair progress in wind generation [15].

### 3.1.1 Biomass

Biomass has always been accorded a low profile in energy policies SSA. There is clear prejudice and side-lining of the sector and this has translated to the apparent lack of support for biomass in the region. Generally, this trend could be said to have had negative effects on many countries in SSA which have not benefited as they could have from biomass. The focus has been on its eradication rather than its modernization to make it more efficient and robust. Policymakers erroneously due partly to not fully understanding biomass development have failed to provide policies to develop the sector, efforts should therefore be put in place to raise the awareness of the benefits of biomass and its prospects in order to support it so that maximum benefits could be derived from it [1, 10]. Research has shown that 1500 ha of land can grow energy crops to produce up to 20,000L of biodiesel per day and the Barrick Gold Mining Corporation (BGMC) a private company in Tanzania implemented this scheme [16], such schemes when implemented and supported by the governments of the region can dramatically transform the energy landscape of SSA.

SSA has been identified as having high potentials for the production of biomass since it has vast amounts of arable land and favourable climates. Krausmann [17] has submitted that at least 5% of agricultural land will be needed to meet 100% of RE. Land availability for sustainable biomass feedstocks is expected to shrink further with the growth of the population of SSA especially in the communities where biomass is largely used for cooking and heating. Also, substituting wood fuel biomass for electricity is not a straightforward approach as they meet different energy demands in the domestic space in the region. The ripple effects of industrial production of biomass could be felt in the reduction of farming lands and by extension food availability. Lands, which are unsuitable for farming, could be recovered to plant biomass feedstocks. This is a necessary approach as biomass remains a good alternative to fossils, but much planning must be done. Policies and legislation must be put in place to protect forests and vegetation and to encourage reforestation.

Biofuel initiatives have been implemented in SSA by private bodies and non-governmental organizations for the last 35 years. Almost all these initiatives are largely driven by foreign investors such as the Ethanol Company of Malawi. Projects conducted by multinational companies are being implemented to increase the production of biofuels in the region such as those in Tanzania but foreign investors only seek financial gains from the region due to the conducive environment for the energy crops such as sugarcane, sweet sorghum, and palm oil but show no substantial commitment to develop the region or improve the lives of the people. Many have called for the reduction or eradication of biomass because of negative and biased perceptions that it is inefficient and dirty. For example, Malawi seeks to reduce biomass energy consumption from 93% to 50% by 2020 while introducing nuclear power by 2050. Also, Tanzania's second National Strategy for Growth and Reduction of Poverty (2010–2015) endorsed a switch from wood fuel biomass to other energy sources such as electricity and doubled the access to "clean and affordable" substitutes [10].

### 3.1.2 PV

Photo Voltaic (PV) and Concentrated Solar Power (CSP) remain the dominant technology in SSA with a potential of generating up to 9261TWh and is projected to be capable of powering nearly 10 times the current electricity demand of the region. Studies have shown that it is also suited for the integration of desalination and gas sectors and for achieving 100% renewable energy in SSA [7]. PV has also been seen as one of the best options for powering domestic needs especially in rural areas where most of the population reside and where there is very little or no access to the grid network. Like all other renewable sources, PV has its own risks which over the years since it has been introduced in the region have been seen to be quite difficult to manage depending on its purpose or the area or location it is installed. The selection of sites for establishing solar PV plants has inherent site-specific risks and technical issues such as geotechnical, grid connection and, solar irradiation uncertainties. The Global Solar Irradiation (GHI) map in Fig. 5 for Sub-Sahara Africa shows that over 95% of locations within SSA receive at least 1826 kWh/m$^2$ annually which is encouraging for energy generation from solar.

Risks are more pronounced when government led panels design projects and select sites compared to private developer-led site selection [18]. There is also the ever-present danger of vandalization of installations and assets which has been prevalent in some parts of SSA such as Nigeria. These reasons are among some of the immediate factors and other associated factors that make investors sceptical about investing in PV energy in the sub-Saharan African region [18]. Notwithstanding, with proper focus on the optimization of PV installations and good site selection, the prospects of energy transition using PV in the region are high.

### 3.1.3 Hydro

With hydro energy schemes having longer life spans of about 40 years [7] compared to 20–25 years for PV, it remains one of the most attractive methods of energy generation in parts of SSA that have access to water resources. Central and southern Africa have one of the best hydro potentials in SSA with Congo DRC, Mozambique, Zambia, Cameroon, Ethiopia, Sudan, and Nigeria among the top [19]. Multiple rivers flow

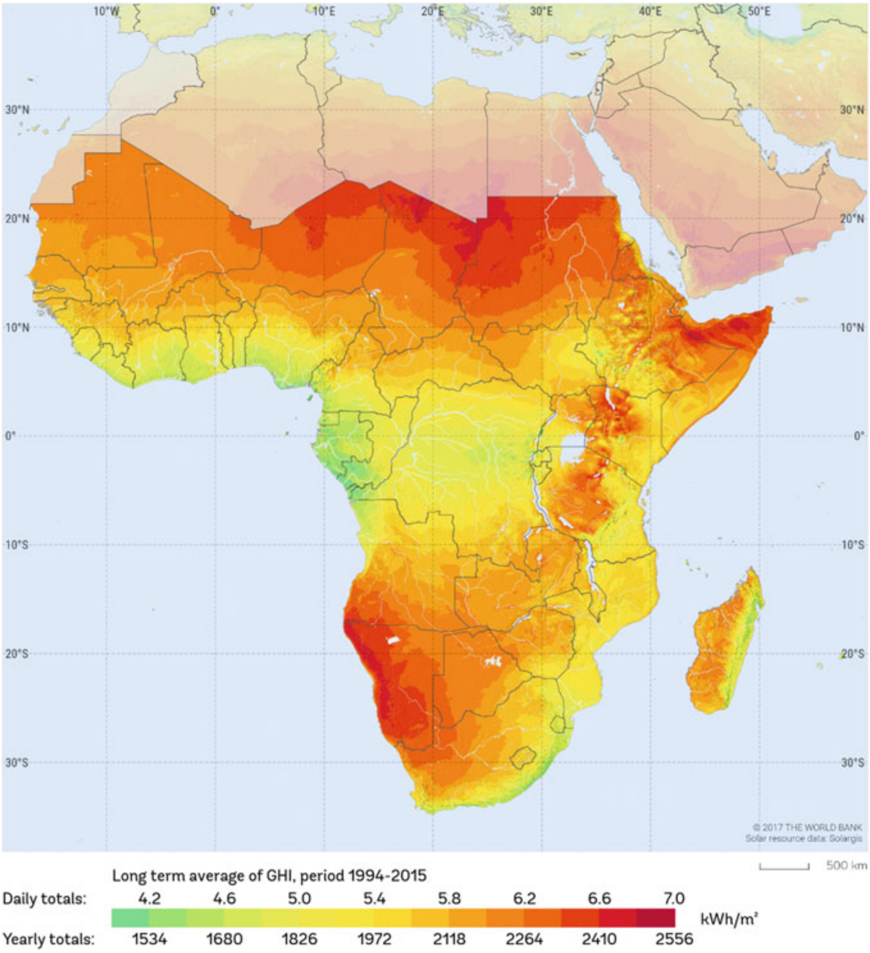


**Fig. 5** Global solar irradiation (GHI) for Sub-Sahara Africa [37]

through central Africa which makes it have one of the best hydro-electric resource that could replace the use of coal which would ultimately cut down on the carbon dioxide emission levels [12].

### 3.1.4 Wind

Wind energy has not been as popular an option in Africa as Solar PV has been and has not been installed on large scales or for domestic dwellings as PV has. Africa has an average annual wind speed of at least 4 meters per second (m/s), which is less than the required minimum of 6 m/s needed for utility-scale wind power plants. This has made wind attractive only to coastal countries of Africa, South Africa, Ethiopia

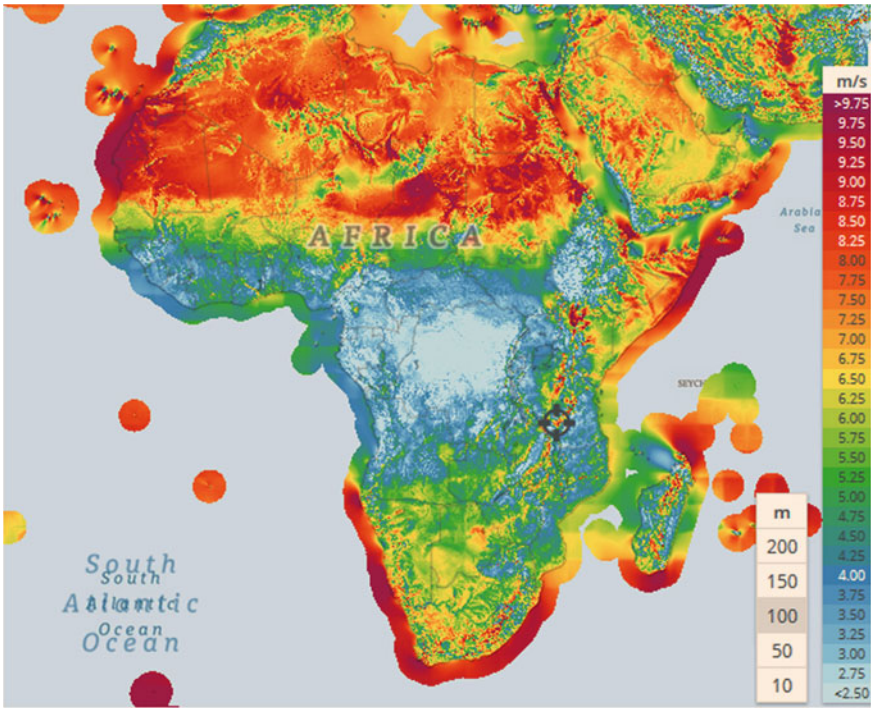


**Fig. 6** Onshore wind speed for Sub-Sahara Africa [38]

and Kenya, and countries towards the north among the few countries in SSA that have installed wind generation capacity and are planning on expansion which could see an appreciable impact from wind energy by 2030 [15]. The input from wind may seem small but its contribution to the energy transition drive of Africa and SSA in particular, go a long way. Figure 6 shows some coastal countries in the south and countries in the north of SSA having average wind speeds of 8 m/s which is sufficient to generate electricity for the RE resource.

### 3.1.5 Geothermal

The geothermal potential in East Africa has given cause for the drive to harness geothermal power from the region, the arid climate makes this a preferred choice [20]. Countries within the central parts of the region and towards the west also have geothermal capacities but have not explored the sector and have not made sufficient investments in geothermal RE [7].

### 3.1.6 Hybrid and Decentralized Systems

There is currently no technical or cost analysis and financial breakdown of Hybrid mini-grids in SSA and this information is crucial to determine and overcome challenges in rural electrification planning, regulation, life-cycle operation, financing, and funding. This information on hybrid systems will help tremendously in the electrification of rural areas especially those without grid access, but where renewable energy sources abound. It is agreed that PV-hybrid mini-grids have the potential to provide energy for the rural population of SSA, but the pre-evaluation of the sector is lacking due to inadequate, unreliable, or unavailable information such as costs and performance of PV/hybrid. This has therefore kept stakeholders at bay as they remain uncertain about the outcomes of investing in the sector [21]. Notwithstanding, the overview of PV/hybrid mini-grids in Sub-Saharan Africa shows that renewable energy (RE) based mini-grid sector is growing slowly and beginning to attract the attention and interest of investors from both the public and private sectors.

The Africa Progress Panel has called for the diversification of energy generation through energy mix with a focus on off-grid systems with PV in the mix. There is also a push for the reduction of the costs for implementation of the system through replicable models which strengthen the SSA market and in turn reduces investment risks [21]. The present energy generation technologies can be applied in a decentralized way with the combination of energy efficiency measures for zero-emissions which will deliver low carbon energy systems. Produced energy from hybrid systems can be in form of heat and electricity which can supplement other forms of generated energy which could be from wind, biomass, and hydro. High efficiency generation using natural gas can also be employed in hybrid systems to supplement production to meet the required demand [22].

## *3.2 Transmission*

Different schemes or methods in which generated electricity could be used to transmitted generated energy across the SSA. These include Regional-wide, where different sub-regions within SSA operate independently to generate and transmit required demand; Country-wide, where HVDC lines all lie within a countries borders; Area-wide, which requires sub-regions to be interconnected using HVDC lines, and an integrated scenario. The integrated scenario will make use of different technologies for generation and transmission and is expected to be more robust and flexible and to meet other demands apart from electricity demand such as industrial gas demand [7]. HVDC transmission is seen as the least cost solution to solving the transmission challenge of SSA by 2030 and the integration of water desalination and industrial gas sectors further reduces the overall costs [7]. Figure 7 shows the SSA Sub-region Transmission HVDC existing and planned line configuration which would facilitate the transmission of the generated energy across the whole region.


**Fig. 7** SSA Sub-region transmission line configuration [7]

## *3.3 Distribution*

Energy distribution in sub-Saharan Africa faces a fair share of challenge; distribution assets are regularly vandalized and key infrastructure stolen. Another major area of daunting challenge with distribution so far is with energy theft, meter bypass, illegal connections, failure of, and the inability of utility distribution companies to collect bills. This is aggravated by the fact that many homes in SSA are not properly marked and households are not clearly identifiable, making it increasingly difficult to bill residences for energy consumed. This situation puts a strain on the general system, and it creates a ripple effect as energy distribution utility companies fail to make required remittances to transmission companies which also can remit effectively to generating companies. A subsequent collapse of the entire system usually becomes inevitable if funds are not injected into the system.

This trend can be mitigated when micro-generation techniques are used as it will narrow the focus to the few homes connected to such systems which will make billing and metering much easier to operate and maintain.

# 4 Challenges of Energy Transition in the Sub-Saharan Africa Region

The lack of adequate infrastructure on ground in sub-Saharan Africa and the apparent lack of government commitment to energy transition are some of the challenges that energy transition will face. Other immediate challenges include limited capital investments, restricted power generation planning, and the lack of adequate skilled manpower for RE developments in the sector. This leads to increased cases of system failure and an unreliable system. Security and vandalism are also another challenge faced in the sub-Saharan African region, conflicts and wars in some parts of Africa have led to the crippling and in some cases, the total collapse of the grid system. The financial implication for transitioning to more reliable, efficient, and safer methods of energy generation and consumption is also a major challenge for SSA as most of its inhabitants cannot afford electricity costs. New methods employed in energy transition will therefore need to be affordable by the common man [20].

## *4.1 Policies*

Energy policies and strategy development are not always implemented due to inconsistencies in government activities in the region, also, not all the authorities in the region have come on board to implement and enact policies to solve the energy crises. Only 13 governments out of the 35 in SSA have set and met the strategic targets they set for themselves for more advanced fuels such as liquefied petroleum gas and natural gas. Despite this being a major energy sector in SSA that must be considered in any development strategy, only seven have moved to improve wood and charcoal stoves [10]. It has been noted that many of the governments do not have any regulatory frameworks which make it difficult to follow any set of rules and to achieve the energy goal of their countries. This has made some private firms take advantage of the opportunity to the detriment of the localities where they operate. They acquire large expanses of land in a rather uncontrolled manner for growing energy crops and other related activities at the expense of food crops and small-scale farmers.

Public-Private Partnership (PPP) can help fix this problem as they help to mobilize financial resources for development [16]. This set of stakeholders however also need the security and guarantee from government policies to protect their investments and ensure that policies are adhered strictly to. A survey showed that countries across Africa have failed to consider individual energy access as an essential part of their development strategy. There is also a call for transnational initiatives such as the Chad-Cameroon pipeline to aid and speed up the development of the energy sector of the region. The United State of America pledged $2 Billion in capacity-building projects, policy and regulatory development, public-private partnerships, and loan guarantees to leverage private investment in clean energy technologies. There is also an initiative in South Africa to connect 500 million people to modern energy by 2025, a few other countries in SSA have shown some level of commitment to energy transition by the policies they make, but much work is still to be done [20].

The policies as a matter of necessity need to focus on rural areas for innovative and conventional business models [8]. The governments need to seek ways to diversify the Renewable Energy they have and harness the potential across its vastly different climatic zones, and consideration must be given to electricity grids that span across countries for the stability of energy supply. As mentioned earlier, this calls for cross-boarder cooperation among countries within the region for projects such as the installation of large dams to cater to regions and not just countries. With Hydroelectric capacity expected to reach 93GW by 2040, clear and visionary policies must be put in place to help with the development of the project and guide the regulatory framework especially in the area of biofuels. The policies will spell out clearly where the government is to come in and how the efforts of both the government and the private sector can be assessed and monitored while maintaining the vision of the country or government of the region.

The positive impact of functional policies will attract foreign investors and international stakeholders and renew the interest of the private sector to invest in the energy sector [16]. Until now, policies if at all present, were not always very clear, for example, only Malawi, South Africa, and Nigeria having set out clear mandates for the consumption of ethanol. The regulatory bodies are usually absent or ineffective from the energy sector, and Europe, America, and other developed countries take advantage of the lack of proper policies in Africa to harness the biofuels. This leaves farmers and those in the rural areas disadvantaged us the opportunity to partake and joint businesses is taking away from them [16]. Public-Private partnership (PPP) is crucial if the energy sector of SSA must be developed and expanded. The governments of the region could give incentives and waivers to encourage participation and investments from the private and public sectors, Uganda has some incentives under which import duties on certain raw materials are refundable under value-added tax (VAT) and a duty drawback scheme [16].

## *4.2 Funding*

The energy sector in SSA is heavily underfunded compared to other regions of the world. This, among other factors, is responsible for the poor electricity and energy situation in the 49 counties of the region. In 2014, SSA with an estimated 800 million people had a generation capacity of less than 92GW, whereas Spain with a population of 45 million had an installed capacity of about 106GW. Over half of SSA generation is in South Africa, 48 other countries share the rest and only 14 countries in the region have more generate more than 1GW. Per capita installed capacity is 44 MW per 1 million people, India is 192 MW per million people and China is 815 per million [23]. The African Development Bank has estimated that a universal access system for all 53 countries in Africa would cost US$547 billion total to implement by 2030, this will require a lot of commitment from the authorities of the region as it will require US$27 billion per year for the period. Currently, the investment in the energy sector is still very far from this amount, only about US$4 billion is currently been invested in the energy sector annually including contributions by China and India. Foreign direct investment in the sector is generally very low in Africa as it receives less than 2% of foreign investment from across the world [24]. The problem of funding is made worse by the high upfront cost of many RE schemes and limited water resources in some regions. It has been seen that the World Bank, governments, and private investors are more confident with investing in tested conventional technologies than innovative ones targeted at the grassroots where energy is desperately needed [25].

Privatization can lead to the generation of funds for the sector, but this will come with inherent risks. It is therefore necessary for policies implemented to check any cons that may arise from privatization of the sector. It is expected that privatization will lead to increased efficiency and reduce overheads spent by governments on the system, this has been seen in Namibia and South Africa where electrification grew by about 40% in 15 years [26]. The downside of privatization is that while it offers many advantages, it could also be faced with issues such as increased market prices. It could also lead to a profitable customer ignoring or avoiding to risk of expanding the service to cover the rural areas and poor customers. Extension of the grid and services may prove too expensive for private firms especially if they have to connect low population density areas. Privatization if not managed properly will negatively affect the poorest of society [24, 26].

Having a Business Model (BM) helps with attracting funding, a business model is important as it provides a clear structure for achieving goals in developing countries. A Tariff-based model does not always solve the problem of business models as it is too expensive for small local communities. These models should have provision for Pico solar and Solar Home Systems to help to provide low capacity supply to low power supply to rural homes. Low costs energy projects and microloans schemes for energy development should also be considered as they can affect the shape of the energy landscape. Conventional generation and transmission grids are very difficult to fund due to high investment costs [8], larger scaled projects come with associated risks and are quite expensive to set up with investors not always available. This must therefore be considered when drawing up a BM. Rural electrification can be funded based on the project size and projects can be classified according to scale; 10–80 W nano-scale power solution which are powering lights or/and household appliances, such as solar home systems (SHS); 5 KW micro-scale power installations which are intended to supply one entrepreneurial point or public institutions such as school, police stations, clinics among others; 30–50 kW medium-scale solution which can serve as an energy centre for communities; and 100 kW and higher mini-grid, consisting of a base station and distribution grid extensions to the consumers. Some of these projects, especially the nanoscale and microscale, can be funded using pay-as-you-go schemes since they are more affordable for rural communities. The vast opportunities in the SSA can attract businesses seeking to make guaranteed profits in the communities. Mini-grid projects always need the intervention of NGOs or financial institutions that are not seeking to make any financial gains [8].

Greenpeace International [22] has mentioned some types of risks that could affect projects in SSA. Regulatory Risks arise as a result of sudden and adverse changes to policy and breeches to already signed contracts. It is agreed that policy security is vital for the success of the investments while it is advised that diversification of the investments across geographical areas; technology and regulatory jurisdictions can help mitigate this risk. Construction risks increase with the type and complexity of the technology involved and the cost of delivering the project, this makes the more common RE technologies less risky due to the fact that they are simple to design and implement. The quality of material used for the project determines the level of risk that could arise. Financial risks also abound in SSA, the misappropriation of funds and loans, the risk of interest rate, volatility, and refinancing at less favourable terms all contribute to different types of financial risks operational risks such as reduced primary RE source which include wind, heat, and insolation can adversely affect the business case of the project. Failure of equipment also constitutes operational risks. Designing the system with the worst-case scenario of RE sources and the use of reliable and premium equipment could help mitigate this risk [22].

Independent Power Projects (IPPs) remain the main source of investment in the power sector and it continues to grow which is a good trend but there is still more than 50 percent investment from the public sector which has not improved over the years. Private and foreign investors especially Chinese investors remain the key players in the energy sector of SSA and this picture may remain the same in the near future [27]. Figure 8 shows that IPPs are however more attractive to investors in some countries than in others due to instability which can be as a result of a host of issues in certain parts of the continent. The returns on investment are also another factor that attracts independent projects. The lack of IPPs has made some of the countries either lose some of their generation capacity or add nothing at all [27].

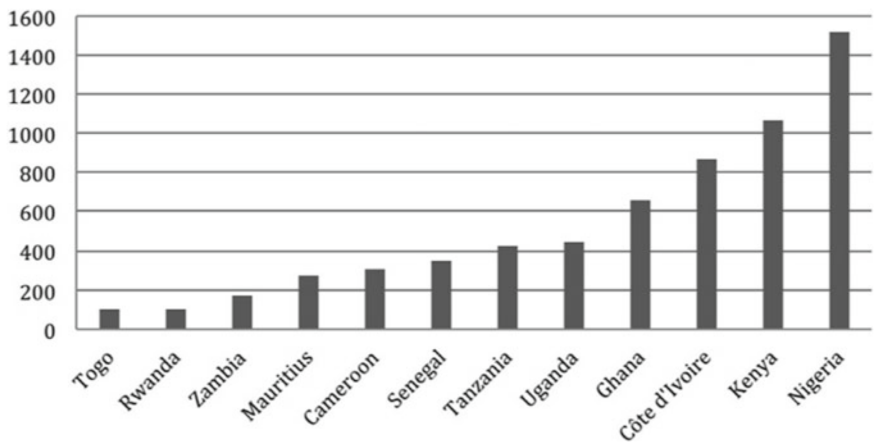


**Fig. 8** Countries with the most independent power project capacity (MW) in Sub-Saharan Africa from 1994–2014 (excluding South Africa) [27]

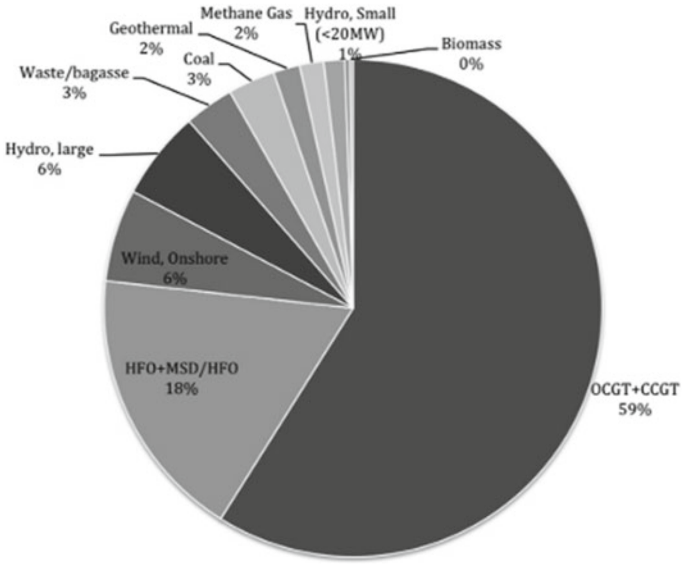


**Fig. 9** Independent power project capacity (% of MW) by technology in SSA (excluding South Africa) from 1994–2014 [27]

Figure 9 shows an overview of IPP involvement in power generation in SSA and is quickly seen that over 75% of IPP involvement is in fossils through gas turbines and heavy fuel oils, their involvement in RE is still very little in the region.

IPP in SSA has a capacity of about 600 MW with over two-thirds of them less than 100 MW. Over 82% are thermal and combined-cycle gas turbines. There is growth in RE schemes run by IPPs in Africa but it is small with PV, CSP, and Wind as the main RE growth areas, state institutions such as Nigerian National Petroleum Corporation NNPC the Ugandan Government have invested in IPPs, but the prominent players remain the private sector. The success of IPPs is linked to factors such as power markets and independent regulation but utility companies are not always creditworthy as a result of the poor performance of the system and their inability to grow. The common model for power sector reform is to unbundle, privatize, and create regulatory institutions and markets; but this has not always worked as expected and has not always attracted investors as projected. IPP are left with different structures and no clear restructuring plan, they are however still very important for energy transition in SSA. Most countries in the region with IPP have independent regulators who create a competetive procurement atmosphere and provide oversight that is fair to all players. The failure of these regulations therefore has been a source of disincentives to investors, it is imperative that the regulators are transparent, fair, and accountable since regulation is crucial. The quality of regulation and not the presence of a regulator has been seen to be more important in SSA [27].

### 4.3 Social Challenges

It is debated that Sub-Sahara Africa has enough land to support farming to feed the population and to grow energy crops for biofuels on the vast underutized land which can be developed and reclaimed for useful purposes. The production of biofuels and biomass can help in poverty alleviation and help to boost the economy especially for rural dwellers in SSA [16]. PV has social impacts on the communities it is installed in, it also uses up land [18], land is a scarce commodity in some localities in SSA. The problem of insurgency and civil unrest in some countries such as Nigeria, Central Africa Republic, and Sudan has affected the investments and discouraged intending investors in the energy sector of SSA [28]. The use of bioenergy has caused negative impacts on the ecosystem, soil fertility, water resources, and forests which the livelihoods of the citizens in some of the localities where bioenergy is used. The quest for energy must therefore not create other hardships for communities where the systems are set up.

The use of lands for energy generation especially RE energy generation has the tendency to reduce the availability of the resource and this could affect the health of the people as a result of limited resources that could cause food shortages and may also lead to conflicts as land tussle is common in many regions of SSA. Bioenergy and energy transition must not create social inequalities and undermine food security all of which could be potential risks when using RE schemes. Priority must be given to communities where projects are located over the global or wider community. Energy transition needs to be resource-efficient and cut down to the minimum of greenhouse emissions, and this could be a challenge [22]. The health implication of the use of fuelwood and inefficient stoves cannot be ignored, as at least 79,000 deaths are recorded annually from pollutants and suffocation from these sources of energy.

It is seen that some cultural norms in some localities influence the choice of cooking fuels which impacts negatively in the long run on the environment. These communities need sensitization programs to help curb this negative trend, forests are being depleted and RE schemes could further impact this trend negatively. The poor economic state of the majority of the people forces them to continue using energy-inefficient electrical appliances such as air conditioners and cookers which have long served their useful life. Cheap inefficient filament light bulbs are still very rampant in many localities across SSA. As mentioned earlier, a serious campaign must also be raised to instill a good energy culture in the people. Traveling across SSA, it is common to see security lights left on even in the daytime. Burst water pipes and leaking taps are also quite common. This situation can be blamed partly on the inconsistency and epileptic nature of the electric sources which make people forget to turn off switches when they leave home during blackouts. A good energy culture will also inform people to cut down on energy use by reducing their extravagant and luxury lifestyles [14].

Corruption remains a worm in the social fabric of SSA. Investments have been made in the energy sector over the years with little or nothing to show. It is estimated that at least $45.6 billion dollars was invested in sub-Saharan Africa with the exception of South Africa between 1990 and 2013, but the current situation of the electricity in the SSA region certainly does not reconcile with this amount. It is reported also that an estimate of a least $490 billion will be needed in investments for additional power generation capacity by 2040 if the current energy demand of the region is to be met [27].

### *4.4 Technical Challenges*

The lack of adequately skilled manpower to maintain and manage installations, especially the new technologies, could create a drawback for energy schemes to run smoothly, electricity is unreliable even in areas covered by the grid network and this affects the generality of the population including industries [26]. The incessant power outages lead to damages of equipment and discourage investors who seek to build factories in the region [29]. SSA also faces the problem of illegal connections which causes technical problems for the overall system. Theft of installed assets resulted in over 80 power failures in Tanzania, Uganda, and Kenya. That figure is much higher for bigger and more complex countries like Nigeria [8].

Transportation is an important element for the deployment and establishment of energy generating schemes around the continent. This raises another challenge—as many countries are land-locked and the transportation network is poor in the region [19].

### *4.5 RE Resource Availability and Environmental Impacts*

Water footprints and displacements impact on the local populace, there is already a shortage of water in some parts of SSA, poor rainfall in some parts of the continent have led to a reduction in hydroelectric outputs. Forest degradation and dessert encroachment are now issues of concern and have prompted agencies such as USAID to contribute to improve forest governance and reduce the rate of forest degradation and loss of biodiversity through protected area management, improved logging policies with the aim to achieve sustainable forest use by local inhabitants [30]. Forests and wildlife need to be protected but currently, they seem to be getting depleted faster than they are regenerated. Trees unnecessarily cut or harvested for bioenergy must be replaced to help combat climate change and environmental impacts and reduce the carbon footprint [22].

The shortage of land has led to bloody communal clashes and land tussle which has affected food production. The seven Sustainable Development Goals (SDG) seek to address some of the environmental challenges that affect RE resources availability by 2030 and some countries such as Nigeria have shown a level of commitment to the realization of the goals [14].

## 5 Benefits of Energy Transition in Sub-Saharan Africa

The SSA region will benefit from energy transition and consequently, the effects will be felt in the environments of the region since renewable energy remains the topmost resource to replace fossil fuels which Africa is blessed with an abundance of. The inexhaustive nature of RE makes it an important part of energy transition. Due to the vast amounts of land that need to be covered by the electricity Grid, many rural communities remain isolated from the electricity Grid. To eliminate energy poverty and cut down carbon footprints in the process of providing energy to these remote areas and in some cases densely populated areas, the use of RE technologies must be heavily employed [5]. RE benefits will lead to developments of the rural areas of the sub-Saharan African region and remote areas especially stand to benefit [7]. The current methods of energy generation depend largely on fossil energy sources and RE integration can help reduce the dependency on fossils on the energy transition path.

### *5.1 Energy Security*

With good solar irradiation prevalent in SSA, the prospects are very high and promising for energy generation through solar. The challenge of expensive transmission installations will be easily tackled for off-grid PV systems. The added advantage of this is that it also controls energy and asset theft and vandalism which is rampant in the region. Microgrids or SHS could solve the ugly situation of a very unreliable grid system and give the common masses access to reliable and affordable energy [8]. Diversity of generation will guarantee the availability of energy and energy security and also aid in energy transition as more efficient systems of energy generation will be employed There are prospects for development and technological advancement especially in combined heat and power CHP plants. This will also assist in climate change mitigation which countries all over the world are currently addressing.

Renewable energy sources will ensure flexibility of use, do not necessarily need to be processed or converted, and is readily available, it will also reduce the importation of electricity generating plants and benefit the region's land, climate, and labour. Modern sources of energy are properly processed before burning and have high efficiencies and clean combustion [10] which is beneficial to the environment and to human life.

### *5.2 Economy and Jobs Security*

Job employment and energy security, around 350 jobs-days are created for every TJ of energy consumed as against only about 100 and 20 job-days created by electricity and LPG respectively. Energy transition will trigger investment in the energy sector which will in turn create new jobs and boost the economy. Economic benefits will include the production and transportation of densified fuelwood to different parts of the world; the production of biomass for export requires land, sunshine, and labour which are surplus in the region [10]. Visagie [31], noted that biodiesel technology if harnessed will create jobs for disadvantaged people in the rural areas of the continent while ensuring energy security and reducing greenhouse gas at the same time. Solar water heaters and biodiesel technology which were installed in South Africa significantly diminished poverty through job empowerment and helped improve the general wellbeing of the people in that vicinity [31]. It has been predicted that renewable energy jobs will account for 98% of jobs in the energy sector by 2030 with the non-biomass sector accounting for declines in biomass energy production [22].

### 5.3 Education and Health

Energy can facilitate the development of schools and enhance learning, it can also help teachers gain access to a wide variety of teaching mechanisms such as computers, and access to the internet. Energy can contribute to the allowance for freedom of education [32]. It will help to provide a comfortable environment required for effective learning to take place. Many school facilities lack basic amenities such as electricity and water which impact negatively on the learning of pupils. Furthermore, students cannot read when they are home after school as most of them who dwell in rural areas have no access to electricity and remain in darkness at night. Norway supported a program in Kenya to replace locally made kerosene lamps—which are dangerous and have negative health effects on people—with alternative solar power. One other key prospect for energy transition in sub-Saharan Africa is that it will help build healthy social connections between students and neighbouring communities.

Energy access reduces the time needed to process and cook meals at the family level where especially the girl child is usually burdened with cooking chores leaving her too exhausted to rest and study well. Gender inequality has been very bad in Africa where the women who are often overburdened with home chores have little or no time for self-development and empowerment. Energy transition will therefore help provide smarter and more efficient ways to quickly complete chores such and washing, cleaning, and food processing and have time for personal development and career pursuits. Food preservation will also be more efficient, as it reduces food wastage and food poisoning from poorly preserved food. Modern energy reduces the harmful emissions from crude cookstoves, ensures better indoor ventilation and air quality, and gives access to cleaner water. This in turn improves maternal health and reduces the risks around childbirths especially at night. Combating diseases is also enhanced by modern energy as nearly all laboratory work must be done using electricity [24].

### 5.4 *Transportation*

The automobile fleet in SSA is about the oldest in the world and more cars are expected to add to that number at a fast-growing rate due to the rapid population growth of SSA. This will lead to increased environmental pollution from the transport sector and an increase in transportation costs. It is seen that individual mobility will become more expensive forcing commuters to opt for smaller more efficient cars as energy demand from transportation is expected to rise by 170% to 10,400 PJ/a. Electric and Hybrid cars will therefore become the preferred and more economical option for transportation as has been demonstrated in most advanced countries in recent years. This trend is expected to keep getting popular and also become mainstream on the African continent. Hydrogen and fuels produced using renewable energy such as biodiesel will further increase the input of RE in transportation as it is projected that electricity will provide 3% of the energy demand of the transport sector by 2030 and up to 25% by 2050. This number could be up to 35% when advanced developments are involved [22].

### 5.5 *Environmental Sustainability*

Renewable Energy technologies reduce the energy demand and carbon footprint from energy consumption, especially in the residential sector. Environmental sustainability is a major concern for governments across the world today as it directly has health implications on humans. This understanding is therefore expected to inform the fuel choices that the governments of SSA [14]. Access to contemporary energy to create jobs and modernize the agricultural sector to eliminate hunger and poverty will have a positive impact on the environment as destructive techniques will no longer be employed. Energy transition can facilitate sustainable development and control the degradation of land resources. The direct link between charcoal production and desertification and deforestation is a testament to this fact [24].

## 6 The Future of Energy Transition

More counties in sub-Saharan Africa will push to eradicate energy poverty and enable their citizens to utilize electricity, this is obvious by the fact that 25 countries in the region joined the United Nations Development Program and UN Capital Development Fund Global Clean Start program [20]. More countries are going to collaborate to have regional pools that will solve the problem of isolation which makes it more difficult and complex to generate and transmit electricity across the regions of the continent. This will help countries support each other by sharing infrastructure but will require the transmission lines across regions [33]. This energy collaboration will reduce environmental impacts, ensure energy security, and make energy more affordable [34]. Ground-breaking technologies that maximize the efficiency of energy-consuming devices such as cooking stoves and processing systems will be employed more and deployed to rural areas across the continent to minimize waste and salvage energy. The funding of innovative technologies and research will enjoy the support of the governments of the region [10]. New models for urban development will be designed and implemented and increase access to electricity to help alleviate poverty and provide opportunities and employment as nearly all businesses such barbershops and saloons, poultry, carpentry, welding, internet café, and many more rely on electricity [27].

Researchers have shown that not only can RE be integrated into the power sector in SSA to solve the energy challenge, but that it can account for 100% of the energy supply of the region by 2030. This integration will be done through Integrated Green Energy Resource Planning (IGERP), with emphasis on the impacts on energy delivery and consumption systems and also the decentralization of the grid system [5]. Also, at least 1000TWh will be saved through the high energy standards and efficient technology mostly in heating for industrial and commercial processes and in cooking and air conditioning systems [22]. It is possible to have 100% renewable energy sources in SA, but challenges remain especially the lack of proper regulatory frameworks and inconsistent regulations. The temptation of fossil-based energy systems is one that is still too strong to be resisted by most of the governments of SSA, and therefore the unwillingness and sheer lack of commitments in energy transition on their part [7]. The private sector and all other well-meaning stakeholders obviously must play a role in achieving its seamless energy transition for sub-Saharan Africa in the future. Governments will also need to collaborate within the region to maximize the potential of RE and reduce the costs of implementation and transition.

Renewable Energy will become the main sector for energy generation and will account for several mini-grids and contribute majorly to the existing grid and not just a small part of the grid. Governments in sub-Saharan Africa will begin to invest more [22] and carry out more feasibility studies on the impact of RE in their localities with country-specific assessments which are detailed and systematic with rules of the game to protect rural dwellers from losing land to those seeking to grow energy crops and establish RE schemes. They must however ensure the right policy and framework and support for such schemes and this could guarantee up to 100% dependence on renewable energy. The benefits of energy schemes, whether they are renewable or hybrid systems, must impact the general populace and the rights of citizens and communities must be protected [16]. Governments will also take the lead in promoting biofuels and RE and support private sector [16] through interventions in governance, taxation, regulation, and technology.

Transparent policies to woo investors are slowly being implanted by the governments of SSA and sustained in the region with very attractive incentives for investors and collaborators in energy schemes. On the flip side, carbon taxes must be implemented to discourage further reliance on fossil fuels and as well encourage the use of renewable and clean energy to reduce carbon footprints. These taxes may lead to an initial hike in tariffs, but will slowly reduce with sustained RE development. Every area of the economy and all stakeholders including the rural dwellers must be part of the transition and this will require relentless efforts from governments of the countries. Dilemmas for policymakers will remain as they may struggle to choose between using resources such as land or finance for food or fuel, and speedy wealth creation, or the negative effects on the environment [16].

## 7 Conclusions

An increase in small scale off-grid energy plants will create positive impacts by improving the efficiency of the power sector and reaching the rural areas [35], this can be achieved through the integration of several or large RE systems and the implementation of smart grids which is critical for a sustainable energy transition [9]. Most RE schemes need to be implemented or supported by IPPs and managed by companies that have sufficient skilled and experienced project developers with the required technical and financial capabilities. The success of the IPPs will depend on the level of implementation of set regulations, and governments must strive to reduce risks that could affect IPP and seek solutions to already existing problems. A level playing field must be provided for all IPPs to boost their confidence and make them more willing to invest. The future of energy is already shaping up and renewable energy can compete with and substantially replace fossils if the right things are put in place. This is a necessary requirement for a sustainable and successful energy transition [27], Biomass remains a dominant renewable energy source as it is the cheapest and most reliable energy source currently on the continent despite the fact that PV dominates the scene currently in electric energy generation. Geothermal energy can go a long way in supporting the energy transition plans of SSA even though it is not currently as popular as the other RE methods of energy generation and it remains confined to specific regions. Climate change remains a matter of concern as it affects the nature of RE sources especially hydro renewable energy sources which are already presently lacking or slightly diminished in some locations across SSA. Tackling the effects of climate change must be met with a determination to sustain and preserve the sources of renewable resources and all stakeholders must be involved in this.

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# Energy and Environmental Security in Nigeria: The Latest Dimensions

**Tijjani Abdullahi, Hamzat Abubakar, and Zainab Tijjani**

**Abstract** The quest for achieving energy security has dominated the agenda for growth, supremacy and sovereignty of most developed and developing countries. The developed countries fall back to many of the developing countries for sourcing of energy supplies. The extraction of the materials, refinement, transportation and recycling or end-life deposition of the used materials constitute a complex chain of processes. This study emphasized the state of energy and environmental security in Nigeria. The findings showed that, with about 5% growth rate in Nigeria, the rise in population demands higher energy consumption. Aggressive action towards achieving energy security has a severe consequence on the environment, which is moderated by economic, social and political influence. Regional and national frameworks and strategies have been designed to manage the nexus between energy and environmental issues. The study recommended the establishment of a unitary and robust body for Environmental Impact Assessment (EIA), with adequately trained indigenous staff to tackle the reckless and unethical use of the environment from the project conception stage. A special marine guard as a mitigating measure to energy infrastructure vandalism is necessary. However, to achieve success, collaboration with the leadership of the oil-producing communities through participatory governance is inevitable.

**Keywords** Energy · Environmental · Security · Nigeria · West africa

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## 1 Introduction

The present society depends on the vast energy supply for conducting almost all communication and economic activities. That is why every country is striving to have adequate access to energy supplies that are reliable and inexpensive (energy security). With a steady rise in population at 5% growth rate, Nigeria requires a lot of energy to power the various sectors of the economy [1]. Nigeria, like every other nation, is adequately harnessing its abundant natural, mineral and environmental resources to meet up with the needs of its citizens. Towards achieving energy sufficiency, the country engages in exploiting its resource mix for export and local supply. Hence, exerting pressure on the environment itself, by multiple use of energy resources to meet the energy consumption demand.

The importance of natural resources for the development of any country cannot be overemphasized; nevertheless, illicit and uncontrolled mining and exploration of such resources could be catastrophic and disastrous to the local populace and their environment. The quest for achieving high export revenue from the sales of crude oil leads to very low utilization of the installed refineries. Thus, giving rise to the risk of high demand against the available stocked fuel reserve. Export quality crude oil and gas are produced at the expense of the environment and ecosystem. Hence, giving birth to a humanitarian crisis, hostility, and youth militancy in Niger Delta—Nigerian oil-producing region. The criminal kidnapping, oil theft and attacking of oil workers have disrupted oil production and reduced the royalty and export gain to the country and also worsen the environmental challenges in the producing community.

Although the earlier legislation and concern on energy security were centered on the security of oil supply, however, the concept of energy security has at present include total energy demand, energy access and consumption [2]. The aim of this chapter, therefore, is to examine the evolving interplay between energy security and environmental security in Nigeria, to highlight the best way to attend energy security, as well as developing the human capability to alleviate or evade the damaging consequences of environmental change. Following this introduction, the second section highlights the Energy, Environmental and Security profile of Nigeria, while the third section provides details on energy and environmental security in Nigeria and within West Africa. The fourth section discusses the considerations in the development of energy and environmental security in Nigeria, while the fifth section examines the nexus of energy and environmental security with economic, social and political growth in Nigeria. The sixth section highlights the competitive and innovative approaches to Nigerian energy and environmental security, and the last section concludes the discourse.

# 2 Energy, Environmental and Security Profile of Nigeria

## 2.1 Energy Profile of Nigeria

Nigeria is the most populous nation in Sub-Saharan Africa with about 196 million people. Nigeria is a country that is rich with sufficient energy resources that can be utilized for meeting the present and future energy demands of the ever-growing population. The country boasts of being the fourth-leading exporter of liquefied natural gas (LNG) in the world with approximately 187 trillion tons of natural gas, as well as having the sixth largest crude oil reserve in the world. [1, 3]. Nigeria's recoverable oil was estimated to be around 35 billion barrels and a significant quantity of approximately 2.7 billion tons of coal [4, 5].

Apart from oil resources, Nigeria is also blessed with a substantial quantity of renewable energy resources that can be utilized for power generation and sustainable growth. It was recorded that the coastal areas of Western Nigeria has a potential annual average daily sunshine of 3.5 h while the arid Northern region has about 9.0 h. Bala, Ojosu [6] Projected that the Solar energy resources in Nigeria is equivalent to about $5.08 \times 10^{12}$ kWh of daily energy. Commenting on the aforementioned potentials, Sambo [7] asserts that "using solar energy technology at 5 percent efficiency and covering about 1 percent of the country's surface area will gain $2.54 \times 10^{6}$ MWh of electricity from the sun, which is equivalent to 4.66 million barrels of oil per day." The solar energy resources in Northern Nigeria in particular, have a more viable potential for photovoltaic use, with insolation of up to 7 kWh/m$^2$/day [4].

The hydroelectric potential of the country consists of the combination of large, small, mini and micro hydropower plants across the country, which is estimated at 12,220 MW [1]. This estimate can grow higher considering the potential of the rich river basins situated in different strategic locations in Nigeria. Ohunakin, Ojolo [8] identified the river basins as; "Sokoto, River Niger, Hadejia-Jama'are, Chad, Upper Benue, Lower Benue, and Cross River." Renewed effort towards "small-scale hydropower" is been experienced and its potentials have been projected to reach 734.2 MW. Like many other energy resources, wind energy varies in different regions of the country. The north-East Yola, Adamawa state has a proven wind energy potential of 8MWh/yr while the plateau area of Jos has up to 51MWh/yr potential of wind energy. The arid area of Sokoto northwest of Nigeria has about 51MWh/yr potential wind energy. The total exploitable wind energy reserve in Nigeria as estimated by [9, 10] stands at 10 M height.

The possible annual produce of wood in Nigeria is estimated to be about 22 million cubic meters [11], whereas the overall biomass consisting of animal and agricultural wastes, as well as wood residues potentials of 144 million tons per year [12]. It amounts to 37% of the total energy demand and it is prevalently used in rural societies [11, 13], where it is popularly used for heating, cooking and food processing. Coal is an alternative energy source that can be harnessed along with oil and gas resources to make up the desired energy mix that will provide an affordable and environmentally friendly energy to Nigerian. Fortunately, Nigeria is the solitary nation in the whole of West Africa producing coal at present, with a total deposit amounting to be over 2.5 billion tons [14, 15].

Nigerian national grid electricity project started in 1846 by the establishment of twin 30 kilowatt generating plants in Lagos. National Electric Power Authority (NEPA) was conceived in 1973, to manage the generation, transmission, and distribution of electric energy in Nigeria. The management of electricity in Nigeria has witnessed a various degrees of challenges including that of policy and legislation to loss of electricity due to aging and broken-down equipment, vandalization or theft of equipment and poor management associated with public enterprises in Nigeria [16].

Seventy-nine percent (79%) of the generated electricity in Nigeria was from fossil fuel sources, while about 20% is generated from hydro sources. Other potential sources like biomass and waste, wind and solar contributed less than 1%. In general, the availability of electricity to Nigerians is quite low and hence clarifies the suffering Nigerians have gone through that necessitate the embracing of backup generators [17]. Fore mentioned discussion endorsed the fact that Nigeria is richly gifted with abundant energy resources, which can be systematically harnessed into the strength of the various energy media available. However, skewed progress in the energy sector towards the use and development of oil and gas has created a false impression by displaying hydrocarbon resources as the only workable energy sources available to provide the energy requirement of Nigeria.

## *2.2 Environmental Profile of Nigeria*

Discussion on the Nigerian environment cannot be disconnected from its population and the human activities towards economic growth and industrialization. Knowing that the sustainable development of a nation is tied to its people's access to natural resources and their vulnerabilities to environmental change [18]. Nigeria, like every other nation, is adequately harnessing its rich natural, mineral and environmental resources for meeting up with the needs of its citizens. These natural resources are important in the development of any country; however, illegal or uncontrolled mining and exploration of such resources could be harmful to the populace and the environment. According to the Nigerian Environmental Study/Action Team [19], natural and human-made disasters like "erosion, floods, drought, and industrial wastes" are at the moment threatening the country's environment.

Presently, there is hardly any part of Nigeria that is not devastated by one environmental disaster or the other. The environmental effect of oil spillage was described as the greatest monster bedeviling the entire Niger Delta region, which is known for its large oil deposits in Nigeria. Owing to the heavy exploration, extraction and refining activities that are taking place in the region. Ayanlade and Proske [20] identified the region as "one of the most severely petroleum-impacted ecosystems in the world." We have seen the effect of oil spillage as it destroys farmlands and polluted the coastal waters, thereby causing scarcity of clean and drinkable water, poor farm harvest and severe drawbacks in fishing.

In Nigeria, the rise in population demands much energy. Hence, exerting pressure on the environment itself, causing uncontrolled deforestation, due to unsustainable uses of forest resources for heating, cooking, and housing, which is one of the main contributing factors to environmental insecurity in Nigeria. Similarly, Amadi [21], Amadi and Mac Ogonor [22] worried about the continued urbanization and industrial development across the country, which has left behind a large cache of "liquid and solid wastes" in the country. The combined effect of these scenarios exposed a serious menace to environmental security in Nigeria.

### *2.3 Security Profile of Nigeria*

The security of a very populace country like Nigeria, with about 196 million people is no doubt a very big challenge. Upon that, the very vast landmass of the country rather worsens the situation. Another factor that makes the security of Nigeria look more cumbersome is its large number of ethnic and linguistic groups. Thus, Nigeria is a country with "huge diversity in culture, ethnicity, religion, and language" [23]. Nigeria has played a regional leader in many coordinated counterterrorism and peacekeeping efforts in the African continent and within the West Africa states. Having the largest number of armies in Africa, Nigeria was able to coordinate the leadership of the Economic Community of Africa Monitoring Group (ECOMOG) for peacekeeping operations in Liberia and Sierra Leone, as well as being a major ally in United Nations (U.N) peacekeeping operations.

The major security issues affecting Nigeria exist in its northeast and south region. The militant groups such as "the Movement for the Emancipation of the Niger Delta" (MEND) that is known to be in the southern oil-rich Niger Delta, were well-known for attacking oil and gas infrastructure and kidnapping oil workers to collect ransom and or settlement fees [24]. The reason for MEND's hostility is largely for political purposes, requesting for a redistribution of oil wealth and for the locals to have more control of the oil sector. More so, the insecurity activities of the armed militant group have increased to include oil theft and sabotage, especially in 2016. These criminal activities resulted in increased oil spillage and illegal waste disposal. Certainly, the criminal kidnapping and attacking of oil workers have disrupted oil production and reduced the royalty and export gain to the country and also worsen the environmental challenges in the oil-producing communities.

Nigeria also struggles with the criminal activities of the Boko Haram extremist group found in the northeast region of the country. Although there was no correlation of Boko Haram's activities on Nigeria's oil and gas fields, but the impact of their activities affects the environment and access to energy and natural resources. Possibly, the activities of Boko Haram can influence the Nigerian state capacity where much oil and gas revenues are invested in boosting military and counterterrorism capabilities for fighting Boko Haram at the expense of infrastructural development. Recently, the incidence of kidnapping and cyber criminality has evolved disturbingly in the whole country and has remained a persistent symbol of the nature of criminal victimization. Notwithstanding, the Nigerian government through various security outfits is righteously fighting insecurity and reclaiming the good reputation of the country.

## 3 Energy and Environmental Security in Nigeria and Within West Africa

### *3.1 Energy Security in Nigeria*

Historically, the attention of the world towards energy security appeared shortly after the 1973 oil shock [16], which prompted most of the oil-importing nations to put energy security at the helm of their energy policy plan. Quite a lot of regimes all over the globe have executed different legislations to curtail the menace of energy insecurity inside their countries [25]. Although the earlier legislation and concern were centered on the security of oil supply, however, the concept of energy security has at present include total energy demand, energy access and consumption [2]. In an attempt to identify the "indicators of energy security" over the years, the International Energy Agency (IEA) in 2005 derived what is known as the simple indicators for measuring energy security and diversity as it affects the net importing countries. In this chapter, the discussion on energy security shall go beyond the IEA indicators to include: Fuel mix, Oil import dependency, stock of critical fuels, energy export price and energy export destination.

#### 3.1.1 Fuel Mix

This indicator provides a detailed description of the energy demand mechanisms available for a country's energy sector. Information obtained can indicate the percentage of certain fuel resources in a country's energy demand at different levels. The analysis on fuel mix could be done at the primary energy consumption level for analyzing the state of diversification for overall energy demand or at the final energy consumption, to evaluate the state of fuel diversity at the final consumption stage. Accordingly, the assessment of the fuel mix indicator can be employed to ascertain the share of a specific fuel derived from the reserved resources in the energy demand of a particular country. Through that, the dependency level of energy demand for electricity, cooking or transportation can be determined. Analyzing the case of Nigeria based on this energy security indicator, Fig. 1, illustrated the annual growth in energy supply of the country for the year 2010 to 2017.

It can be deduced from the figure that there is a progressive increase in the total primary energy supply in Nigeria from the year 2015 (145 Mtoe) to 2017 (157 Mtoe). Nonetheless, the information

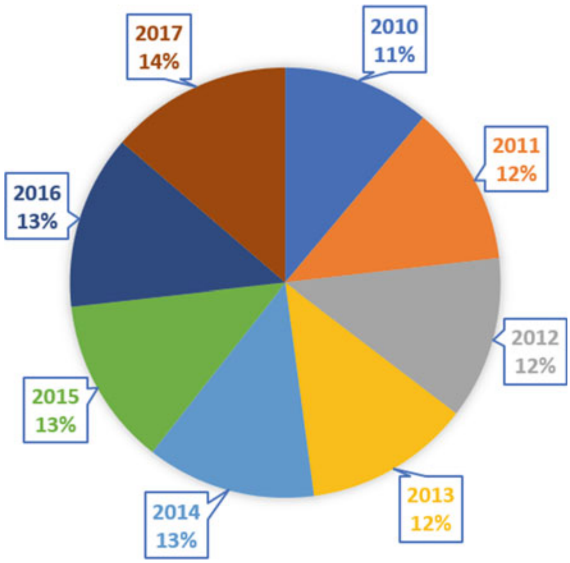


**Fig. 1** Annual growth in energy supply for the year 2010–2017 *Source* International energy agency [17]

obtained is not sufficient to indicate the percentage of a certain fuel resources in Nigeria's energy supply, hence, the total primary energy supply of Nigeria by the source is presented in Fig. 2. Biofuel sources dominated Nigeria's energy supply chain, by supplying 76.87% of the total primary energy. Similarly, Momodu [11] mentioned that biomass in the form of firewood and other agricultural waste are the main source of energy for many rural and some urban dwellers.

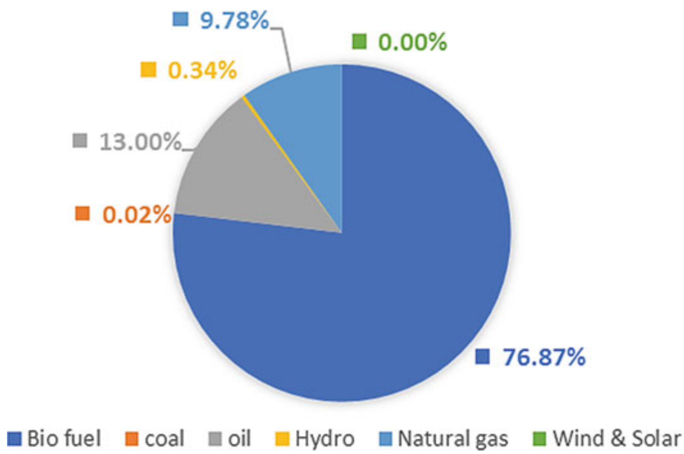


**Fig. 2** Total primary energy annual supply of Nigeria by source for the year 2010–2017. *Source* International energy agency [17]

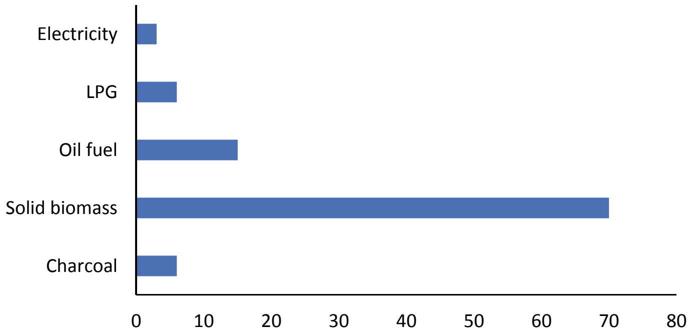


**Fig. 3** Nigeria fuels and technologies used for cooking. *Source* Compiled by authors, 2019

In the same way, our team conducted a survey study in the Northeast Nigeria, the result as shown in Fig. 3, revealed that 70% of the surveyed sample uses solid biomass (firewood/agro waste) for cooking energy, while only 6% utilizes charcoal and LPG. The use of electricity for cooking is at the lowest, having only 3% of the populace are inclined to use electricity for cooking. The use of oil source for energy superseded the Natural gas because of the high rate of using gasoline fuel in the area of transportation and for powering of stand-alone generators. This conformed with the previous report by IEA, in their studies affirmed that Nigeria has the second-largest vehicle stock in sub-Saharan Africa [26].

For identifying the share of energy used for electricity generation, the electricity generation mix is employed to categorize the type of fuel and technology a country uses for its electricity generation. In Nigeria today, about 80% of the electric power generation comes from natural gas, while most of the remainder is generated from oil and other polluting fuel, this is evident since Nigeria is the largest user of oil-fired back-up generators in the whole Sub-Saharan Africa [26].

### 3.1.2 Import and Export Dependence

The self-reliance of a nation towards its needs and supply tells more about its sovereignty and control. The import and export dependence index of a nation can be employed to ascertain the total supply capability or dependence of a country to external supplies towards meeting up to a particular demand. On the order hand, export dependency ascertains the degree of dependence among "domestic producers" on foreign markets as well as able to tells the share of the influence of foreign suppliers to the country's GDP. Although there are differences in opinion on how to correctly calculate the oil import dependency [27, 28], the common means is by taking "the ratio of net energy imports to the primary energy supply" for a certain period to figure out the country's level of dependence on imported supply, while the export dependency can be calculated by "dividing exports by GDP and expressing the ratio as a percentage" [28].

The major energy resources exported from Nigeria is oil and natural gas. However, with the current development at the international and regional oil market and polity, this study shall concentrate on measuring the import and export dependency of Nigeria on oil and how it affects the country's energy security. To evaluate the import and export dependency in Nigeria, this chapter obtained export and import record of oil from the Central Bank of Nigeria [29] and CEIC Data.com [30], Organization of the Petroleum Exporting Countries [31]. The data obtained were used to calculate the oil "import and export" dependency index using Eq. (1) and (2) respectively.

$$\boldsymbol{MD} = \frac{\sum_{k=1}^{2} \boldsymbol{M_k}}{\sum_{k=1}^{2} \boldsymbol{GDP_k}} * \mathbf{100} \tag{1}$$

$$\boldsymbol{XD} = \frac{\sum_{k=1}^{2} \boldsymbol{X_k}}{\sum_{k=1}^{2} \boldsymbol{GDP_k}} * \mathbf{10} \tag{2}$$

where

(I) = total imports

(E) = total export

(K) = country

The calculated value obtained for Nigerian import and export dependency for oil from 1999 to 2018 is presented in Table 1. It is obvious, Nigeria has a very low oil "import dependence" with an average index of (4%) for 20 years. Consequently, we can say that Nigeria has a high supply of energy concerning oil. However, the oil "export dependence" index is relatively high with an average index of (30%) for 20 years. The consequence of this finding shows that the Nigerian GDP is 30 percent solely dependent on oil export, implying that any slight drop in demand for Nigeria's oil or unfavorable oil prices regime would have a terrible consequence on the economic and energy profile of Nigeria.

This trend according to [32] is typical of oil-producing countries. However, the authors recommend that diversification of export destinations and control of oil prices by the producing countries can be of help. In the case of Nigeria, the oil export dependence hit the highest 49% in 2005, which has declined significantly to 17 percent in 2017 (see Table 1).

### 3.1.3 Stocks of Critical Fuels

Nigeria has four oil refineries, which include: Port Harcourt I, Port Harcourt II, Warri, and Kaduna refineries. The four refineries have a total of 445,000 b/d crude oil distillation capacity [33]. Even so, oil production is seeming to be hampered by instability and supply disruptions [1]. Despite having refineries with a production capacity that can satisfy the domestic demand, the country is obliged to import petroleum resources because of the very low utilization rates of the refineries. Thus, giving rise to the risk of high demand against the available stocked fuel reserve. This

**Table 1** Oil import and export dependence in Nigeria

| Year | Import dependence index (%) | Export dependence index (%) |
|---|---|---|
| 1999 | 7 | 37 |
| 2000 | 5 | 42 |
| 2001 | 5 | 39 |
| 2002 | 5 | 24 |
| 2003 | 5 | 35 |
| 2004 | 3 | 39 |
| 2005 | 5 | 49 |
| 2006 | 4 | 39 |
| 2007 | 4 | 39 |
| 2008 | 5 | 40 |
| 2009 | 4 | 35 |
| 2010 | 3 | 21 |
| 2011 | 5 | 23 |
| 2012 | 4 | 20 |
| 2013 | 3 | 18 |
| 2014 | 4 | 18 |
| 2015 | 4 | 18 |
| 2016 | 3 | 17 |
| 2017 | 3 | 17 |
| 2018 | 3 | 17 |

*Source* Compiled by authors, 2019

situation, therefore, highlights how vulnerable Nigeria's energy security is in terms of the stability of fuel supply for satisfying the domestic demand of the country.

### 3.1.4 Energy Export Price

The backbone of the Nigerian economy is the oil and natural gas resources, which according to the International Monetary Fund (IMF), oil and natural gas export revenue is responsible for about 58% of Nigeria's total government revenue in the year 2014. Thus, revenue derived from fuel oil and gas is the major means of foreign exchange, amounting up to 95% of the country's total exports to the world in 2014 [26, 34]. Being the major fuel source of energy in Nigeria, the price of oil has become an important index for measuring the energy demand security of Nigeria. One of the main approaches for gaining favorable prices on Nigeria's exported oil is through the manipulation of its OPEC membership. OPEC crude oil production benchmark for Nigeria was above 2 million bpd for nearly one decade, because of the desirable nature of the Nigerian oil. Hence, the price for the "Nigerian Bonny light oil" usually sells above the OPEC controlled price [35, 36].

### 3.1.5 Energy Export Destination

Apart from gaining favorable export prices, the export destination is another factor that should be considered when assessing the energy export of an exporting country like Nigeria. Table 2, contains the annual oil export data of Nigeria for twelve years.

The table shows that Nigeria's oil export data (for 12 years) reached a high of 2,464.120 b/d in 2010 and the lowest of 1,737.968 b/d in 2016. Racial and communal hostility leads to various agitations in the oil-producing region of Nigeria, causing the fall in oil production in 2008 and early 2009. In late 2009, amnesty was declared to establish peace. Hence, the rise in oil production in the year 2010 was somewhat credited to fewer attacks on the oil refining facilities. Nonetheless, the reduction in oil export can be directly hinged to the deterioration in production because of natural field decline. Concentrating on the export location for Nigeria's crude oil, Fig. 4, shows a graphical details of Nigeria's crude oil exportation by destination, based on countries and regional exportation.

Nigeria is a major oil supplier to the U.S before the substantial import reduction in U.S. imports of crude oil that are of the same grade with the Bakken and Eagle Ford light, sweet crude. The sharp reduction of U.S demand is partially responsible for the fall in Nigeria's export in 2013 through 2014 [38]. Thus, indicating the vulnerability of the country's dependency on export destination. However, in 2015, the narration changes with the coming of India, purchasing almost 400,000 b/d or 20% of Nigeria's total crude exports. The graph Furthermore, showed that Europe maintained a continuous lead among the regional importers of Nigerian oil, which is responsible for 41% of the total oil export. At a much high degree, Nigeria's export destination has greatly been diversified, especially with the renewed trade relationship with China. Which helped in easing the consequence of the reduction in demand from North America.

Nigeria's energy security index is fairly alarming. The economy is highly dependent on export sales. The implication of this development to Nigeria's energy security lies on the fact that favorable oil export translates to the economic buoyancy, which in turn translates to the ability of the country to better manage energy demand and supply as well as able to control environmental vulnerability that might arise from the activities of energy and oil production. To better have sufficient firsthand information on the role or influence of oil extraction and energy generation on the environment, the subsequent paragraph shall discuss the environmental security situation in Nigeria.

**Table 2** Nigeria's annual oil export for twelve years

| Year | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Oil export (b/d) | 2,217.14 | 2,092.34 | 2,160.17 | 2,464.12 | 2,377.0 | 2,368.0 | 2,193.0 | 2,120.1 | 2,114.0 | 1,737.9 | 1,811.1 | 1,979.5 |

*Source* Nigerian national petroleum corporation [37]

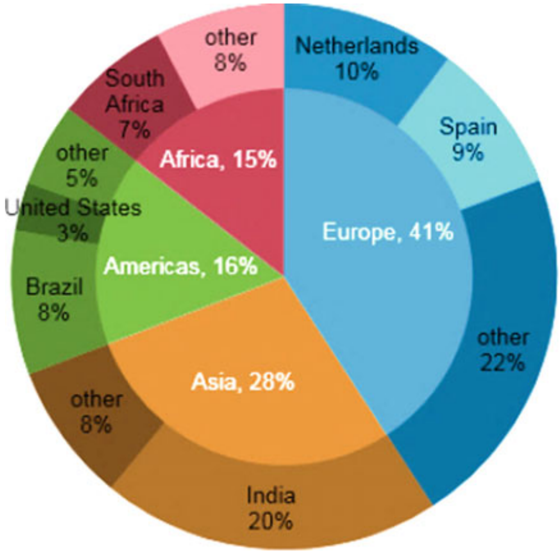


**Fig. 4** Nigeria's oil export by destination. *Source* Energy information administration [38]

## *3.2 Environmental Security in Nigeria*

The most interesting approach to discuss environmental security in Nigeria is to examine the complex connection between human activity and the environment. The activities by man towards achieving security of life and property required the supply of energy for the maintenance of daily needs for sustainable development. Sustainable development according to Okeke and Nzekwe [32] is the human progress that meets the needs and aspirations of the present generation, without compromising the ability of future generations. This definition is in harmony with the report of the World Commission on Environment Development [39]. However, this chapter will not overstress the discussion on the intricacies of the impression of sustainable development. Rather, the study shall highlight the fact that energy security is fundamental to virtually all aspects of sustainable development. Without a secured environment, the attainment of energy security will be very difficult and sustainable development will remain an illusion [40].

Brashares, Abrahms [41], broadly described environmental security as the ability of persons to have access to clean water, unpolluted air, a healthy climate and less degradation of the ecology. In Nigeria, there are manifestations of environmental insecurity at different levels of the social order, be it singular, household or community of states or region. According to the Nigerian Environmental Study/Action Team [19], "natural and human-induced disasters such as erosion, floods, drought, industrial wastes and so on are currently threatening Nigeria's environment". Largely, the discussion so far presented the general scenario of Nigeria's environmental insecurity, further discussion shall concentrate on the environmental vulnerabilities caused by continued urbanization and industrialization across the country, such as; air pollution, liquid and solid wastes menace that arises in the process of achieving energy security.

### 3.2.1 Air Pollution

Nigeria was ranked as the major industrial producer and the largest chemical exporter in Sub-Saharan Africa. International Energy Agency [17] forecasted that Nigeria's chemical production will be tripled by 2040 because of the new coming gas-based methanol and ammonia plants. Invariably, as the production of these chemicals increases, the polluting waste generation will also exacerbate. Being the second-largest vehicle stock in Sub-Saharan Africa, Nigeria has approximately 14 million vehicles. These vehicles operate using oil fuels, thereby emitting exhaust fume that contribute to polluting the atmosphere. Similarly, it has been stated that over 67% of the country's population still uses solid biomass (firewood) for cooking, hence the increase in pollution index [11, 26].

Gas flaring in Nigeria has reached an alarming level in 2011, where Nigeria was ranked the second-highest gas flaring country in the world [42]. However, a sharp decrease in the amount of gas flared was recorded in 2014, which placed Nigeria to the fifth-highest gas flaring country that is responsible for 8% of the total flared gas around the world [31]. The Federal Ministry of Environment [43] estimated the consequences of the flared gas to the emission of 16.5 million tons of carbon dioxide. The Nigerian government has devised a lot of initiatives targeted towards ending natural gas flaring for several years with very little success until recently when gas flared was estimated to about 10% of the gas pulled from the ground. Interestingly, the current leadership in Nigeria has developed a Gas Master Plan aiming at promoting investment in pipeline infrastructure in addition to establishing new gas-fired power plants for the generation of electric energy. The background notion is to help reduce gas flaring as well as providing more gas for electricity generation.

### 3.2.2 Liquid and Solid Wastes Pollution

The interplay between energy and environmental security can be well discussed to reflect the environmental insecurity challenges arising in the oil-producing region as direct or indirect consequences of oil extraction or electricity generation activities. The major solid and liquid waste that is causing serious environmental damage in the Niger Delta region is as a result of pipeline sabotage from oil theft and bunkering, as well as intentional spills from illegal refineries, and due to old and badly maintained oil pipelines [44]. There is no correct record of the total amounts of oil spilled across the entire Niger Delta region. The United Nation Development Project (UNDP) studied the spillage that occurred between 1976 and 2001 and published that about 6,800 spills which are estimated to 3,000,000 barrels of oil leaked to the environment [24].

It is imperative to mention that the published value by UNDP may not truly mirror the degree of the problem because it represents only the cases of spillage that is recorded by the Department of Petroleum Resource (DPR). The amount of spillage due to oil theft, aging infrastructure and/or operational failures is strongly disputed among stakeholders. But the reality remains that oil spillage destroys farmlands and contaminate clean water that can be used for drinking and house chore. Spilled oil also pollutes the coastal waters, which adversely affects fishing activities, the major source of income to the people. The vulnerability effect of oil spillage even endangers the people of the "Niger Delta region" to several health risks, loss of biodiversity, forest destruction, economic destitution, military suppression, and militancy. The damage is ongoing and United Nations Environment Program [45] estimated that "it could take 25 to 30 years to repair".

### *3.3 Energy and Environmental Security in West Africa*

The West African region covered a landmass that measures up to 5,112,903 km$^2$, and an estimated population of more than 360 million people or about one-third of sub-Saharan Africa's total population. The region is blessed with a diverse ecosystem that is largely dominated by a mix of desert and tropical rainforests [46]. The West African region hydrology is dominated by the river Niger which runs through most of the region, to provide the area a spectacular hydrological characteristic of many river paths. Merem and Twumasi [47] identified these river paths as the sources to many reservoirs and dams. These reservoirs and dams such as "the Senegal basin, the Niger basin, the Volta basin, and the Chad basin" enriched the region with agricultural potential, water sources and hydroelectric capability.

Energy demand is projected to continues to rise in the West African states at an average yearly growth rate of 7% in Nigeria and 6% in other West African countries [48]. This explains why many of the West African countries are vigorously developing infrastructure in energy generation, power transmission, distribution and renewables [49]. Accordingly, renewable energy development in West Africa is attracting increased attention not merely on developing the potential of small hydropower stations, but towards the enormous wind resource, thermal and ocean wave energy resources available in the region. The region also has a very large solar energy potential due to the estimated averages radiation of 6 kwh/m$^2$ present throughout the year [50]. Figure 5, shows the available energy capacity of the ECOWAS member states.

From the chart above, Nigeria, Ghana and Cote d'Ivoire are the major producers of energy in the region. Nigeria is responsible for almost 54% of the total energy reserve in West Africa, followed by Ghana and Cote d'Ivoire with 20.05% and 12.14% respectively. Consequently, the West Africa region have been recognized to have rapid population growth and poor access to affordable and sustainable energy.

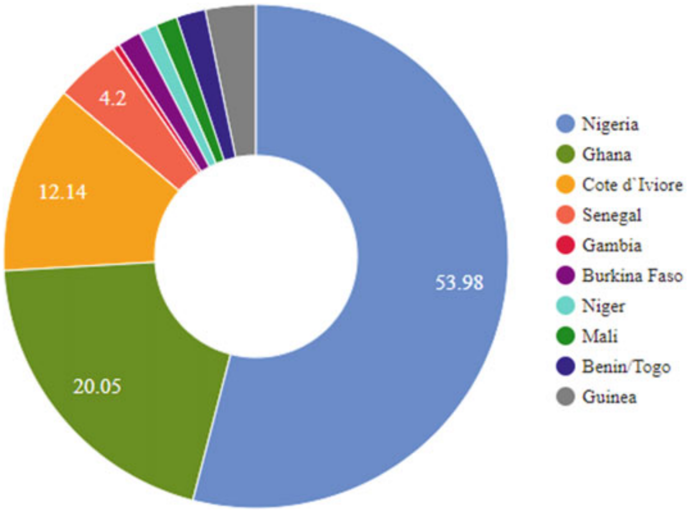


**Fig. 5** Energy capacity of the ECOWAS member states. *Source* West African power pool [51]

The region has one of the lowest energy consumption rates in the world [52], where most homes have limited quality energy services and therefore, people are forced to using solid biomass to satisfy their energy needs. Large scale urbanization and economic development will increase energy poverty and its consequences for local economies and social development will remain as the major challenges for West Africa states.

The West African states have taken a collaboration arrangement towards adopting a regional energy policy [51]. The "West Africa Power Pool" (WAPP) is a teamwork of 14 countries in the West African region. The WAPP initiative aims at establishing an affordable and reliable integrated regional power market. If the integration succeeded, it will allow all countries to benefit from least-costly, cleaner and sustainable resources available in the region. It will eliminate the use of polluting oil-fired power generators and thus, improve the environmental security of the region. Another regional initiative worthy of mentioning here is the West African Gas Pipeline, covering up to 421-miles, the gas pipeline was designed to carry natural gas from Nigeria's Escravos region to reach Togo, Benin, and Ghana. The gas pipeline has since commenced commercial operations in 2011under the management of the West African Gas Pipeline Company Limited (WAPCo).

Apart from electric energy, West Africa has an appreciable reserve of oil and gas [50]. The popularity of west African oil multiplied between 2007 and 2009 due to the offshore oil discoveries in some West African states. The region has seen an intensified presence of oil companies and importing countries into both substantial oil-producing states of Angola and Nigeria and to São Tomé and Principe and Côte d'Ivoire, who are new into oil production. At present, almost every state of the West African region is experiencing petroleum exploration efforts in one form or another. Most, if not all the activities and initiatives towards achieving energy security in the West African region have its accompanying challenge, especially to the environment. However, there is no evidence of significant greenhouse gas (GHG) emissions from the West African region even during the industrialization era. But the region biodiversity has been affected by the effect of global warming [50].

The region also received its share of environmental challenges due to oil and gas exploration. These challenges include but not limited to oil spillage, piracy, gas flaring and disruption of biodiversity. Over the past few years, the rate of piracy in West Africa has escalated to an alarming level, such that it undermined the growth of the region's oil business as well as the marine transportation. In general piracy activities include; "armed robbery, kidnapping for ransom, boarding offshore oil platforms, stealing tankers or cargoes, and siphoning oil from tankers". However, the piracy attacks around the West Africa coast has been directed more on the theft of crude oil and refined product, unlike the in East Africa that usually has to do with kidnapping for ransom.

## 4 Considerations in the Development of Energy and Environmental Security in Nigeria

The energy need of Nigeria is on the increase daily due to the continuous growth of its population. Based on the antecedence it is not adequately clear whether the pressure of demand that comes along with population increase is been considered in the energy development program in Nigeria. This study considered the concept of energy security as postulated by Orazulike [53] as "a condition in which a nation and a majority or all of its citizens and businesses have access to sufficient energy resources at reasonable prices for the foreseeable future, free from serious risk of disruption of service." Thus, petroleum products, gas, and electricity are the energy resources to be considered for achieving energy security in the Nigerian context. The following paragraphs shall identify the current developments in Nigeria to improve access to energy services sustainably and efficiently.

Adequate literatures have established how the energy need of most Nigerians is usually provided through the use of fossil fuel and biomass resources [11, 46]. Being the largest producer of oil in Sub Saharan Africa, Nigeria has enough reserves of oil and gas as well as other resources to achieve sustainable energy mix that will satisfy the country's demand. To achieve this, the government needs to design efficient strategies to discover, manage and control the abundant energy resources in a sustainable way to meet up with the local energy and environmental needs. Historically, the 1978 energy conference marked the beginning of promulgation on energy governance in Nigeria. The Nigerian president at that time indicated the willingness to pursue the cause of energy security.

However, the declaration was not accorded the right enforcement and implementation. the Federal Ministry of Science and Technology in 1984, formulated an Energy

Policy Guideline which was not able to mitigate the Nigerian energy crisis due to its shallow scope [13, 16]. In 1993 the Energy Commission of Nigeria (ECN) enhanced the 1984 drafted energy policy guideline to produce a draft of the national energy policy. After nearly a dace, the 1993 draft of the national energy policy was reviewed by a presidential committee. At the end of the review, a copy of the policy guidelines on energy for Nigeria was presented in 2003 [54]. Afterward, other guidelines and agencies were established to ensure the effective attainment of the country's energy target.

This chapter concentrates on three recent important considerations in the development of energy and environmental security in Nigeria; '*National Energy Policy*' (NEP), '*National Renewable Energy and Energy Efficiency Policy*' (NREEP) [54, 55]. And the "*National Environmental Standard and Regulations Enforcement Agency*" (NESREA) [43]. The major goal of the NEP in Nigeria is to achieve an excellent energy mix in the expansion of the country's energy resources in a sustainable manner that would guarantee energy, environmental and national security. The policy hoped to achieve its goal by taking regular inventory and providing adequate maintenance of the energy resources in Nigeria. The guidelines also addressed the need for continuity and self-sufficiency in energy supply in the short, medium and long-term, at favorable costs.

The NEP intends to accomplish the planning and implementation of energy policies by harmonizing collaboration and communication among the ECN and other agencies in the energy sector. The guideline also plans on decentralizing the energy planning and implementation down to the level of various state governments, at the same time ensuring uniformity with NEP strategies. To sustain performance, the policy aims at the establishment and implementation of energy masterplan based on the updated data obtained from corresponding institutions, and to ensure endorsement of appropriate financial measures for funding the energy policy implementation plans. The policy identified the need for the protection of the environment and the people from the profit or loss linked with the manipulation and consumption of energy resources [54].

On the other hand, the primary mandate of NREEEP is to meet the electric power supply targets in Nigeria through a sustainable means. The policy focused on renewable energy sources which include: "hydropower, solar (PV and thermal), wind, geothermal, wave and tidal energy". The policy also strategized on achieving "a national energy efficiency policy framework" to match action along with the planned renewable energy policy. The policy also targeted the expansion of micro and mini-hydropower systems in a manner that will ensure the protection of the environment and socially accepted. Furthermore, the document seeks for the accelerated completion of "Mambila, Zungeru, and Gurara" hydro projects, which are expected to provide more than 100 MW. The policy also aimed to achieve a minimum of 10% of the total Nigerian electricity generation from hydropower. Thereby allowing the mix of various scale installations in the power generation, with private sector participation.

Additional focus was centered on the use of Solar PV as a decentralized option for off-grid and standalone power applications, which is between 1–10 kW. This was strengthened by the distribution of assembled solar thermal power stations of more than 20 MW capacity in some appropriate sites. The policy targeted a contribution of three percent (3%) by 2020 and six percent (6%) by 2030 from both solar PV and thermal sources to the energy generation. In addition to the promotion of energy-saving technologies and providing suitable tariff to the energy distributing companies that can help achieve high efficiencies.

Agreeing with the implications of energy resources manipulation on the Nigerian environment, "National Environmental Standard and Regulations Enforcement Agency" (NESREA) is the Apex, most recent and effective legal mechanisms created by the government of Nigeria to manage environmental crisis and implement environmental protection and awareness plans [43]. Other responsibilities for the agency include:

> enforcing compliance with laws, guidelines, policies and standards on environmental matters; carrying out activities necessary for the performance of its functions; prohibition of processes and use of equipment or technology that undermine environmental quality; conducting field follow-up of compliance with set standards and take procedures prescribed by law against any violator; conducting public investigations on pollution and the degradation of natural resources; developing environmental monitoring networks and do such other things other than in the oil and gas sector as are necessary for the efficient performance of the functions of the Agency. (NESREA, 2017)

Given this summary of policies and guidelines in the development of energy and environmental security in Nigeria, legal mechanisms and guidelines towards rescuing the perilous state of our environment and the ubiquitous energy crisis in Nigeria have been adequately captured. Contrary to the view of Akin [13], Borok, Agandu [16] who lamented on faulty energy policy as the cause of energy crisis in Nigeria. For more clarification, the following subchapter shall highlight the nexus of energy and environmental security with economic, social and political growth in Nigeria.

## 5 The Nexus of Energy and Environmental Security with Economic, Social and Political Growth in Nigeria

When Environmental insecurity meets and interacts with other energy, economic, social, and political shocks, and pressures, it can increase the possibility of instability or conflict. This threat is particularly strong in underdeveloped and uncivilized nations where governments are struggling to accomplish energy security and sustainable development. At the same time, various stages of exploiting energy resources often contribute to environmental degradation and undermine the ability to achieve sustainable development, thus creating a vicious circle of increasing vulnerability and fragility. The complex and systemic risks that arise out of the interaction between the environment and other economic, social, and political pressures at various stages of exploiting energy resources are what this subchapter will bring forth.

The need for achieving energy security in any country has a lot to do with fears of demand surpassing supply (scarcity) and possibilities of supply surpassing demand (abundance) and how each scenario affect the economic development of the nation. Particularly for developing countries like Nigeria, economic development is very much coupled with energy access, which is in turn dictated by export revenue, price changes, and the exporting destinations. The nexus here lies on the fact that favorable oil export leads to economic buoyancy, which in turn translates to the ability of the country to better manage energy demand and supply. The quest for more oil exploration exalts pressure on the environment, which mostly leads to deflection of the ecosystem and depriving access to the necessary benefits endowed by nature. Herein, it is shown that the pressure on the growing Nigerian economy leads to intensified oil production to increase revenue.

However, continuous oil exploration and refining activities are mostly reckless and environmentally damaging [45]. The new energy enclosures engaged with to achieve “energy security” of demand and supply are creating a lot of environmental vulnerability in the form of “scarcities and insecurities as people are dispossessed of energy, food, water, land and other necessities of life” [56]. The vulnerability effect of such reckless activities even endangers the people to several health risks, loss of biodiversity, forest destruction, and economic destitution. In short, the inability to protect the environment has resulted into serious economic, social and political insecurity. The consequences have been-incessant political instability, where some militant groups such as MEND appeared, with activities like “oil bunkering and pipeline vandalism, armed robbery, kidnapping for ransom, and siphoning oil from tankers” [57].

The nexus between the environment and security have been rightfully captured by Khagram, Clark [58] that, “a great deal of human security is tied to peoples’ access to natural resources and vulnerabilities to environmental change—and a great deal of environmental change is directly and indirectly affected by human activities and conflicts”. In the case of Nigeria, human activities towards achieving energy security have severely influenced the environment and natural resources. Certainly, echoes on the need for environmental security have come to be acknowledged as a factor of consideration for energy security. Previous studies by Momodu [11] have established a unidimensional relationship between energy consumption and economic growth in Nigeria. Herein, the rate of energy consumption or demand is serviced by the available energy resources or electric power supply. Where the enhancement of people’s quality of life as a result of the improved economy will further offshoot energy demand.

Nigeria has the largest fleet of vehicles in Sub-Saharan Africa, as well a large number of electricity generators, which is no doubt expected to increase as a result of economic growth. The correlation between energy consumption and environmental degradation with economic growth in Nigeria has been highlighted in various studies [59, 60]. Several issues presented in this subchapter brought forth some examples of energy and environmental insecurity triggers. Nonetheless, the discussions that followed suggest that environmental security can be sought for, and be achieved at various stages of energy production. Thus, approaches on how to attain energy security without necessarily leaving for the next generation the reckless environmental damaging activities is crucial and very necessary. The following subchapter highlights the innovative approaches for achieving energy and environmental security in Nigeria.

## 6 Competitive and Innovative Approaches to Nigerian Energy and Environmental Security

The economy of Nigeria depends on oil revenue, such that it principally influenced the environment, economic, social and political scene of the country. The consequential impact is however on the environment. By implication, the aggressive action towards achieving energy security has a severe consequence on the environment. In the past, energy security discourse speaks predominantly about crude oil supply, however, the concept of energy security has at present include total energy demand, energy access, consumption, and safeguarding the environment. This subchapter aims at joining the debate on energy security in Nigeria, but ensuring that discussions followed the principles of sustainable development, which emphasized on "human progress which meets the needs and aspirations of the present generation, without compromising the ability of future generations to meet their own needs."

### *6.1 Politics & Governance*

Inclusiveness of an energy policy is not a guaranty to energy security in any country. Certainly, energy security can be achieved only by the implementation of meaningful policies, using productive approaches. Politics in government and policy-making performs a critical role in shaping the drive for energy and environmental security in Nigeria. However, it has not been able to produce resistance to energy and environmental insecurity in the country. Rather, there exist common distrust in oil sector public appointments among ethnic groups and the near absence of public confidence in oil public policies. There should be transparency in all energy-related policies, through devotion to corruption isolated governance and in the administration of oil and gas institutions. Nigeria should also move up to "participatory governance", that advocates honesty, fairness and transparency in legislation and management of energy and environmental policies. Attention should be geared towards increasing investment in R&D on energy, power, and environment security, through Nigerian research institutes and Universities.

### 6.2 Oil & Gas and the Environment

Adequate legislation and enforcement mechanism must be put in place to forestall reckless and environmentally damaging activities. Thus, there is the need for enhancing the oversight, transparency and strict enforcement clauses of the prospective Petroleum Industrial Bill prior to final ratification. Establishing a unitary and robust body for Environmental Impact Assessment (EIA), with adequately trained indigenous staff will be a solution to the reckless and unethical use of the environment. At a time of favorable oil export and economic buoyancy, attention should not be limited to fiscal buffers like the "Excess Crude Account and the Sovereign Wealth Fund" only. Maintaining the serenity of the environment, biodiversity and ecology (water bodies) is equally important.

A special marine guard as a mitigating measure is necessary with adequate modern infrastructure. However, to achieve success, collaboration with the leadership of the oil-producing communities is inevitable. Also, it is expected that the government will engage with the international communities to discourage the business of illegal oil by foreign partners. regularly auditing and monitoring of exports and oil revenues collection methods, and to apply the Anti-Money-Laundering (AML)/Combating the Financing of Terrorism (CFT) framework to help combat oil-theft-related money laundering. National Money Laundering/Terrorism Financing Risk Assessment (NRA) also provides a well-timed opportunity

### 6.3 Electricity and Renewable Energy

Seeing the positive linkage between energy access and growth, as well as the implication of various stages of exploiting energy resources on the environment increasing access to renewable services should be amplified and the cost of energy-efficient equipment ought to be subsidized for the people, more especially for the rural and villages. Due to tariff inconsistency with regards to power delivery targets, establishing a location-specific capacity expansion masterplan will ensure the production of electricity from distant areas (away from the grid) based on the prevalent source of renewable energy. And provide tax immunity and or capital allowances for renewable energy initiatives and investors. Establish a detailed national target of a sustainable energy mix and pursue its implementation towards reducing the use of fossil fuel sources.

## 7 Conclusion and Projection

Given the state and complex nexus (interplay) evolving between energy and environmental security in Nigeria and the Sub Saharan region of West Africa, in a way not seen before did set the research different from others, with quite a lot of revealing findings. The aggressive action towards achieving energy security has a severe consequence on the environment, which is moderated by economic, social and political influence. Thus, recommends that environmental security can be sought for, and be achieved at various stages of energy production. The authors are of the view that faulty energy policy as widely speculated is not to be considered as a catalyst to the prevalent energy crisis in Nigeria. Rather, the challenge is of poor management of abundant energy resources, failing to deploy correct technology and suitable energy mix, plus the danger of not understanding the consequence of energy resources manipulation on the Nigerian environment.

The study recommended that the government should enact policies that will lead to the establishment of a unitary and robust body for EIA, with adequately trained indigenous staff that can prevent irreversible impact right from the project conception stage, rather than managing the environment after it has been altered. This can only be achieved through "participatory governance", that advocates honesty, fairness, and transparency in legislation and management of energy and environmental policies. And to pronounce state of emergency on power, energy, and environment and increase budgetary allocation for related investment or partnership on power, energy, and environment.

Considering the socio-economic status of the greater populace, it is imperative to establish energy tariff support for low-income households to enhance access to electricity and for building public confidence. Collaboration with the leadership of the oil-producing communities is inevitable. Also, since the bulk of the pirates operating around offshore West Africa are said to be from Nigerian militant groups that are found in the Niger Delta region, measure to curtail their activities is believed to be handy. it is expected that the government of ECOWAS member states should engage with the international communities to a joint surveillance initiative to curtail piracy in offshore West Africa.

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# The Evolution of Electrification in South Africa and Its Energy-Environmental Impact

**George Alex Thopil**

**Abstract** South Africa is amongst the largest economies in Africa and is considered the most industrialised country in Africa. One of the primary reasons for industrialisation has been affordable electricity that was made available for manufacturing. South Africa accounted for 32% of the electricity generated in Africa in 2015, of which 92% was generated from coal. However electricity access and penetration within the local population was still lagging (at 86% in 2018) in spite of relatively large volumes of generation. In order to address the lopsided nature of electricity access, national policy prioritised access to electricity, which meant diversifying the nature of electricity from primarily thermal generation to include renewable sources. As part of the diversification, South Africa embarked on an ambitious renewable energy programme that involves private participation. As of 2017, South Africa generated 41% of wind energy, 56% of solar PV and 62% of solar thermal energy, for electricity generation on the African continent. The penetration and prevalence of renewable electricity generation is bound to increase considering the abundance of resource in the region. While renewable energy plants are environmentally less harmful due to limited emissions, limited information is available about the effects of utility scale renewable power plants in developing countries. This chapter aims to provide an investigation into the potential external (or unaccounted) effects of utility scale renewable plants particularly from a developing country perspective, where utility scale adoption is relatively new and where plant data is not readily available. The chapter aims to provide a comparison of external effects and external costs of renewable technologies with external effects and external costs of conventional thermal electricity generation within South Africa. Based on data considerations, a life-cycle based approach is employed, where possible. The investigation compares three power plants employing different technologies, namely coal power, on shore wind power and concentrated solar power (CSP). The results of the analysis indicate that environmental costs (USD 2.76 c/kWh) from coal fired electricity are significantly high by more than an order, whereas non-environmental impacts that include

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human health, have lesser variation depending on the technology. Wind power was observed to have the least impact and cost across totalled environmental and non-environmental impacts (USD 0.08 c/kWh). While investigation of the coal plant was limited to the generation stage, a full life cycle analysis was considered for other technologies. It was seen that the extraction and manufacturing stages of renewable technologies have a higher share of impacts whereas operations and maintenance had the least, which was prominent for the CSP plant, that had a total impact cost of USD 0.23 c/kWh. It is expected that, with more developing countries adopting utility scale renewable plants, such energy-environmental impact assessments within a developing country context will be useful in understanding localised impacts on the environment related to energy generation activities.

**Keywords** Electricity · Developing country · Sub-Saharan Africa · South Africa · Coal · Renewable · Environment · Human health · Impact · Cost

## 1 Background

South Africa's energy policy, with particular focus on the electricity policy has seen continuous change in order to accommodate social, economic, political and environmental demands. The policy modifications brought about and being brought about, are with the intention of providing the country with a sustainable socio-economic future.

South Africa is often seen as a paradox with high unemployment, income inequality, sluggish growth while having high energy demands, high electrification rates, boasting first world transportation and infrastructural facilities [24]. The government of the country has borne the impact of this paradox, with the responsibility of catering for the socio-economic needs of a large population while trying to meet the demands of an energy intensive economy. This situation has seen the government often trying to maintain a very delicate balancing act, requiring constant review in energy policies while bearing sustainability in foresight.

South Africa has an energy intensive economy linked to manufacturing and industrialisation, which was historically supported by availability of cheap electricity. Table 1 provides a comparison of energy indicators of selected countries (and regions) which highlights South Africa's energy intensity.

However, the availability of cheap electricity has changed and the following section will attempt to provide historical context within which the status quo has changed.

**Table 1** Country comparison of energy indicators

| 2017 country data | TPES/pop toe/capita | TPES/GDP (PPP) toe/1000 in 2010 USD | Elec. Cons./pop (kWh/capita) | $CO_2$/population (ton $CO_2$/capita) |
|---|---|---|---|---|
| **South Africa** | **2.33** | **0.19** | **4004** | **7.43** |
| China | 2.21 | 0.15 | 4546 | 6.68 |
| Turkey | 1.83 | 0.07 | 3263 | 4.71 |
| Malaysia | 2.68 | 0.1 | 4808 | 6.67 |
| India | 0.66 | 0.1 | 947 | 1.51 |
| Germany | 3.77 | 0.09 | 3078 | 8.7 |
| United Kingdom | 2.66 | 0.07 | 4951 | 5.43 |
| USA | 6.61 | 0.12 | 12,573 | 14.61 |
| Africa | 0.65 | 0.14 | 574 | 0.94 |
| OECD | 4.1 | 0.11 | 7992 | 8.94 |
| World | 1.86 | 0.12 | 3152 | 4.37 |

*Source* IEA [10]

# 2 Electrification in South Africa

Electrification in South Africa has a long and rich history when, in 1879, the city of Kimberly (located in modern day Northern Cape Province) became the first town in the Southern Hemisphere to have electric street lighting [22].

## *2.1 A Brief History*

The Reconstruction and Development Programme (RDP) post the first democratic elections in 1994, had two primary aims; the need to achieve more rapid economic growth and the need to eliminate poverty through sustained development. The energy sector was seen as a primary player towards achieving these national goals. Within the international context the aforementioned objectives were critical to South Africa's commitment to the UNFCCC, along with policy commitments within the African continent. South Africa's energy policies post-democracy has seen major shifts and changes. The primary priority of the government has been to provide electricity to the rural and poorer populations of the country. To this end the Integrated National Electrification Programme (INEP) was initiated in 1994 [5]. This programme saw a major shift in energy policy with social equity and environmental sustainability being priorities over energy security and industrialisation. Still on-going, the INEP has seen tremendous success over the last decade. The electricity industry was monopolistically managed by Eskom[1] prior to 1994. The introduction of the National Energy Regulator of South Africa (NERSA) commenced the process of regulation. Eskom was mandated by NERSA to undertake the electrification programme [5].

In 2001 the Department of Energy[2] (DoE) took over the implementation and management of the electrification programme, while liaising with Eskom. The DoE is the governmental body which oversees the energy industry in South Africa. Post 2001 the DME employed local municipalities as well as Eskom to implement the roll out of electricity connections to private users and small businesses. The funding for the local municipalities is provided by National Treasury and is managed by the DoE. To date the national electrification rate stands at 86.15% [5] compared to 57.6% in 1996. The average Sub-Saharan electrification rate is 44.5% [29]. South Africa's National Development Plan [23] devised in 2013, which is a roadmap for national development until 2030, has been a forward thinking strategy. One of the priorities of the roadmap includes access to basic electricity to the population while transforming the electricity portfolio to a cleaner mix. The plan was devised prior to the establishment of the 2015 United Nations Sustainable Development Goals (SDGs), thereby indicating the earlier national strategy alignment in line with SDG 7 (which is to provide affordable, reliable, sustainable and modern energy to all). South Africa's increasing rates of electrification and attempts to shift the electricity portfolio are statement to the alignment with SDG7.

Much of the electrification and industrialisation in South Africa was achieved as a result of the efforts of Eskom. However developments within Eskom over the past 10 years have constrained electrification and industrialisation within South Africa negatively. Table 2 provides an historical overview of the phases linked to the company which is government owned. Eskom was incepted in 1923 with the establishment of the Electricity Supply Commission (Escom) by the government. The period from 1930 to 1950 saw Escom trying to lay solid foundations by erecting governance structures and establishing basic electrification infrastructure to facilitate national supply. The Klip power station was built to cater for the increasing demand for electricity from the mining industry. World War II adversely affected Escom's functioning, but the challenges were overcome once the war ended, with Escom being able to acquire and expand existing regional power stations, such as the Port Shepstone power station and municipal undertakings in the present day region of the Eastern Cape. Several extensions to existing levels of infrastructure were made to supply increasing demand.

The period from 1950 onwards saw tremendous growth, with Escom's generation capability more than doubling and the construction of new power plants featuring

[1]Eskom is the national public utility which generates, transmits and distributes electricity to majority of the users and municipalities in South Africa. The governance of Eskom lies with the Department of Public Enterprises and not the Department of Energy.

[2]The Department of Energy (DoE) was known as the Department of Minerals and Energy (DME) prior to April 2009 and the two departmental names will be used intervariably based on timeframe. The name changes occurred as part of the government restructuring.

**Table 2** South African electricity production phases

| Period | Description | Occurrences |
|---|---|---|
| 1930–1989 | Eskom establishment and growth | This period saw the roots of one the largest electricity entities in the world. Eskom would go on to build multiple coal power plants and one nuclear plant and generate more than 95% of the electricity produced in the country Electricity supply was largely oriented to the population that had political rights and with a heavy emphasis on industrialisation. Heavy industries received heavily subsidised electricity to promote industrial production |
| 1990–1999 | African Renaissance—post democratic elections | National Energy Regulator was formed to ensure the regulated generation, transmission and supply of electricity in the country. Emphasis was on supplying electricity to rural and previously disadvantaged populations. Eskom Enterprises was formed with Eskom playing a larger role in Africa and all being involved in projects in the developing world |
| 2000–2008 | Renaissance hits a plateau | National electrification programme was introduced by supplying monthly 50 kWh of free electricity to poor households. Formation of the first and second Integrated Energy Plans. This period coincided with extended delays to infrastructure expansion plans and low priority on maintenance |
| 2008–current | Stalling and debt | The effects of delayed maintenance, delayed and prolonged construction of two new coal power plants and maladministration, leading to intermittent load shedding and large amounts of debt |

*Source* Adapted from Thopil and Pouris [26]

increased generational capacity. This trend continued through the 1960s with industrial electricity demand fuelled by the rapid growth of the mining industry, resulting in the construction of the next generation of coal power plants, some of which are even still operational. Establishment of the national power network was undertaken to connect the Cape Province with the Upper Transvaal. The 1970s witnessed the introduction and commissioning of hydro power plants to stabilise and moderate peak supply demands.

The construction of the Koeberg nuclear plant was also a major milestone in the utility's history from the viewpoint of diversifying generation techniques. The 1980s saw more coal power plants being built. Towards the end of the 1980s and the start of 1990s there was a period of democratic political transition. The utility had to put capacity expansion on hold and restructure policies with expansion of electrification the priority. These changes saw restructuring along with Escom being renamed Eskom by a government appointed commission. During this period electricity access and electrification rates improved rapidly. The onset of 2000s saw calls for capacity expansion to accommodate the needs of increased industrial activity as well as a larger population. Priority was placed on access to electricity while plans were drawn out to build two large coal fire plants. Reduced maintenance resulted in the performance of existing fleet of power plants being affected leading to first rounds of load shedding in 2008. Low priority maintenance and maladministration, coupled with delays and budget overruns in building new power has led to repeated bouts of load shedding over the previous ten years.

Of the 234.4 TWh available for distribution in South Africa—which includes 11.34 TWh purchased from independent power producers (IPPs) and 7.35 TWh imported from the neighbouring countries—coal-fired electricity power constitutes 200.2 TWh [9]. The numbers indicate a high dominance (i.e. 85.4%) of coal fired power within the electricity mix. The situation arises from South Africa's abundant reserves of coal [10].

Eskom has sixteen power plants that supply baseload electricity, of which fifteen are coal fired power plants and one nuclear power plant. Two coal plants (namely, Medupi and Kusile) out of the fifteen, are partially operational and have been beset with constructional and design issues. Hydroelectric, pumped storage and open cycle gas turbine plants supplement the grid during peak load demands. Table 3 provides a breakdown of power plant technology mix and nominal capacity [9].

In addition to the capacity mentioned in Table 3, 4981 MW of installed capacity from IPPs are also available for supply and demand management. Therefore a total of 49,153 MW of nominal capacity is available to the grid. Based on the available nominal capacity which has led to the distribution of 234.4 TWh of power, the average generation load factor can be calculated as 60.71%, in spite of coal fired plants contributing to 74.2% of the nominal capacity. Again, this highlights the reduced capability of the older fleet of coal power plants and unreliability of the commissioned units of the new coal power plants.

The silver lining amidst the bleak reliability has been an increase in IPPs. IPP production constitutes mainly solar PV, concentrated solar power (CSP) and wind installations. The following section looks at how renewable energy installation and production has evolved over the last decade in South Africa.

**Table 3** Power plant technology mix and capacity

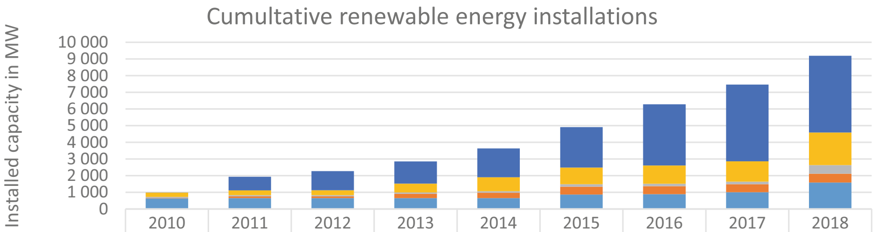
| Technology type | Installed capacity (MW) | Nominal capacity (MW) | % of nominal total |
|---|---|---|---|
| *Baseload stations* | | | *78.10* |
| Coal fired (× 15) | 40,170 | 36,479 | 74.2 |
| Nuclear (× 1) | 1940 | 1940 | 3.9 |
| *Peaking stations* | | | *11.60* |
| Gas fired (× 4) | 2426 | 2409 | 4.9 |
| Pumped storage (× 3) | 2732 | 2724 | 5.5 |
| Hydroelectric (× 2) | 600 | 600 | 1.2 |
| *Renewable*[a] | | | *0.2* |
| Wind (× 1) | 100 | 100 | 0.2 |
| Total (Eskom) | 47,968 | 44,172 | 89.9 |
| IPPs | 4981 | 4981 | 10.1 |
| Total (Grid) | 52,949 | 49,153 | 100 |

[a]Not used for supply and demand management
*Source* Eskom [9]

## 2.2 Recent Shifts in Electrification: A Trendsetter in Africa

In spite of the abundant sources of renewable energy in South Africa, renewable energy and IPP production had never been envisaged up until the late 2000s. This was primarily because of the abundance of coal as cheap source of fuel and the capability of the power plants to produce affordable and reliable electricity. However the first bout of load shedding in 2008 altered the electricity status quo. As part of South Africa's commitment to limiting emissions [3] and diversifying from coal fired power, the DoE gazetted the regulations of new generation capacity under the electricity regulation act [15]. South Africa had led the growth in renewable energy installation in Africa. Figure 1 provides an indication of the growth in renewable energy installations (excluding hydro and geothermal) over the past decade.

As a result, the renewable energy independent power producers' procurement programme (also known as REI4P) was initiated. The aim of the programme is to align the country with broader policy programmes such as the National Development Plan [23] and the Integrated Resources Plan [17, 18]. The aim of REI4P is to procure and install 17.8 GW of IPP power, between the years 2011 up until 2030, which comprises primarily of renewable energy technologies determined by the minister of energy. These determinations have comprised of four tranches—during the years 2011, 2012, 2015 and 2016—as part of four major bid rounds and three smaller rounds. Table 4 provides a breakdown on target and status timelines based on technology mix.




| | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|---|---|---|
| South Africa | 12 | 811 | 1 150 | 1 331 | 1 732 | 2 431 | 3 669 | 4 602 | 4602 |
| Morocco | 255 | 289 | 291 | 531 | 838 | 999 | 1 101 | 1 225 | 1958 |
| Kenya | 73 | 74 | 76 | 80 | 90 | 145 | 146 | 152 | 517 |
| Ethiopia | 21 | 103 | 103 | 256 | 322 | 475 | 480 | 478 | 528 |
| Egypt | 632 | 652 | 652 | 652 | 652 | 862 | 885 | 1 006 | 1587 |

**Fig. 1** Renewable energy installations in select African countries. *Source* IRENA [16]

**Table 4** Independent power producer programme targets (in MW)

| | Target 2030 | Interim target 2020 | Determined to date | Procured to date |
|---|---|---|---|---|
| Solar PV | 8400 | 2700 | 6225 | 2292 |
| Wind | 8400 | 2800 | 6360 | 3357 |
| CSP | 1000 | 500 | 1200 | 600 |
| Other | – | – | 940 | 173 |
| Total | 17,800 | 6000 | 14,725 | 6422 |

*Source* IPP Office [14]

A breakdown of IPP technology mix based on determination, procurement, installed and operational capacity in shown in Table 5.

Further to the target status, a breakdown of the procured technology mix relative to the each bid window is indicated in Table 6.

**Table 5** Independent power producer programme (Technology mix vs. target status, in MW)

| Technology versus status to date | Determined | Procured | Installed (vs Operational) |
|---|---|---|---|
| Solar PV | 6225 | 2292 | 1986 (1474) |
| Wind | 6360 | 3357 | 2094 (1980) |
| CSP | 1200 | 600 | 500 (500) |
| Biomass, Hydro & landfill | 540 | 74 | 22 (22) |
| Small renewables (incl. PV) | 400 | 99 | 0 |
| Total | 14,725 | 6422 | 4602 (3976) |

*Source* IPP Office [14], IRENA [16]

**Table 6** Independent power producer programme (Technology mix vs. bid window, in MW)

| | BW 1 | BW 2 | BW 3 | BW 3.5 | BW 4 | 1S2 | 2S2 |
|---|---|---|---|---|---|---|---|
| Solar PV | 627 | 417 | 435 | 0 | 813 | 30 | 50 |
| Wind | 649 | 559 | 787 | 0 | 1363 | 9 | 0 |
| CSP | 150 | 50 | 200 | 200 | 0 | 0 | 0 |
| Hydro | 0 | 14 | 0 | 0 | 5 | 0 | 0 |
| Biomass | 0 | 0 | 17 | 0 | 25 | 10 | 0 |
| Landfill | 0 | 0 | 13 | 0 | 0 | 0 | 0 |
| Total | 1426 | 1040 | 1452 | 200 | 2206 | 49 | 50 |

*Source* IPP Office [14]

As part of this programme, installed nominal capacity from IPPs have increased from 803 MW during the year 2011 to 4981 MW in 2019 [9] which translates to a compound annual growth rate of 22.48%. The growth in procurement has however stalled due to wrangling related to power purchasing agreements, between the power utility Eskom and the IPPs. The factors leading to impasse are discussed in the following section.

## *2.3 Roadblocks in Policy Setting*

While IPPs are allowed to generate electricity in South Africa they do not have access to the transmission grid. In order to circumvent this situation Eskom currently enters into long-term power purchase agreements with the IPPs. The signing of the purchasing agreements stalled in 2017 when Eskom cited reasons such as, surplus capacity for the grid, and above market pricing [11]. The signing was also delayed by mining union NUMSA taking the agreements to court—during March 2018—citing reasons related to job losses in the coal mining industry [12]. The complexity of the situation arises from Eskom trying to protect the company's market share, the mining industry expecting a downturn via job loses for working class citizens and IPPs not having access to transmit their own energy [12]. The case brought in by the union was dismissed and the outstanding power purchase agreements were signed by the minister of energy in April 2018 paving the way for procurement of 27 stalled IPP projects [7]. While the signing of purchase agreements was a positive sign for the energy industry, the uncertianty has left potential investors hesitant and also halted the momentum of procurement of additional capacity to achieve 2030 targets. To date, the request for proposals for the next round IPP projects have not been announced. However the recent version of the IRP [18], which is the electricity blue print of the country, accounts for plans for future procurement timelines in order to achieve the target of 17.8 GW (see Table 7), as envisioned in the NDP and via the IPP programme. This gives hope that in spite of the recent delays in renewable energy procurement, South Africa can continue being the trendsetter on the continent

**Table 7** Electricity roadmap transition (current to 2030)

| | Coal | Nuclear | Hydro | Storage | PV | Wind | CSP | Gas/diesel | Other | Embedded generation | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| MW in 2018 | 39,162 | 1860 | 2196 | 2912 | 1474 | 1980 | 300 | 3830 | 22 | 200 | 53,936 |
| Decommissioning | 12,047 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| MW in 2030 | 33,847 | 1860 | 4696 | 2912 | 7958 | 11,442 | 600 | 11,930 | 499 | 2600 | 78,344 |
| % total 2018 (%) | 72.61 | 3.45 | 4.07 | 5.40 | 2.73 | 3.67 | 0.56 | 7.10 | 0.04 | 0.37 | 100.00 |
| % total 2030 (%) | 43.20 | 2.37 | 5.99 | 3.72 | 10.16 | 14.60 | 0.77 | 15.23 | 0.64 | 3.32 | 100.00 |

Accounting differences between Eskom and DoE estimates exist for 2018
*Source* Adapted from [18]

in diversifying the electricity mix, in a manner that incorporates renewable energy while allying socio-economic factors. The following section aims to discuss the short to medium term electricity roadmap, with a focus on the transition between the major electricity generation technologies.

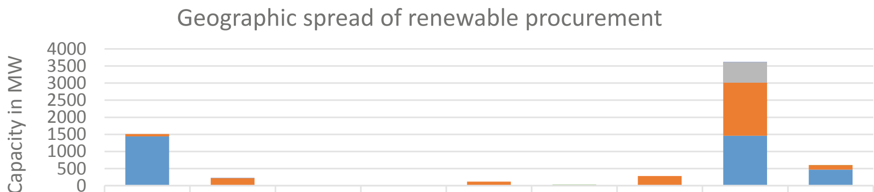
## 3 Electricity Technology Mix and Forecasts

The IRP [18] is an active plan which provides the roadmap for electricity technology transition, procurement and installation up until the year 2030, with revisits planned every 2–3 years. Table 7 provides an indication of the technology mix transition between 2018 and 2030. It is noteworthy to highlight the shift in transition in coal based electricity.

Coal fired capacity is expected to decline from current levels of 72–73% to roughly 43% in 2030 when taking into account decommissioning of roughly 12 GW of old power plant capacity. However adhering to the proposed decommissioning schedule is only subject to new capacity coming online from new coal power plants (Medupi and Kusile). Major changes include an almost four fold increase in PV capacity and wind capacity, and doubling of gas fired capacity which includes conversion of existing diesel fired plants to gas fired infrastructure. One critical aspect of the 2030 plan is that new procurement of renewable energy IPP is scheduled to occur only from the year 2025.

Also noteworthy is the increase in embedded generation which seems to be underestimated within the plan. There are increasing calls by industry players and municipalities to change regulation in order to enable municipal, industry and domestic consumers to produce their own electricity while being integrated to the grid [8]. While current limits for unlicensed generation is set at 1 MW, recent signals suggest that regulations could change, with the President indicating that regulations could be lifted upto 10 MW capacity [13].

These shifts and changes are bound to change the electricity landscape of the country. Majority of the centralised coal power plants were limited to north eastern parts of the country based on the location of coal reserves. However with the introduction of the REI4P, renewable energy plants have been spread out across the western, northern and central parts of the country. Figure 2 provides an indication of the spread of RE procurement across the nine provinces of the country. Majority of the projects are located in the Northern Cape, Western Cape and Eastern Cape, where historically only one power plant (i.e. nuclear power plant Koeberg in the western cape) existed prior to the renewable energy programme. The province of Mpumalanga is historically where almost all coal power plants are located, whereas Kwazulu Natal has had hydro power located within the province. Gauteng meanwhile has been the financial and economic powerhouse in spite of being the smallest province. As part of the RE procurement the spread of projects across these provinces includes 13 MW of landfill in Gauteng, 30 MW of biomass in Mpumalanga and 17 MW of biomass in Kwazulu




| | Eastern Cape | Free State | Gauteng | Kwazulu Natal | Limpopo | Mpumal anga | North west | Northern Cape | Western Cape |
|---|---|---|---|---|---|---|---|---|---|
| Biomass | | | | 17 | | 30 | | | 5 |
| Hydro | | 9 | | | | | | 10 | |
| Landfill | | | 13 | | | | | | |
| CSP | | | | | | | | 600 | |
| Solar PV | 70 | 219 | | | 118 | | 280 | 1552 | 134 |
| Wind | 1441 | | | | | | | 1459 | 467 |

**Fig. 2** Geographic spread of RE project procurement per province. *Source* IPP Office [14]

natal. The spread in projects have been based primarily on resource availability while socio-economic development within communities have also been a main factor.

The spread and arrival of renewable energy within South Africa is a welcome boost towards energy security, commitment to climate change and socio-economic development. However with the advent of new technologies in the local scene—particularly within local communities—the impact of these technologies need wider understanding, and gets addressed in the following section.

## 4 Impact Damage Assessment of Prominent Technologies

Impacts that are related to electricity production are usually not accounted for and are therefore quantified as external impacts. In order to fully understand the effects of theses impacts, costs are associated to the impacts, thereby accounting for monetary damage caused by the impacts under consideration [4, 27].

Impacts can range across wide range of impacts that are local or wider in nature depending on the technology. Impacts can also effect a range of parties ranging from humans, animals, crops and infrastructure. Quantifying impacts are data cumbersome process and can have a range of estimates. A comprehensive study (known as the ExternE study) to quantify impacts was undertaken during the mid-1990s up until mid-2000s [1]. The ExternE study (also known as the Externalities of Energy) consists of a comprehensive multi-country analysis across a range of technologies, focused on Europe.

The function used to evaluate external costs is deduced in terms of a damage function obtained from quantification of impacts and economic valuation as,

$$\text{Damage} = \text{Impact} \times \text{Cost}$$

where

Impact = Total number of cases per externality (impact).
Cost = Monetary value per case of externality (valuation).
Damage = Total monetary external cost.

The extent of quantification of external costs is largely dependent on the scale of impacts quantified, the availability of local data and the reliability of assumptions made when local data is unavailable. The framework for external cost analysis is based on the Impact Pathway Approach (IPA) as shown in Fig. 3.

For the purposes of this analysis, two blanket categories of impact being considered include;

(a) Effect on human health
(b) Effects on the environment

Impacts can be analysed over a single stage of the life cycle or even the entire life cycle. For the purposes of this analysis and the technologies under consideration, the analysis will cover stages as indicated in Table 8.

Due to different technologies being considered, methodological variations exist between the modelling of pollutant dispersion. For e.g. during coal fired generation dispersion of pollutants occur via a chimney at significant height above ground level. In order to account for such, tools that have the capability to model such dispersions were used. However for the other technologies dispersion occurs in other forms owing to which a life cycle tool was used, which will be discussed in the following sections.

### *4.1 Coal Fired Power Plant*

Coal fired electricity requires the extraction of coal from the surface below. Coal mining can be conducted in two ways, open cast mining or underground mining. For the purposes of this analysis the impacts of coal mining was not quantifiable because of the lack of data related to mining activities linked to the power plant under consideration. Therefore only the generation stage of the power plant is considered. As part of the analysis, a coal power plant, located in the province of Limpopo with 3690 MW nominal capacity producing 25,800 GWh of electricity, is considered. The power plant consists of six units of 665 MW installed capacity and is located in a semi-arid region. The first category of impacts linked to the power plant is discussed below.

(a) Health impacts

The impacts are evaluated using the Riskpoll[3] software. The pollutants considered in the analysis are sulphur dioxide ($SO_2$), oxides of nitrogen (NO and $NO_2$) and

[3]Riskpoll is the open source software used to evaluate damages from air pollutants from power plants.

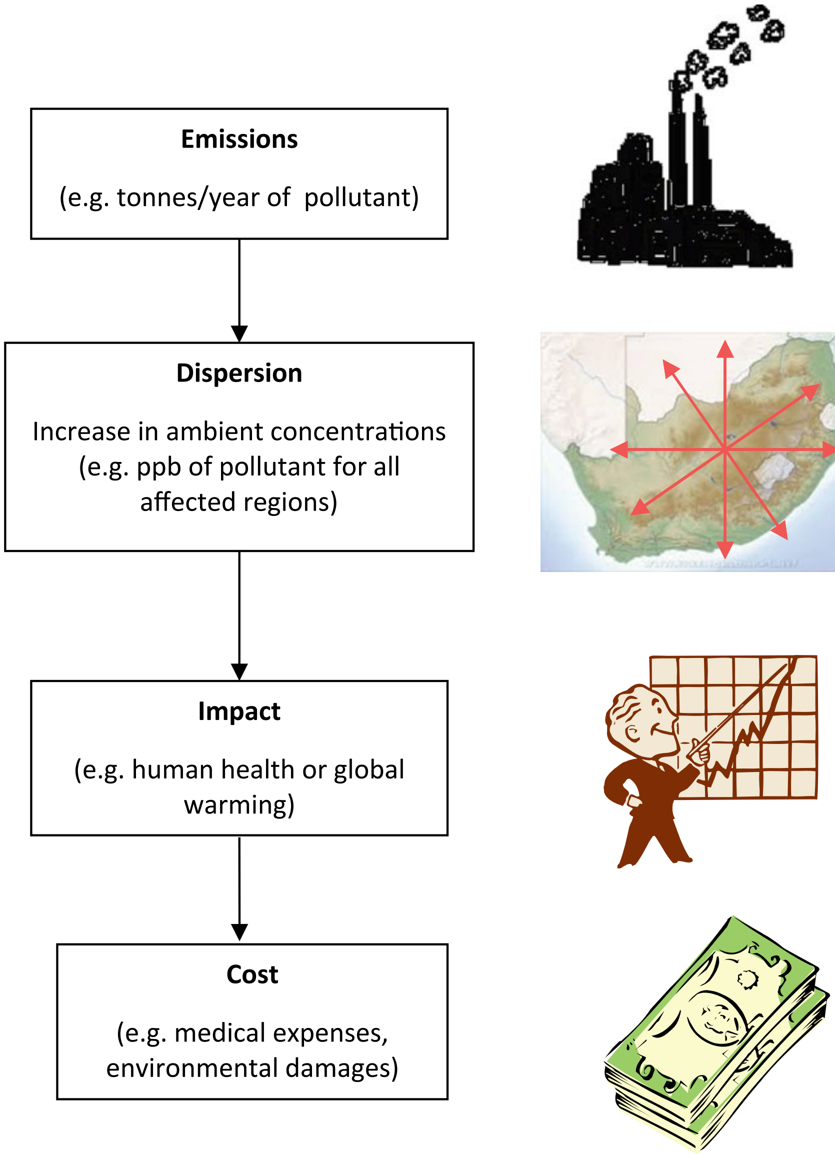



**Fig. 3** Impact pathway approach

**Table 8** Technology versus impact versus life cycle analysis matrix

| | Health | Environment | Life cycle stage |
|---|---|---|---|
| Coal | x | x | Generation |
| CSP | x | x | Full life cycle |
| Wind | x | x | Full life cycle |

particulates ($PM_{10}$). The emission inventories and characteristics (such as chimney height, physical location, etc.) for the power plant are used as inputs. Meteorological data local to the power plant was collected from local weather stations and the National Weather Service. The health impacts considered in this study included restricted activity days, long-term mortality, short-term mortality, chronic bronchitis and respiratory hospital admission. The critical choice of exposure–response functions for the mentioned health impacts, were used from the ExternE suit of studies [1]. These data sets were combined with population data (obtained from Statistics, South Africa) within a radius of 500 km of the power plant.

The atmospheric dispersion model within Riskpoll constitutes a robust uniform world model which is based on assumptions such as constant emission rate and depletion velocity of pollutants, uniform regional population, linear with zero threshold exposure response, uniform wind rose distribution and mean local meteorological conditions. The model in conjunction with local meteorological, population, power plant data and exposure–response functions is used to calculate the number of externalities or impacts. The economic cost (or monetary valuation) per case of impact is adapted from Riskpoll using exchange rates, as recommended in the ExternE study. The emission profile of the power plant includes 279.3 kilo tonnes of $SO_2$, 65.93 kilo tonnes of NOx and 7.59 kilo tonnes of particulate matter (PM10).

The range of impacts associated with the emissions stated above are indicated in Table 9.

Quantification of impacts indicate that restricted activity related to chronic conditions are a major contributor to overall impacts. While mortality impacts are lower in number, the cost per impact is considerably high. The number of years lost in terms of mortality for both long and short-term can be translated back into cases/year by

**Table 9** Health impacts estimated from coal power plant (central estimates)

| Health aspect | Units | Impact | Unit cost (SA Rands)[a] |
|---|---|---|---|
| Chronic bronchitis | Cases in person | 433 | 67,847 |
| Respiratory hospital admissions | Cases in person | 239 | 17,264 |
| Restricted activity days | Cases in days | 282,880 | 439 |
| Long-term mortality | Number of years | 193 | 383,919 |
| Short-term mortality | Number of years | 90 | 661,427 |

[a]An exchange rate 1 USD = 14 South African Rand and 1 Euro = 15 South African Rand can be used. These rates are based on January 2020 exchange rates, prior to the market volatility caused by the COVID 19 pandemic

**Table 10** Damage cost of coal power plant during generation phase

| Cost categories | Low | Central | High |
|---|---|---|---|
| Environmental cost (GHG eq.) in million Rand | 3991.50 | 9978.75 | 13970.25 |
| Human health in million Rand | 168.83 | 554.52 | 1915.66 |
| Total cost | 4160.33 | 10533.27 | 15885.91 |
| Environmental unit cost (SA c/kWh) | 15.47 | 38.68 | 54.15 |
| Human health unit cost (SA c/kWh) | 0.65 | 2.14 | 7.42 |
| Cost per unit (SA c/kWh) | 16.12 | 40.82 | 61.57 |

dividing the damages by 11.2 and 0.75 years respectively, which would amount to 17 long-term, and 120 short-term mortalities.

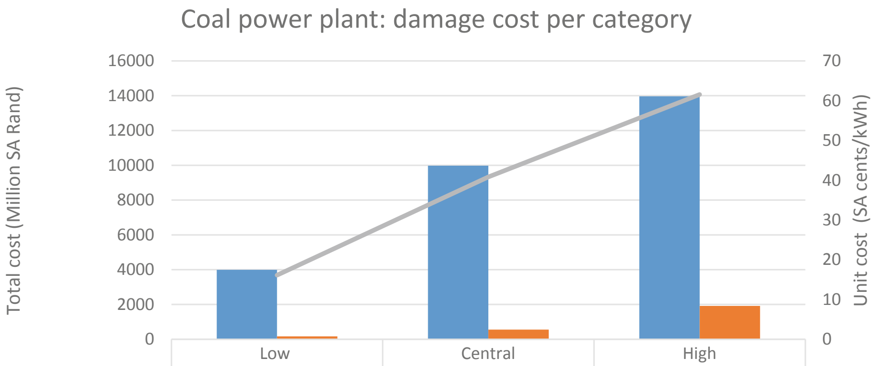
(b) Environmental impacts from greenhouse gases (GHG)

South Africa has an emission intensity that is relatively high compared to other countries, as indicated in Table 1. It was identified that the emission intensity (kg/kWh) for the power plant under consideration was 1.03 kg/kWh (the average being 1.00) with older power plants being less efficient as expected. The damage cost for a tonne of $CO_2$eq with lower, middle and upper bounds are chosen as 10 Euro, 25Euro and 35Euro respectively based on 2018 costs [2]. These values are converted to local values using an exchange rate of 1Euro = 15 SA rand. Therefore, the price of one tonne of $CO_2$eq in SA Rand with lower, middle and upper estimates is 150, 375 and 525, SA Rand respectively.

Based on the aforementioned set of data and model parameters, the damage cost associated with the two categories are shown in Table 10.

The numbers in the above table indicate the significant impact of GHGs during coal fired electricity generation. While costs associated with human health are much lower, total costs in this category are still significant. Figure 4 depicts the variation on environmental cost and human health cost. The variation between low and high estimates is larger in the human health category when compared to the environmental category. This is because of the higher uncertainties associated with human health impacts when taking into account treatment costs and costs associated with short term and long term loss of life.

The results indicate that the overall damage cost for the coal power plant was 16.12 SA c/kWh (low estimate), 40.82 c/kWh (central estimate) and 61.57 c/kWh (high estimate). Overall environmental costs related to GHGeq emissions account for 94.73% of the total damage cost. While there exists multiple studies and information about the impact of coal fired electricity [4, 27], investigations accounting for the impacts of renewable energy power plants are limited in nature. The following section will investigate the damage costs associated with an onshore wind farm.




| | Low | Central | High |
|---|---|---|---|
| Env cost | 3995.5 | 9978.75 | 13970.25 |
| Human cost | 168.83 | 554.52 | 1915.66 |
| Total unit cost | 16.12 | 40.82 | 61.57 |

**Fig. 4** Total and unit damages during generation stage for coal plant

## *4.2 On Shore Wind Power Plant*

Discussions on the transition of electricity supply in South Africa and forecasted technology mix indicate that wind powered electricity will be a popular form of electricity generation. Considering high wind resource availability along the southern eastern coast, it makes logical sense to locate wind power plants in this region. For the purposes of this analysis, a wind power plant of 138 MW installed capacity, located in the Eastern Cape province, is investigated. The power plant's design rating indicates a production of 460 GWh per year (and 9200 GWh over 20 years), which translates to a capacity factor of 38.03%. The expected life time of operation for the power plant is 20 years [28]. Unlike the analysis of the coal fired power plant which is limited to the generation stage, the analysis in this section will cover the entire life cycle. The analytical tool used for the investigation includes the GaBi Education LCA software [25] for lifecycle process modelling and the EcoInvent database for inventory analysis [6]. GaBi LCA allows for the estimation of GHG and non GHG impacts, therefore the wind farm impact analysis will account for all impacts as part of the same analysis (unlike the separate methodological estimations for the coal power plant).

The category of non-GHG impacts under consideration, in addition to GHG impacts, include,

(1) Human health: Costs linked to human mortality and morbidity due to the following emissions, Non-Methane Volatile Organic Compounds (NMVOC's), ammonia ($NH_3$), NOx, primary particulate matter (PPM) and sulphur dioxide ($SO_2$), are considered in this category

**Table 11** Impact categorisation across life cycle for wind power plant

| Impact sub-categories | Impact g/kWh | Impact per life cycle phase (g/kWh) | | | |
|---|---|---|---|---|---|
| | | E&M | T&C | O&M | D&D |
| Climate change (GHG eq) | 6.59 | 3.65 | 2.37 | 0.24 | 0.33 |
| Human health | 0.065 | 0.026 | 0.030 | 0.001 | 0.007 |
| Biodiversity | 0.035 | 0.015 | 0.017 | 0.001 | 0.002 |
| Crops | 0.031 | 0.011 | 0.017 | 0.001 | 0.002 |
| Materials | 0.035 | 0.015 | 0.017 | 0.001 | 0.002 |
| Total non GHG | 0.166 | 0.068 | 0.081 | 0.003 | 0.014 |

(2) Loss of biodiversity: Cost due to damage to the environment that is caused by the following air emissions, $NH_3$, NMVOC's, NOx, PPM and sulphur dioxide ($SO_2$).
(3) Local effects of crops: Cost of damage and positive externalities to crops due to the emission of $NH_3$, NMVOC's, NOx and $SO_2$, are considered under this category.
(4) Damage to materials: Cost of damage to buildings and other infrastructure and materials due to the emission of $SO_2$) which forms acid rain that causes damage through corrosion and NOx.

GaBi LCA was used to model a power plant inventory of 60 turbines of 2.3 MW capacity (i.e. equivalent of 138 MW capacity) across full life cycle stages that include extraction and manufacturing, transport and construction, operation and maintenance, and dismantling and disposal. The pollutants considered for the analysis include, $NH_3$, NMVOC, NOx, $PM_{2.5}$ and $SO_2$ [2]. Table 11 provides a breakdown of the impacts per impact category and across each life cycle phase. The four stages of the life cycle are extraction & manufacturing (E&M), transportation & construction (T&C), operations & maintenance (O&M), and dismantling & disposal (D&D).

From the above table it can be seen that GHG impacts are dominant compared to non GHG impacts, with majority of the impacts being accounted during the extraction & manufacturing and transportation & construction phases. Amongst non GHG impacts, the impact on human health is also prominent, during the same stages of the extraction & manufacturing and transportation & construction phases. The impacts during transportation & construction, compared to extraction & manufacturing, is marginally higher for all non GHG impacts.

Once impacts have been estimated, the impact cost associated with each pollutant from the CASES study [2] is used to estimate the damage cost across the each impact category and across each life cycle phase. Costs are adjusted for local costs using an an exchange rate of 1 Euro = 15 SA rand. A breakdown of total GHG cost per life cycle phase, compared to impact categorisation is shown in Fig. 5. The unit cost used for $CO_2$eq per tonne is the same as the costs used for the coal power plant.

As expected, operation & maintenance of is the least impactful life cycle phase, whereas extraction & manufacturing activities incur most impacts and therefore more

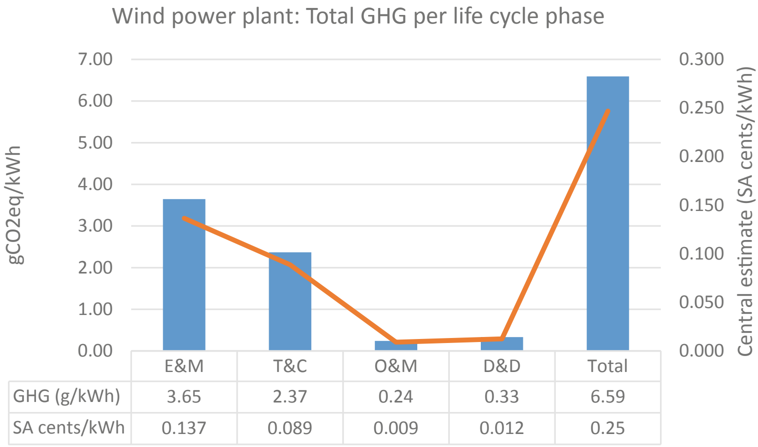



**Fig. 5** Total GHG damages over life cycle stages for wind plant

damage cost. A breakdown of non GHG impacts per life cycle phase is shown in Fig. 6.

While non GHG pollutant damage (g/kWh) is lower across all life cycle categories, the costs associated are higher, which is linked to the higher cost attributed to human health. Across the life cycle stage, transportation & construction contributes to higher pollutants, though extraction & manufacturing contributes to higher costs. This is due to the higher contribution of pollutants such as $NH_3$ and particulate matter linked to human health impacts, during the extraction and manufacturing stage.

Table 12 provides a combined breakdown of both GHG and non GHG costs in relation to total costs across all life cycle stages.

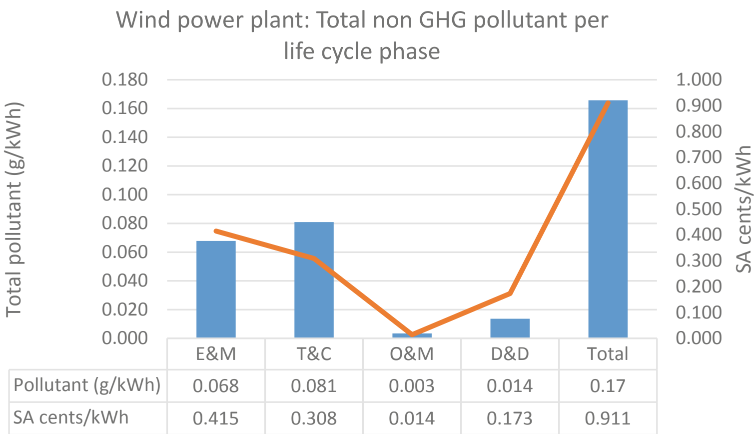



**Fig. 6** Total non GHG damages over life cycle stage for wind plant

**Table 12** Damage costs of wind power plant during life cycle

| Impact sub categories | Impact g/kWh | Cost/sub category (SA c/kWh) | E&M | T&C | O&M | D&D |
|---|---|---|---|---|---|---|
| Climate change (GHG eq) | 6.59 | 0.095 (low) | 0.053 | 0.034 | 0.003 | 0.005 |
| | | 0.247 (central) | 0.137 | 0.089 | 0.009 | 0.012 |
| | | 0.329 (high) | 0.182 | 0.118 | 0.012 | 0.017 |
| Human health | 0.065 | 0.852 | 0.386 | 0.283 | 0.013 | 0.169 |
| Biodiversity | 0.035 | 0.038 | 0.020 | 0.015 | 0.001 | 0.003 |
| Crops | 0.031 | 0.009 | 0.004 | 0.005 | 0.000 | 0.001 |
| Materials | 0.035 | 0.011 | 0.005 | 0.005 | 0.000 | 0.001 |
| Total non GHG | 0.166 | 0.911 | 0.415 | 0.308 | 0.014 | 0.173 |
| Total external cost | – | 1.006 (low) | 0.467 | 0.343 | 0.018 | 0.178 |
| | | 1.157 (central) | 0.551 | 0.397 | 0.023 | 0.186 |
| | | 1.239 (high) | 0.596 | 0.427 | 0.026 | 0.190 |

The overall damage cost for the wind plant was 1 SA c/kWh (low estimate), 1.16 c/kWh (central estimate and 1.24 c/kWh (high estimate). The results indicate that human health impacts account for roughly 73.6% of the total central estimate, which is primarily attributed to activities during the extraction & manufacturing phase as well as the transportation & construction phases. Local effects on crops and damage to material for the solar CSP plant may be classified as having low damage costs in comparison to the other sub-categories. It can be seen that the effects are almost non-existent during the O&M phase.

## *4.3 Concentrated Solar Power Plant*

The lifecycle analysis in this study is based on a parabolic trough CSP plant located in the Northern Cape region of South Africa. The power plant has an installed capacity of 100 MW, with a rated capacity factor of 36.5%. The plant has an expected life expectancy of 20 years, which translates to an expected output of 6400 GWh over the life cycle (i.e. roughly 320 GWh/year of produced electricity). The Northern Cape region has high solar intensities and is a sparsely populated area. The plant occupies 1100 ha of land and benefits from a direct normal irradiation (DNI) of 2900 kWh/m$^2$ [21] with a solar field aperture area of 800,000 m$^2$ using 1200 solar collector assemblies which uses thermal oil as heat transfer fluid (HTF). The installation incorporates 2.5 h thermal energy storage (TES) system based on two-tank indirect molten salt technology.

The framework of analysis used in this section is similar to the one used for the wind power plant and will cover the entire life cycle. The analytical tool used for the investigation is also the same, which uses GaBi Education LCA software [25] for lifecycle process modelling. However inventory analysis is based on methodological estimations used in Pihl et al. [20] and as adopted in Mahlangu and Thopil [19]. Impacts are categorised similarly into GHG impacts and non-GHG impacts across the life cycle. The non-GHG impacts being considered are similar to the previous section and are stated again for clarity.

(1) Human health: Costs linked to human mortality and morbidity due to the following emissions, Non-Methane Volatile Organic Compounds (NMVOC's), ammonia ($NH_3$), NOx, primary particulate matter (PPM) and sulphur dioxide ($SO_2$), are considered in this category
(2) Loss of biodiversity: Cost due to damage to the environment that is caused by the following air emissions, $NH_3$, NMVOC's, NOx, PPM and sulphur dioxide ($SO_2$).
(3) Local effects of crops: Cost of damage and positive externalities to crops due to the emission of $NH_3$, NMVOC's, NOx and $SO_2$, are considered under this category.
(4) Damage to materials: Cost of damage to buildings and other infrastructure and materials due to the emission of $SO_2$) which forms acid rain that causes damage through corrosion and NOx.

The life cycle stage classification being considered is also similar to the wind power plant, with four stages of life cycle being considered, namely, extraction & manufacturing (E&M), transport & construction (T&C), operation & maintenance (O&M), and dismantling & disposal (D&D). The pollutants being investigated as part of the analysis include, $NH_3$, NMVOC, NOx, $PM_{2.5}$ and $SO_2$. The breakdown of the impacts per impact category and across each life cycle phase are provided in Table 13.

It can be seen that GHG impacts are significantly higher than non-GHG impacts, which is attributed to the manufacturing phase, during which process intensive activities are required for components such as molten salt and solar glass. Figure 7 provides a breakdown of GHG cost per life cycle phase, in comparison to the impact per phase. The O&M phase tends to have higher emissions owing to self-use electricity requirements and diesel use during operations. D&D phase also tends to have higher

**Table 13** Impact categorisation across life cycle for CSP plant

| Impact sub-categories | Impact g/kWh | Impact per life cycle phase (g/kWh) | | | |
|---|---|---|---|---|---|
| | | E&M | T&C | O&M | D&D |
| Climate change (GHG eq) | 32.2 | 14.1 | 3.1 | 7.3 | 7.7 |
| Human health | 0.214 | 0.093 | 0.046 | 0.021 | 0.054 |
| Loss of biodiversity | 0.149 | 0.061 | 0.038 | 0.011 | 0.039 |
| Local effects on crops | 0.13 | 0.032 | 0.041 | 0.013 | 0.045 |
| Damage to materials | 0.122 | 0.039 | 0.037 | 0.011 | 0.034 |
| Total non GHG | 0.615 | 0.224 | 0.162 | 0.056 | 0.172 |

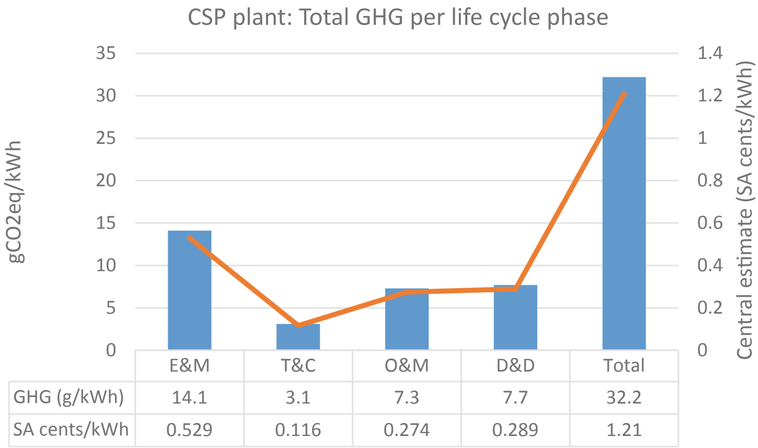



**Fig. 7** Total GHG damages over life cycle stages for CSP plant

emissions associated, owing to the nature of material being disposed, which includes molten salt.

Figure 8 provides a breakdown of non GHG impacts per life cycle phase for the CSP plant. Within non GHG pollutant impacts, the E&M phase tends to be dominant, owing to the emissions of $NH_3$, $SO_2$ and NOx. The damage during O&M phase is comparatively lower owing to the nature of renewable resource availability.

A combined breakdown of both GHG and non GHG costs in relation to total costs across all life cycle stages is provided in Table 14.

The overall damage cost for the CSP plant was 3.15 SA c/kWh (low estimate), 3.88 c/kWh (central estimate and 4.36 c/kWh (high estimate). The results indicate

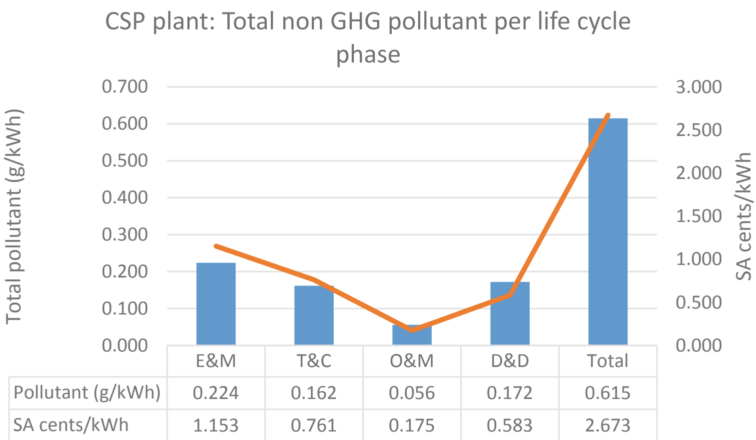



**Fig. 8** Total non GHG damages over life cycle stage for CSP plant

**Table 14** Damage costs of wind power plant during life cycle

| Impact sub-categories | Impact g/kWh | Cost/sub category (SA c/kWh) | E&M | T&C | O&M | D&D |
|---|---|---|---|---|---|---|
| Climate change (GHG eq) | 32.2 | 0.48 (low) | 0.211 | 0.046 | 0.109 | 0.115 |
| | | 1.21 (central) | 0.529 | 0.116 | 0.274 | 0.289 |
| | | 1.69 (high) | 0.74 | 0.163 | 0.383 | 0.4 |
| Human health | 0.214 | 2.259 | 0.937 | 0.667 | 0.158 | 0.497 |
| Loss of biodiversity | 0.149 | 0.330 | 0.193 | 0.068 | 0.010 | 0.059 |
| Local effects on crops | 0.13 | 0.063 | 0.013 | 0.023 | 0.003 | 0.023 |
| Damage to materials | 0.122 | 0.022 | 0.010 | 0.004 | 0.003 | 0.004 |
| Total non GHG | 0.615 | 2.673 | 1.153 | 0.761 | 0.175 | 0.583 |
| Total external cost | – | 3.153 (low) | 1.364 | 0.807 | 0.284 | 0.698 |
| | | 3.883 (central) | 1.682 | 0.877 | 0.449 | 0.872 |
| | | 4.363 (high) | 1.893 | 0.924 | 0.558 | 0.983 |

that human health impacts account for roughly 58.2% of the total central estimate, which is primarily attributed to activities during the extraction & manufacturing phase, transportation & construction phase, and the dismantling & disposal phase. The nature of materials used for storage tends to have a higher contribution towards overall damage costs. Local effects on crops and damage to material for the solar CSP plant may be classified as having low damage costs in comparison to the other sub-categories.

The following section will compare the damage cost for the multiple technologies that have been analysed taking into account the variations in methodologies and life cycle phases.

## 5 Comparative Damage Cost Assessments

Having analysed multiple technologies and the multiple impacts of such, enables a unit cost comparison of the impacts and costs. Comparisons however will have to be based taking into account variations in methodologies and tools.

While the impact and cost analysis of the coal power plant was based on the impact pathway approach for the generation stage, the impact assessment of wind and CSP power plant was conducted using the life cycle approach for all stages of the life cycle. The tool used for the assessment of the coal power plant was Riskpoll whereas the assessment tool used for wind and CSP plants was GaBi LCA. The choice of Riskpoll was based on the capability to model emissions from a single point source whereas the choice of GaBi LCA was based on the capability to model life-cycle processes.

**Table 15** Comparison of central damage cost (categories vs technologies)

| Central cost (c/kWh) Rand[a] (USD; Euro) | Coal[b] | Wind[c] | CSP[c] |
|---|---|---|---|
| Climate change (GHG eq.) | 38.68 (2.76; 2.58) | 0.247 (0.017; 0.016) | 1.21 (0.086; 0.08) |
| Human health | 2.14 (0.153; 0.142) | 0.852 (0.061; 0.057) | 2.259 (0.161; 0.151) |
| Other | Not accounted | 0.058 (0.004; 0.039) | 0.414 (0.029; 0.028) |
| Total | 40.82 (2.92; 2.72) | 1.157 (0.083; 0.077) | 3.884 (0.227; 0.259) |

[a]Rand values are bolded; [b]Assessment limited to generation stage of life cycle; [c]Assessment for all stages of life cycle

Table 15 provides a comparison of the central unit damage cost across all three technologies that are under consideration. Costs are separated across GHG costs, human health costs and costs linked to other categories. The table also provide a cost indication in US dollar (for an exchange rate of 1 USD = 14 SA Rand) and in Euros (for an exchange rate of 1 Euro = 15 SA Rand).

## 6 Conclusion and Way Forward

The comparison provides some interesting insights. While as expected, the costs associated with GHG emissions is the highest for a coal fired plant, the costs associated with human health is higher for a CSP plant. This can be attributed to the scope of analysis being limited to the generation stage of the coal plant but also on the materials being used for the CSP plant. The variation of costs between the wind plant and CSP plant also makes for interesting insights. While total costs associated with the CSP plant compared to the wind plant is more than 3 times, the component that provides larger variation is the GHG cost (i.e. almost 5 times).

Another important observation is that while the impacts and damages related to human health tend to be more dispersed, the impacts within the same category for a wind plant and CSP plant are more localised. These observations need to be taken into account within the REI4P (which is the renewable energy roadmap) as well as the future iterations of the IRP (which is the electricity roadmap). In order to successfully navigate the vision of clean, affordable and reliable electricity in line with South Africa's national development plan and SDG7, accounting for unaccounted damage costs are crucial.

The nature of electrification has changed considerably over the past decade in South Africa both through proactive and reactive policies. These changes have brought about a shift in power plant infrastructure from being primarily large coal based power plants towards multiple dispersed renewable energy technologies. This nature of dispersion has added benefits and impacts. The benefits and impacts of dispersed utility scale power plants tend to be more prominent in the communities located near these plants.

The investigation conducted in this chapter adds to the body of knowledge relating to impacts and the costs associated with impacts for renewable technologies that are relatively new within the South African and Sub-Saharan context. As the scale of these technologies increase there is an added need to mitigate the impacts of these technologies and the activities related to such. Investigations also have to be undertaken for technologies not covered in this assessment, primarily utility scale solar PV power plant. Investigations also have to be conducted to compare the impact of similar power plant technologies located at different locations.

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# The Politics of Electricity Access and Environmental Security in Mozambique

**Matthew Cotton, Joshua Kirshner, and Daniela Salite**

**Abstract** Electricity access is a key aspect of achieving Sustainable Development Goal 7. Alleviating poverty by increasing the availability of grid connections, system reliability and generation capacity is a key driver of economic growth. However, 2.7 billion people still rely upon unsustainable wood fuels (such as charcoal) for heating, lighting and cooking. A sustainable transition to low carbon energy has positive health and social benefits (e.g. reductions in air pollution, deforestation and carbon dioxide emissions); and secondary economic benefits from energy supply service jobs (such as installation and maintenance jobs), market disruption and innovation (from community decentralised systems, for example), and reduced labour and time costs (such as reducing costs associated with mobile phone-charging). However, representing electricity access in terms of numbers of grid connections over-simplifies the energy access challenge—hiding unreliability, community exclusion from planning processes, and potential socio-environmental damage from energy sources (e.g. from coal-use), and complex political-institutional and socio-technical system relationships. This two-part chapter examines first the benefits of electricity access provision for developing countries, and second focuses on resolving these challenges through examination of the case of Mozambique—a low income, high resource abundance nation that is undergoing rapid electrification. The chapter explores the colonial history of Mozambique and its influence upon energy technology socio-technical system development across the diverse physical and cultural geography of the country; the effects of internal political conflict and contestation; and the impact of large-scale foreign investments, especially in extractive resources. We conclude by discussing how the changing political economy of Mozambican energy production, distribution and use at the national and regional level has yet to significantly

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transform everyday energy practices in rural and urban areas. The majority of the Mozambican population remains dependent on environmentally insecure fuelwood (in rural areas) and charcoal (in urban areas), especially for cooking. The consumption of biomass is of concern to authorities because of rapid deforestation, particularly within the hinterland of major cities. Moreover, fuel supply chains remain disconnected from the electricity generation and distribution systems and the extraction of resources such as coal or natural gas. Recommendations for policy, technology implementation and development practice are discussed throughout.

## 1 Introduction

This chapter examines the issue of electricity access as a key socio-environmental development challenge in the Global South. Energy services such as heating, refrigeration, cooking and lighting, meet both the basic needs to sustain life and provide secondary socio-economic benefits such as recreation, telecommunications, educational attainment, economic productivity and poverty alleviation. Meeting energy service needs for the world's poorest people necessitates diversity in fuel sources and technologies under varying geographic, political and socio-economic conditions. Yet for many in the developing world, energy services are met at the expense of environmental security. By burning solid carbon-based fuels such as charcoal, wood, peat or lignite (commonly referred to as brown coal), energy services deplete or degrade ecosystem services that provide other benefits, such as construction material provision, flood abatement, biodiversity protection and soil integrity [56, 105]. Solid fuels also produce a range of negative health and environmental impacts. Transition towards cleaner burning gas and electric sources is therefore a critical development policy priority. As such, the expansion of electricity transmission and distribution systems and increasing the number of connected commercial/residential properties, has become an energy policy priority—one driven by intergovernmental organisation and donor programmes to improve (primarily rural) electrification as a key community development outcome.

Electricity infrastructure provision does not guarantee improvement in livelihoods or community wellbeing. Electricity access is commonly measured by the total number of grid-connected communities/households/businesses. However, other factors such as variable electricity pricing, supply intermittency, poor grid-connection reliability, as well as cultural and social practices of energy service use (such as preferences for specific solid/black carbon-cooking fuels for example) create a complex interwoven picture of energy use, demand and supply. Moreover, electricity access expansion is embedded in institutional and policy contexts that favour certain outcomes, geographies and social groups. Problems of *unequal* access are exacerbated by endogenous domestic and regional disruption—i.e. civil unrest, political contestation and military conflict—and exogenous factors such as extreme weather events (exacerbated by anthropogenic climate change), flooding and drought, deforestation, regional or global financial crises, changes in diplomatic relations, inward investment and enclave economies (the latter dominated by international or non-local capital so that resources flow away from the developing country in which they are extracted, towards the country which financed the investment [92]). Electricity access is therefore fundamentally an issue of *social justice*—access is not something defined through grid-connectivity alone, but is bound up in complex environmental security concerns related to climate change and land use governance, of political factors related to political security and community development, and economic factors related to investment, capital flows and the alleviation of poverty.

In this chapter we examine the complexity of the electricity access challenge in the context of social and community development. Our chapter is structured in two parts. The first outlines the difficulties and opportunities of expanding grid access to improve electricity service provision to the poorest people globally, and the second explores the complexity of the political and justice implications of electricity access provision, with reference to Sub-Saharan African nations (more generally) and to an in-depth case of Mozambique (specifically).

## 2 The Electricity Access Challenge

Poverty alleviation for low income developing nations is understood as a multi-dimensional problem that involves simultaneous progress across 17 Sustainable Development Goals (SDGs). The SDGs cover health, gender equality, jobs and livelihoods, environmental protection, and institutional governance: providing a comprehensive policy and planning tool to end global poverty [99]. However, despite significant political progress in the last decade, nearly 800 million people still live in extreme poverty (defined as those earning $1.90 per day or less: SDG Atlas [89]). The global challenge of multi-scalar and multi-sectoral poverty alleviation involves a complex array of policy and economic development options. At the core, however, is a need to improve *opportunities* for the poorest people, primarily by widening access to public services (including health and education) and basic infrastructure such as energy access [107], as well as their respective *capabilities* to meet their own needs [36].

SDG7 emphasizes the need to “ensure access to affordable, reliable and modern energy for all by 2030” [99]. *Energy access* is posited as the mirror opposite of *energy poverty*—a condition of unstable and/or unaffordable access to electricity and clean fuels. Alleviating energy poverty requires the simultaneous development of both physical resources (including technological infrastructures, minerals and other extractive commodities, research and innovation, and ecosystem services) and social infrastructures (including political institutions, public services, cultural assets, capacity building and nurturing local capabilities, and transparent governance systems), such that social welfare is maximised through access to energy services, and not just the private profit of energy companies. Social scientists commonly refer to these inter-related sets of social and physical components as ‘socio-technical’ systems that bring together a web of inter-connected human, physical, material and technological elements [102]—the physical built infrastructure of generation and transmission is woven into a pattern of relations between energy services, contexts and cultures through which energy connects with the social life of users. Electricity access also underpins related commitments to reduce the risk of anthropogenic climate disruption from greenhouse gas emissions, and so the socio-technical system of energy services connects deeply with the broader ecological and geophysical systems that support human and non-human life and wellbeing on a global scale.

Energy access as a *policy priority* involves increasingly complex and interconnected international agreements on sustainable energy access and climate change. The global spotlight on rural electrification and sustainable energy transitions is mobilising billions of dollars in finance for technology transfer to the Global South, either to increase generation capacity or to extend grid infrastructures and domestic, or household connections [51, 83]. For instance, in 2013 investors mobilised US$13.1 billion globally in energy access, with 97% of that funding targeting electricity networks [83]. However, the deployment of significant financial resources to advance sustainable energy goals has often reproduced what could be termed *neoliberal* policy prescriptions. Public sector roles in energy services provision are, in many cases, limited to regulatory functions such as creating an 'enabling environment' for clean energy technologies to grow [22]. This represents a shift towards the development of the 'regulatory state', characterised by processes of privatisation and deregulation which replaced the 'dirigiste state' of the past (whereby the state exerts a strong directive influence over investment) [62]. Thus *regulation*, rather than public ownership, planning or centralised administration, have become the key contextual factors influencing how low carbon energy transitions have come to be governed [32].

Despite the socio-technical nature of electricity services, analysts frame sustainable energy provision as a matter for technical experts—a challenge of increasing transmission distances and maximising the number of consumer connections to centralised grid infrastructures. With a strong international focus on electricity grid extension, much existing development research has focused upon binary metrics, such as whether or not a household has an electricity connection [16]. Yet the energy access challenge is more complex. Clearly, the expansion of domestic connections does not automatically guarantee access to reliable and sustainable electricity. Moreover, even where the headline metric of grid access is increasing, this does not necessarily help policymakers to understand how expanding energy access relates with overall socio-economic development.

On a simple level, electricity access can be understood in terms of the three "Rs"—rural electrification (*the process*), reform of the electricity sector (*the catalyst*), and renewable and other low carbon energy technologies (*the means*) [28]. Yet, in trying to improve access, across the world there has been significant growth in the development of centrally planned electricity transmission and distribution networks, with little attention paid by policy-makers, infrastructure development bodies, and planners to the broader social impacts, institutional configurations and local–regional development goals that drive particular socio-technical system changes. It is necessary therefore, to structure energy transitions and socio-technical system changes in context-specific ways—to incorporate 'bottom-up' assessment of the political, economic and social circumstances of regional, national or sub-national energy systems in which new technologies are to be applied [46]. Moreover, quantifying the impacts of energy access gains (or conversely the lost opportunities) to vulnerable populations is highly challenging, so that calculating the costs and benefits of different electrification strategies is difficult. Furthermore, many centralised grid systems globally, rely on fossil fuels. Energy networks are commonly subject to technological 'obduracy' and 'carbon lock-in'—or, how a combination of political, economic and technological path dependencies resulting from colonial histories, poverty, resource availability and technological capacity, steer energy system development down a carbon intensive pathway, which becomes increasingly difficult to reverse [100].

Electricity access can be problematised in multiple ways. First, is that where electricity grid access exists, it is often unreliable (especially in remote and rural locations). In many developing states, electricity access is commonly through irregular, patchy and informal (often illegal) connections [94]. On a technical level, there are further questions to consider, e.g. —is the connection to the central grid or an independent 'islanded' micro-grid? Are connections safe and well maintained? Are grid connections and electricity supply affordable? Is access dependent on one or more energy generation technologies? Is there sufficient skills capacity for repair and maintenance of electricity services? [8]. Second, is the inherent politicisation of energy infrastructure. National governments are often motivated to expand centralised grid networks (either low-carbon or carbon-intensive) because domestic and commercial energy consumption is a key tool for economic growth of local and national economies. Some states are further motivated to invest in large energy-related infrastructures as a means forge visible connections with citizens (and voters) in their daily lives, at least at the level of political rhetoric [82], and often as a means to secure votes. Moreover, the planning and construction of energy infrastructure raises issues of risk distribution, land rights, and procedural justice in infrastructure decision-making that become the focus of socio-political contestation [12, 63], with civil unrest, direct action and conflict emerging around key energy projects such as pipelines, hydro-dams and extractive sites. Third, for electrification programmes intended to connect users nationally, these often do not significantly contribute either to the intensification of electricity consumption nor to the reduction of biomass use (such as charcoal and fuelwood) in households. This is because the domestic choice of energy source is dependent on factors such as fluctuating and uncertain prices and on household capability to invest in new energy-consuming appliances. Conversely, however, biomass sources and kerosene are often more expensive per unit of useful energy than higher-grade sources, suggesting that although electrification has proved challenging, it *should* remain a key poverty alleviation strategy [6], in a normative sense.

## 3 The Benefits of Electrification

The relative benefits of electrification relate to a range of inter-related social development outcomes:

(1) Improved health outcomes

For many people across the world, heating and lighting is provided by open flames—such as wick lamps or oil lamps, open fires and candles. These are low-efficiency and highly polluting heating and lighting sources. A shift from black-carbon based energy and fuel sources (e.g., lignite [brown coal], peat, dung or domestic charcoal) towards domestic electricity-powered lighting and gas or geothermal heating will greatly reduce associated health risks with black carbon fuels such as: respiratory disorders, cancer and heart disease associated with prolonged exposure to black-carbon fuels [41, 109]. It will also reduce the health risks associated with ambient air pollution, such as smog and ozone pollution that blights many of the world's most populous cities. There is a need therefore for the simultaneous mass electrification and rapid transition towards low-carbon/low-particulate pollutant energy-generation technologies.

Electricity-based solutions to heating, cooking and lighting improve local/domestic air quality, reduced risk of uncontrolled fires and associated injury and death. Electrification also provides domestic cost savings, reducing household expenditures for energy services (such as kerosene) by replacing them with direct access [86, 97].

(2) Reduced environmental impacts

A shift from centralised fossil fuel-based electricity production from coal (particularly lignite) will reduce the carbon emissions per unit of energy and thus mitigate climate change impacts from rapid economic development [24, 101]. Moreover, reliance upon black-carbon fuel sources for heating and lighting is associated with widespread local environmental degradation and poor environmental health, primarily from deforestation for fuelwood and charcoal. An estimated 2.7 billion people globally rely upon wood-based fuels for cooking [14]. There is a lack of reliable baseline data on global charcoal consumption, and as such, there is a risk that over-generalisation around the extent to which charcoal is causing forest damage is preventing an effective policy response [68]. However, case studies in different developing country contexts using different methods (including satellite image observational studies and ethnographic studies) do show deforestation occurring [59, 76, 96]. Mass charcoal production provides opportunities for income-generation [53], though it commonly damages biodiversity and ecosystem service provision, with resultant negative impacts upon agricultural capacity and human health and well-being [2, 29]. Over 80% of urban households in sub-Saharan Africa employ charcoal as a primary cooking fuel, and charcoal also provides a significant source of income for rural households in areas with access to peri-urban and urban markets; though charcoal use is of course not limited to rural communities [66, 69, 70, 111]. As Zulu and Richardson [110] have observed, poorer households are more likely to participate in the production and sale of charcoal, primarily to provide an economic safety net by supplementing other sources of income. Policy responses to reduce household dependence on charcoal must therefore not only replace wood fuels in domestic settings but must also provide an alternative income stream for farmers and labourers.

(3) Improved communication networks

In the public sector, social services in rural areas such as schools, hospitals and health centres require electricity for lighting, data management, and refrigeration [1]. Mobile phones (often presented in the popular media as non-essential luxury items), are becoming a basic needs technology—they improve mental health, political engagement, better integration of family and social support networks (particularly under conditions of forced or seasonal migration due to environmental stressors, civil unrest or market changes), and improved communication with business services, supply chains and financial organisations (including participation in the marketplace through mobile banking and money transfer using smartphone apps and telephone banking) [10, 44, 93]. Access to Internet services through mobile phone data also improves access to educational materials, practical information to improve community adaptive capacity and diverse livelihood strategies. Mobile phones and underlying electrical and terrestrial telecommunications infrastructure reduce communication costs, allowing individuals/firms to send and to obtain information quickly and cheaply on a variety of economic, social, and political topics. Reduced cost of mediated communication, in turn, leads to tangible economic benefits, improving agricultural and labour market efficiency, producer and consumer welfare, alongside with wider rural connectivity [4, 79]. As such, the poorest people (particularly those living in off-grid rural communities) spend significant time and financial resources charging phone batteries and so reliable electricity for this purpose alone would have beneficial development outcomes [7].

(4) Secondary supply-side benefits

Improvements in the availability of electricity services increases the direct and indirect employment opportunities for supply-side energy services. These include electricity generation, technology installation, distribution and sale across the energy delivery chain, and the economic development effects on the demand side—such as improving productivity of rural industries (such as food processing) [28, 86]. As mentioned in relation to the twin commitments of improving electricity access and reducing global climate change risk, numerous innovations have emerged in the low-carbon energy innovation ‘space’. These include micro-renewables, such as stand-alone solar water heaters and solar photovoltaics (PV), wind power and geothermal technologies, micro/mini-grids, alongside innovations such as “agrivoltaics” [38] or “floatovoltaics” [85]. With such innovation there is a corresponding expansion of local markets for renewable electricity generation, technology installation, maintenance and consulting [65]. Enhancing electricity access therefore represents an opportunity for bottom-up community energy provision, entrepreneurial activity, new forms of public–private partnerships, and models of community ownership for energy generation. As Alstone et al. [5] argue, the contemporary electricity technology landscape is permeated with rapidly developing (and rapidly spreading) *decentralised* network models and systems. Community energy provision is primarily brought about through the deployment of decentralised energy networks, which combine high-efficiency consumer and end-use appliances and low-cost renewable energy generation technologies including (but not limited to) low-cost photovoltaic cells [15, 31]. Such systems are *disruptive* in that they increase electricity service access whilst driving low-carbon transition—effectively bypassing the need for centralised and grid-connected fossil fuel-based systems [5].

Electrification also has other secondary social benefits. Reducing the time spent gathering wood fuels and seeking mobile phone charging will likely improve opportunities (particularly for women and girls) to engage in recreation and education, thus improving wellbeing, health and social outcomes [104]. Studies of rural electrification find that the greater the likelihood of a household's access to an electric grid, the more time the household's children are likely to spend studying at home, offering indirect evidence of an improvement in levels of schooling [3, 35]. Other researchers have shown electrification to accelerate opportunities for women. Domestic electricity access helps to move women and girls into more economically productive activities, and Samad and Zhang [88] find that electrification measurably improves women's decision-making ability, mobility, financial autonomy, reproductive freedom, and social participation.

### *3.1 Summary*

Overall, the analyses discussed here have implications for the ability of lower income developing economies to promote and sustain increases in energy access, along with a range of associated benefits to this process. Given the extent of the energy access challenge, with an estimated 1.1 billion people currently lacking access to electricity [50], several authors argue for developmentalist and publicly-funded interventions, alongside nurturing opportunities for innovation and entrepreneurial approaches [22]. Yet, the picture remains complex; and apart from highlighting these direct and indirect benefits reached through increasing and improving energy access, geographers, STS (science and technology studies) scholars, and other critical social scientists have developed new lines of research on energy access in the global South. Such research has focused heavily upon energy poverty, justice and people's everyday lived experiences (Castán Broto [26] for example, discusses low carbon energy transitions, along with social and cultural aspects of new lighting and cooking technologies [58]).

Related to the emerging debates in which the concept of 'energy justice' figures prominently, Castán Broto [25] and Castán Broto et al. [19, 26] have recently explored the notion of 'energy sovereignty' over energy generation, transmission and distribution systems. In a developing and postcolonial context, this means learning to recognise how people themselves engage with the making of technologies of everyday life through hybrid forms of contextually generated innovation. Another stream of literature highlights the local and global infrastructures of production, transport and distribution of energy, along with practices of securing such activities and their spatial manifestations [18]. Such spatial justice issues concern problems of land-grabbing, displacement and social oppression linked to large-scale energy investments [61, 91]. This analysis seeks to uncover emerging spatial dimensions of power and politics, adding to our understanding of state-building and geopolitical relations, particularly in postcolonial contexts.

In the second part of this chapter, we narrow the focus of electricity access within a geographically bounded case study. Specifically, we explore these issues in the context of Sub-Saharan electricity access and development. This is followed by a discussion of a *critical case* of electricity access in Mozambique: one of the Southern African region's largest hydropower-generating yet energy access-poor, countries. We outline and analyse some of the challenges involved in extending energy access in an equitable and sustainable manner, and then reflect upon the Mozambican case for broader energy-and-development policy and planning.

## 4 Electricity Access in Sub-Saharan Africa—A Case Study of Mozambique

Despite the clear benefits of electrification, for many sub-Saharan African states, investments in the energy sector fail to meet the energy needs of the poorest people, even in countries where access to grid-connected energy services, unplanned service disruptions and power outages are commonly experienced. Moreover, supply of electricity is not always affordable, and many rural, off-grid and micro-grid systems only have sufficient capacity to provide a few hours of electricity services per day. Consequently, even for those with a permanent grid connection, the absolute level of electricity consumption and access to electricity services is low, and there remains no universally accepted minimum threshold for what constitutes electricity access, particularly in establishing policy targets [48, 49, 51].

Fully two-thirds of total energy investment across the African continent is dedicated to producing energy for export while roughly half of current electricity consumption is used for industry—primarily mining and refining [48]. Moreover, the needs and priorities of users, particularly those of the poor, have been widely overlooked in national energy planning, as the focus has largely been on locating strategic resources for global markets rather than providing energy services tailored to local needs and conditions, or offering a meaningful voice to users [83, 84]. It is necessary, therefore, to better understand and engage with the interests, power relations and policy networks that shape the prospects of realising climate and energy policy goals; acting as barriers in some cases and as vehicles for change in others.

Energy access is often approached from "top-down" policy perspective—such that concerns with energy security and sovereignty compete with the demands of export markets and the need to facilitate global trade and resource flows. Such national economy-scale concerns often take precedence over household and community perspectives on energy access and use, stymieing progress towards universal access to modern energy services. Electricity infrastructure planning, construction, operation and maintenance remain technically challenging within countries that have geographically isolated and politically fractured regions [55]. Expanding centralised electricity infrastructure is also coupled to complex long-term governance challenges, not least the effective mobilisation of funding from both internal sources (e.g. taxation-based public monetary and fiscal policy, public–private partnerships) and external sources (donors, loans, inward investment and venture capital) funding [45]. Furthermore, complex financing programmes for energy system investment require greater emphasis both upon the productive uses of energy, and upon good governance to break the vicious circle of low incomes leading to poor access to modern energy services, leading to further poverty.

Diversification of energy resources, policies, investment models and governance practices would aid rapid, socially sustainable energy transitions. However, the dominant economic model across much of sub-Saharan Africa is to promote the interests of large-scale energy consumers to grow top level economic indicators (notably Gross Domestic Product—GDP); domestic and rural electricity benefits are conversely construed as ‘social welfare’ or ‘uneconomic’ policy objectives [90]. Top-down economic and policy models follow the electrification and social development trajectory of mid-20$^{th}$ Century European and North American energy systems: the emphasis is upon centralised ‘megaprojects’ such as fossil fuel, hydro and nuclear power plants, and electricity transmission systems radiating outwards towards rural communities. The development of this megaproject-scale infrastructure model creates a mutually reinforcing system of governance—i.e. it promotes state ownership and control [55, 60], which in turn leads to socio-technical lock-in of centralised energy service provision.

## 5 The Case of Mozambique

Mozambique is a low-income developing country in Southeast Africa with a population just below 30 million, ample arable land, water, energy and mineral resources, and offshore natural gas reserves. The economy is strongly influenced by its agricultural sector that, despite only accounting for 22% of GDP, employs approximately 71% of the population (roughly 94% of the poorest people work agriculture World Bank [108]). Despite sustained economic growth since the mid 2000s, due primarily to the expansion of the extractives industry, it suffered a sharp downturn in 2016 triggered by falling commodity prices, adverse climate conditions, and the discovery of US$1.4 billion in previously undisclosed public debt (equal to about 10 percent of GDP) [78]. The overall social development outcomes, environmental security futures and uptake of energy access across rural, peri-urban and urban centres are therefore contextualised by a combination of resource abundance and move to extractive industries (particularly of natural gas and minerals), a primarily agricultural labour force, and growing political contestation and debt crisis causing economic unrest.

Mozambique's political economy is heavily shaped by its colonial past. Mozambique lived for four centuries under Portuguese rule, and the violent effects of colonial action remain significant—with the oppression of the slave trade and brutal civil political repression by Portuguese authorities remaining salient in Mozambican memories [23]. Mozambique's current energy systems are also shaped by this colonial history and by deep divisions between the northern, the central Zambesi valley, and the southern regions. Under Portuguese rule in 19$^{th}$ and early twentieth centuries, the territory that was to become Mozambique was divided into separate concession areas and governed by charter companies, commonly British, until 1942 [73]. Geographical constraints to an integrated national development strategy also stem from the location of the capital in the far south, physically distant from the rest of the country. Infrastructure networks (railway corridors, roads and later electricity transmission lines) were constructed to link productive regions of the country to inland neighbours (South Africa, Zimbabwe, Malawi) rather than to interior regions [52, 73], and so contemporary energy security of access is patterned against colonial infrastructure development priorities. The political fragmentation of the colonial territory is imprinted in the modern electricity network, which developed into three distinct subsystems: one in the south, around Lourenço Marques (the colonial designation of Maputo); another in the centre, associated with the city of Beira; and a third consisting of dispersed urban centres, but largely disconnected from each other [11] (see Fig. 1). The coastal city of Beira is connected to the central grid, which extends through the central region to Zimbabwe, and draws on the Chicamba and Mavuzi dams built in 1950 and 1960, respectively, as opposed to Cahora Bassa hydro-dam, which supplies the south and far north.

After Portugal's Carnation Revolution of 1974 and the decolonisation of its African overseas colonies, the People's Republic of Mozambique formed in 1975, though after two years of independence, the country descended into a protracted civil war lasting from 1977 to 1992. During the conflict, the FRELIMO-led (*Frente de Libertação de Moçambique*) government sought to use energy infrastructures as part of the larger project of national unity and modernisation. The Cahora Bassa hydroelectric dam was to play a key role, but it would also require the integration and expansion of the very limited colonial-era electric grid. To this end, the government created a state-owned electricity utility, *Electricidade de Moçambique, E.P.* (EDM) in 1977, integrating some two-dozen dispersed colonial production and distribution units [11]. The government provided EDM with a 'social mandate' to support national social and economic development, but this was curtailed until the end of the civil war in 1992. From 1995, the post-war democratic restructuring of Mozambique saw the implementation of multi-party presidential and parliamentary elections—a process of democratisation that nonetheless has created a divide in civil authority between the ruling FRELIMO party, and the opposition party RENAMO across multiple political scales—affecting both national policy and local frameworks of governance [103].


**Fig. 1** Map of Mozambique's electricity grid system. *Source* https://www.geni.org/globalenergy/library/national_energy_grid/mozambique/mozambiquenationalelectricitygrid.shtml

The post-war period also saw the rebuilding of civil infrastructure. As such, EDM began to expand the domestic grid, with support from the donor community, regional partners and foreign investment (ibid). The grid then expanded substantially, connecting all provincial centres and all 128 districts (as of 2014) [106]. However, several important limitations remain. The existing network bypasses extensive rural areas, where the low density and low-income population makes it technically difficult and costly to connect such communities. Central and northern provinces depend largely on a single, ageing transmission line each, a single line failure is enough to cut electricity to a vast area [39]. This is a key environmental security challenge, particularly in light of recent extreme weather. In March 2019 the cyclone Idai hit the port city of Beira hard, with the closure of major infrastructure (including the airport), alongside domestic dwelling destruction and widespread electricity cuts. Under scenarios of growing climate emergency that see a rise in the intensity and frequency of such events, the vulnerability of transmission and distribution networks across the central and northern provinces is of crucial concern to ongoing economic development and social wellbeing. The cost and governance challenges of rebuilding a resilient electricity network system in the affected areas require ongoing financial support and political scrutiny.

As a consequence of these factors, Mozambique has one of the lowest levels of electricity access in the world, with roughly one-quarter of its 28.8 million inhabitants having access to electricity in 2018 [40]. It is a critical case study for energy access analysis because it enjoys abundant natural energy resources (natural gas, coal and hydropower, wind and solar potential) yet continues to face entrenched energy poverty. Furthermore, regime change from socialism to capitalism resulted in mass-privatisation of the means of production, along with protracted job scarcity and a host of new socio-economic dynamics and challenges [73], such that some commentators raise concerns that post-war redevelopment and privatisation of state-owned firms and assets is tantamount to re-colonisation [81]. Energy access underpins many of these challenges, including rapid urban growth, gender and spatial inequality, and long-term environmental degradation. The Mozambican state has made electrification—both urban and rural—a major component of its development programs [98]. Despite the Mozambican government's modernising aspirations from the post-independence period to the introduction of multiparty democracy in the 1990s, through to recent efforts to attract global investors in the 2000s, a uniform energy provision infrastructure has failed to emerge. Policymakers and agencies have struggled to coordinate interventions around domestic cooking, electrification and mechanisation needs in agriculture into a long-term, integrated energy planning model.

Energy provision relies heavily upon biomass. In urban centres, charcoal is the major energy source for cooking, whilst fuelwood remains the primary fuel in rural areas [11, 64]. Growing demand for both fuel types drives high wood extraction rates over increasing areas of forest [64]. Also, though $CO_2$ emissions per capita remain comparatively low amongst Southern African states, at an estimated 0.2 metric tons per capita (2016), these rates are growing at an average annual rate of 5.52% [54], making renewable and low-carbon electricity provision a growing sustainable development policy priority. By most accounts, Mozambique's energy system is in transition: renewables are shifting the expectations of energy access, particularly in rural areas [57]. As growing deforestation pushes the supply of charcoal and fuelwood further from major cities, raising costs and secondary environmental impacts, there are growing calls to use domestic fossil fuel resources (including the newly-discovered natural gas deposits in the northern Rovuma basin, on the border with Tanzania) for the social benefit or *public good* of citizens [47]. The ambivalence and contradictory implications of an emerging energy transition are yet to be fully addressed, including long-term environmental degradation from a fossil-fuel-based transition pathway.

The country's electricity connection metrics include 20.17% of the population being grid-connected, where access in rural areas remains low at 5.7%, whilst urban areas continue to grow [40]. There is wide variance across the rural–urban continuum, though electricity access rates also vary by province and city. For instance: 95% of households have access to electricity in Maputo City, the capital of Mozambique, but this figure is 66% in Beira, historically Mozambique's second largest city [11]. EDM [40] attributes the low figures and divergence in access to electricity to the uneven distribution network, the historical exclusion of the private sector from investing in electricity projects, and low tariffs that are insufficient to fund new expenditure without subsidies (despite the tariffs being too high for many Mozambican households). Electrification rates have, however, significantly increased, growing from 5% in 2001 to 27% in 2017. These figures renew political optimism about achieving 50% by 2023, and delivering universal access 2030 [40]. Indeed, EDM has recently secured a senior debt loan facility of USD $81.30 million from the Development Bank of Southern Africa (DBSA) for the rehabilitation and upgrading of the energy supply network; though this expenditure still prioritises urban electrification, with initial projects located in Pemba City and Maputo City [20].

At the national policy-level, the Mozambican government has endorsed the Sustainable Energy for All (SE4All) targets by 2030 and the Sustainable Development Goals (SDGs). It intends to achieve the SDG#7 through separate rural and urban policy strategies. This separation then shapes state agency and donor responses to energy access provision on the ground. First, there is a strategy of grid expansion in which the state-owned utility, EDM, extends transmission infrastructure to meet growing demand, particularly in cities and areas well-linked to commercial networks. Second is a strategy of decentralised generation off the main grid and shaped by a recognition of the limits of grid extension and by donor priorities for addressing clean energy and climate agendas. The latter is implemented by *Fundo the Energia* (FUNAE), a public institution established in 1997 with Danish assistance, to promote access to low-cost, sustainable and alternative sources of electricity in areas not served by the grid [40]. FUNAE promotes off-grid solar PV, stand-alone systems and mini-grids, mini-hydropower and biomass [43]. However, less than 1% of households have benefited from such off-grid connections, as FUNAE has mostly focused on electrifying schools, hospitals, administrative offices and pumping stations with solar panels [37]. What is more, many of the household connections have failed, due to operational and management issues [13], stymieing progress towards connecting the 5.9 million households needed to achieve universal access [37]. Urban population growth is also outstripping the pace at which households have been connected to the grid [17, 30], making the challenge even harder.

Some analysts emphasise the role of private sector participation in scaling-up and accelerating the pace of off-grid connections [13, 98], whilst reducing the burden of infrastructure provision on public finances [13]. However, electricity networks often lead to natural monopolism following privatisation: the high costs of construction make it difficult for 'new players' to enter electricity supply markets without public finance assistance, and so a centralised system is likely to fail without strong public sector support. Moreover, Fael [42] suggests that greater private sector involvement necessitates stronger regulatory authority to control and inspect operator tariffs to avoid oligopolistic/cartel practices, protect consumers' rights and interests regarding tariffs and network costs, and the type and quality of service provided, including complains related to damage to their household electrical appliances due to power overload after a blackout or brownout.

## 6 Mozambique's Colonial History Influences Its Evolving Energy System

Mozambique's electricity generation is heavily dependent upon hydropower. Hydroelectricity is the primary energy source, accounting for about 77% of all electricity generated [39]. Alongside production from other smaller dams, with a combined capacity of 565 MW [30], the Cahora Bassa dam (2,075 MW) sits at the heart of the national energy system, supplying 25% of electricity supplied by EDM. The bulk of the electricity load (1500 MW) is then exported to South Africa under a long-term Power Purchase Agreement (PPA) between *Hidroeléctrica de Cahora Bassa* (HCB) and South Africa's electricity utility (Eskom), in force through 2029 [40]. Mozambique has registered a deficit, however, between demand and supply as the PPA restricts its capacity to increase the supply to meet growing national and regional demand of electricity access. This means that EDM has purchased electricity from other emergent energy sources including privately owned gas-fired power stations (referred to as Independent Power Producers—IPPs). The tariffs from these new plants are higher than for HCB-supplied power, yet they exceed the amount that can be recovered from current electricity tariffs [106]. This use of IPPs has negatively impacts EDM's finances and constrained its ability to raise funds for grid extension and maintenance.

In political terms, the Government of Mozambique has recently approved a new mandate for the energy regulatory authority, ARENE, to operate from 2018, with enhanced powers over tariff-setting, concession-granting and compliance controls [37]. ARENE's main activity is to regulate electricity subsectors, including those resulting from any source of RETs, liquid fuels, biofuels, and the distribution and commercialisation of natural gas. Accordingly, ARENE could potentially bridge the grid-connected and off-grid approaches, and foster links between electrification and fuel provision. Other shifts in Mozambique's political economy for energy have been ongoing since the push towards large-scale foreign investments in the early 2000s, specifically around extractive resources (including coal and offshore gas). Government strategy is to use this investment to reduce long-term aid dependence and develop untapped markets [27, 80], yet they also serve to lock-in carbon-intensive resources to the system.

Broader fossil-fuel intensive trends notwithstanding, two other major policy initiatives towards electrification have emerged. These include the Energy Reform and Access Programme (ERAP) aimed at increasing the efficiency of the electricity distribution services and to expand access (mainly in the urban and peri-urban areas) [75]; and the Roadmap for a Green Economy (GER) since 2012, collectively aimed at rational natural resource utilisation (particularly energy) to preserve ecosystems for meeting the SDGs. The Government of Mozambique leveraged funding and support from the African Development Bank to generate what it describes as a high-level policy strategy. The roadmap establishes a series of ambitious development targets, namely, to become an inclusive middle-income country by 2030, whilst simultaneously increasing ecosystem service protections. The GER policy led to the Green Economy Action Plan (GEAP), which the Council of Ministers approved in October 2013. GEAP was lauded as an inclusive and pluralistic model of policy development—including the participation of multiple governmental institutions, alongside regional and local authorities, civil society and private sector stakeholders, and operating in concert with regional-to-national scale public consultation thus broadly improving the procedural justice of energy policy reform. The GEAP intended to shape the government's 5-year plan and to provide the basis for greening the National Development Strategy currently under development. The plan is based on three pillars: sustainable infrastructure, efficient and sustainable use of natural resources and strengthening resilience and adaptability. These pillars include 15 sub-sectors and a total of 119 green growth policy options, all identified through the technical review and this participatory process.

## 7 Broader Governance Challenges

Aside from the electricity grid access, affordability and reliability, Mozambique faces multiple broader governance challenges. Although government policy focuses on energy system development, economic growth and policy alleviation measures, external reviews of government policy programmes show slow progress on the ground due to a range of governance factors. External evaluation of energy governance institutions deems them to be operationally inefficient and plagued by poor institutional reform [67, 75, 77]. As such, The World Bank Doing Business indicator for 'getting electricity' suggests that the process for connecting businesses and consumers to electricity grids is very slow even when they are in full reach of grid capacity [106].

In Mozambique, in broad terms, the logic of neoliberal restructuring [81] has worked against distributive intentions. For instance, hydro-dam mega-projects have stimulated rapid GDP growth, but have created few jobs and local linkages [34]. Foreign companies are lured to these large-scale, export-oriented projects, rather than connecting the poor to the grid, while the ongoing financialization of the energy sector makes it complicated for national energy companies, such as EDM, and local communities to exert influence. These problems of governance are then exacerbated by the high levels of debt accumulating from megaproject-scale energy technologies

[9]. Moreover, there has been a lack of connection between EDM's planning for grid expansion and municipal planning around which areas are, in turn, growing and expanding. This has affected EDM's capacity to supply electricity, including the quality of electricity supplied to both old and new customers [74]. Officials in Frelimo have been, until recently, committed to this model of centralised provision of services, in order to promote security of energy supply, and specifically the supply of electricity [82]. Yet, the revelation in late 2016 of undisclosed government loans and debt have caused economic turmoil, which in turn has affected the provision of social services [21, 71, 87]. There has been resurgent conflict between the ruling party and Renamo, which resulted in armed clashes in 2013 through 2017. This political-economic contestation and insecurity has affected the central government's push to expand energy provision and access to energy by local populations affected by the conflict.

Aside from these deeper political challenges, better understanding of the practices of acquiring and using energy at the household level in Mozambique is needed. It is clear that shifts in the political economy of energy production have yet to fully transform energy provision and everyday energy practices in Mozambican households and businesses. For instance, the fuel supply chains remain disconnected from electricity generation and distribution systems and the extraction of resources such as coal or natural gas [66]. The consumption of biomass is of concern to authorities because of rapid deforestation, particularly within the hinterland of major cities. Maputo has the highest electrification rates in the country, but many of the outer *bairros* (neighbourhoods) are characterised by the ubiquitous presence of charcoal for cooking and heating water. Castán Broto [25] observes that the persistence of charcoal use in Maputo's periphery is due to the fact that it enables a measure of local control, or 'sovereignty' over energy resources. Baptista [12] similarly accounts for the shift to a prepaid electricity meters in Maputo, implemented by EDM since 2004 to facilitate access among consumers, reduce households' non-payment of electricity bills and discourage illegal connections to the grid. Using ethnographic research to examining everyday practices in local communities, Baptista found that the prepaid system has given households greater control over their own electricity consumption and allows urban dwellers to more easily gauge and understand what they consume, whilst reducing unexpected high, cumulative or incorrect billings by EDM, and thus avoid debt. Pre-payment has extended access to residents facing energy vulnerabilities, despite the structural inequalities in Maputo's provision of services [12]. On the other hand, the electricity tariffs that are above most household incomes have limited their continuous use of electricity services, and have forced households to adjust their electricity consumption to the financial resources available by combining charcoal use with limited use of electricity [12, 25]. These conditions resonate with the concepts of energy justice [95], scalar justice [33], and just transitions [72], which have argued that we must consider the multi-faceted entanglements of electric power and political power when discussing generational and spatial justice within energy production and consumption, and so further research into the intersection of local household dynamics with broader regional-to-national energy policy planning is needed.

## 8 Conclusions

Mozambique is a major centre of hydropower production and has extensive coal and natural reserves, making it a potentially energy-resource rich nation. Yet, while energy resources in the country are abundant, Mozambican citizens has thus far received little direct benefit, especially those of lower-income status or in rural and peri-urban areas. Demographic growth, new energy consumption patterns, growing risks of extreme weather and climate disruption events, and institutional accountability deficits are all exacerbating what is experienced on the ground as an *energy crisis* [74]. As discussed above, increased electricity access can support economic development and the eradication of extreme poverty by supporting citizens in securing sustainable, cleaner and safer energy sources to power multiple productive activities, mediated communication, education, social network growth and entertainment. However, this movement in Mozambique, as with other rapidly developing low-income economies, is neither linear nor guaranteed, given wider political-economic frameworks and the institutional opportunities, constraints and conflicts that we have outlined in this chapter. We must better understand and enlarge our analytical frameworks to account for the contextual factors that have shaped the growth and stagnation of electricity network development and its effects on everyday practices and uses of energy, including but not limited to an analysis of post-colonial development, governance practices and the impacts of privatisation and megaproject prioritisation on social development outcomes.

Finally, when examining electricity access as an energy and environmental security challenge, it is important to explore scenarios of future development—how they might be achieved or resisted by government and private interests in order to enact practical and sustainable grid access benefits to the poorest in the country. What is needed is further decision-support related research, in which policy responses can be tailored to future access goals in a way that accounts for broader socioeconomic and governance challenges and the ways in which social and political dynamics may reshape new energy systems. Currently, there is a gap between seeking to fulfil national SDGs (including SDG#7 on universal energy access by 2030) and the needs of poor households [37]. Fostering local ownership of community-based systems, capacity-building approaches and stakeholder empowerment are approaches with untapped potential to secure energy services without creating additional environmental pressures upon delicate and fragmented ecosystems from charcoal and fuel wood extraction, and to coordinate electricity grid connection is a manner consonant with ‘bottom-up’ community-led climate adaptation planning that would reduce livelihood vulnerability from electricity cuts resulting from extreme weather events. The case of Mozambique also points to the importance of examining social and material practices of acquiring and using energy, in some cases produced by new technologies such as solar PV and gas-fired cooking, and the ways in which people interact with them given long-standing socio-cultural practices of solid fuel utilisation. Furthermore, we must better understand the historical and geographic scope of electricity sector reform in regions beyond the capital, Maputo, and move beyond static understandings of grid extension to go beyond simply counting grid connections as a measure of socio-economic progress.

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# Energy and Environmental Security—Latin America's Balancing Challenge

**Kankana Dubey and J. Andrew Howe**

**Abstract** Energy is imperative for accelerating economic development and improving lives by raising living standards. However, accelerating fossil fuel extraction or increasing imports to boost rapid industrial activities or accelerate economic development do not provide the desired socioeconomic benefits. On the contrary, some of the economic gains are offset by environmental damage. The counterbalancing concepts of energy security and environmental security have relative meanings that vary based on the national resource- and economic-context in which it is discussed. The countries in Latin American have distinct advancements and advantages which vary across the region, including almost universal access to electricity, a high proportion of which is generated renewably. On the other hand, extensive inequality, marginalization, corruption, and regional conflict are limiting the extent to which living standards are raised for the burgeoning population. The drive to generate public revenues by participating in international energy markets may be causing Latin American countries to deplete their hydrocarbon reserves too rapidly, which threatens both environmental and energy security. Indeed, even if a complete shift to renewable energy were possible in the near future, though it would improve environmental security, it would not guarantee energy security, which is a significant concern to Latin American governments. There are several possible risk mitigation strategies through which a country (either importing or exporting) can secure energy supply and promote measures to protect the local environment. However, there are many risks opposing effective implementation in Latin America. Heavy fuel subsidies tend to increase domestic demand, increase consumption of local fuel, more rapidly deplete domestic reserves, and ultimately reduce fuel export revenues. Failing the balancing act of resource nationalism vs. energy security, this is the paradox in which Latin America finds itself. Latin American countries face several particular

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challenges in driving sustainable economic development. This chapter documents the energy and environmental security challenges faced by Latin America.

**Keywords** Energy security · Environmental security · Resource nationalism · Energy access · Fuel subsidization · Resource curse · Decarbonization

## 1 Introduction

Energy can be defined as the most fundamental and valued resource for the existence of human life. In itself, a human being is a complete energy cycle: electrical and chemical energy is generated from respiration and the ingestion of food, which is then consumed to undertake physical and mental activities. The survival of human beings depends on the continuous supply of oxygen and plant- and animal-based sources of food, which in turn requires the support of the natural environment (sun, water, air). It is this need for consumption that has evolved and multiplied many orders of magnitude over centuries, and humans are no longer limited to just consuming basic sources. Our extended needs now include many categories, such as clothing, shelter, agriculture / farming, transportation, communication, gourmet fare, national security, entertainment etc. Generation of the energy needed to meet all these requirements, which have become virtual necessities, requires multiple energy fuel sources—both fossil fuel and non-fossil fuel. It is common knowledge that the volume of fossil fuels available is both finite and unevenly distributed across the world.

Countries which are rich in fossil fuels are mostly considered to be at a relative advantage, but there are several developing or underdeveloped countries with abundant natural fossil fuel resources which suffer from the *resource curse* (economic stagnation due to over-reliance on a natural resource), or who do not have sufficiently-developed technology to exploit their resources. Some countries in Latin America demonstrate this paradox. Contrary to non-renewable fossil fuels, at least some forms of renewable energy sources, such as solar, wind, tidal, or geothermal, are available in every country around the world. Unfortunately, the practical development of these sources of energy has been rather patchy, and the integration of renewable energy into the existing energy system—parts of which have been around since the dawn of the industrial revolution—is slow.

Though the global reserves of fossil fuels are vast, they are also finite; the fact that the earth's finite resources are being depleted has been known for much longer than it has been acknowledged, and has not deterred the ever-increasing demand for fuel. According to a report by Energy Charter Secretariat [9], this situation changed in the 1970s with the Oil Crises, when the concept of energy security gained prominence and became a priority in many political agendas worldwide. Indeed, energy security has been a pivotal issue since the first World War, to supply armies with essential fuel. By the second World War, controlling the oil supply of enemies had become a major aim for several combatant nations.

Historically, energy has also played a pivotal role in the economic progress of a country; it can be considered as one of the most important factors of production, along with land, labour, and capital. Every economic sector requires energy; insufficient generation of energy can curtail economic development and can cause a country to lose its economic advantage. Along with the economic concerns, there is also the threat to national security, in the absence of energy supply. This is becoming an area of concern for most developing countries: the large importers as well as exporters of energy.

Latin America has a high share of renewable energy, yet is confronted by extensive environmental threats; Latin American countries face several particular challenges in driving sustainable economic development. This chapter documents the energy and environmental security challenges which they must surmount together, despite their diversity: Latin America is a mix of energy exporters and importers, developing, and underdeveloped economies. It is to be noted that there are multiple definitions of the term "Latin America". Latin America can variously refer to all of the South American continent, South America and Central America together, or any combination of these with the Caribbean island nations. In this chapter, Latin America refers to the countries in South and Central America, plus the Caribbean island nations, as indicated by the map in Fig. 1. The below table on Latin America provides a guiding structure to the discussion of energy and environmental security, focusing on resource, social, and economic developmental indicators. Table 1 indicates for each country the human development index, population, land mass area (as a proxy for resource capacity), and GDP. In addition, for each statistic, the global and Latin American rankings are given. The statistics and rankings give highly relevant context to the rest of the chapter.

## 2 Energy Security—Ambiguity and Evolution

Energy security is an ambiguous concept with an ever-evolving definition. Indeed, despite the high priority many national governments give energy security, there is no consensus about what it even means. In addition, ensuring the more-specific states of *security of supply* and *security of demand* requires fundamentally different considerations [9]. As further demonstration of the ambiguity, consider the 2013 efforts of the Energy Charter Secretariat to update the European Energy Charter (adopted in The Hague in 1991) with a common definition of energy security, which faced a serious challenge [9]. The problem was that the member nations had developed individual definitions of the term, which depended upon their level of economic development and position in the international energy markets, according to Luft et al., "where countries stand on energy security depends on where they sit" (quoted in [9]). Sovacool [22] identified 45 different definitions of energy security, though they were all variations on the same theme.

It should not be surprising that the varying definitions of the concept of energy security could be grouped into two distinct clusters, depending on if a defining nation


**Fig. 1** Map of countries included in this chapter. (*Source* unknown)

is predominantly a net importer or exporter of energy. Net importing countries tend to be more focused on ensuring security of supply, with security of demand the primary concern for net exporters. Of course, many energy-exporting countries must also face the potential insecurity of domestic energy supply, to ensure domestic need for energy consumption.

Besides varying spatially and economically, the concept of energy security has also evolved temporally, matching the evolution of energy challenges. Focusing on the security of energy supply, the concept started quite simply, mainly emphasizing the physical availability of energy (especially oil), until the 1970s. With the shock of the Oil Crises, price made it into the definition, adding the qualifier of "affordable" or

**Table 1** Statistics for Latin American countries in this study

| Region | Country | HDI | Global Rank | LA Rank | Population | Global Rank | LA Rank | Area (sq. km.) | Global Rank | LA Rank | GDP ($M) | Global Rank | LA Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Caribbean | Barbados | 0.813 | 56 | 3 | 287,025 | 182 | 25 | 430 | 182 | 28 | 5,189 | 150 | 22 |
| Caribbean | Cuba† | 0.778 | 72 | 8 | 11,333,483 | 81 | 10 | 109,884 | 104 | 14 | 100,023 | 62 | 7 |
| Caribbean | Dominica | 0.724 | 98 | 17 | 71,808 | 204 | 28 | 751 | 173 | 26 | 178 | 593 | 28 |
| Caribbean | Dominican Republic | 0.745 | 89 | 13 | 10,738,958 | 85 | 12 | 48,671 | 128 | 19 | 89,475 | 64 | 8 |
| Caribbean | Haiti | 0.503 | 169 | 27 | 11,263,770 | 82 | 11 | 27,750 | 143 | 20 | 8,819 | 141 | 21 |
| Caribbean | Jamaica | 0.726 | 96 | 15 | 2,948,279 | 138 | 19 | 10,991 | 160 | 24 | 15,702 | 118 | 18 |
| Caribbean | Saint Lucia | 0.745 | 89 | 13 | 182,790 | 189 | 27 | 616 | 177 | 27 | 1,992 | 166 | 27 |
| Caribbean | Bahamas | 0.805 | 60 | 4 | 389,482 | 178 | 24 | 13,943 | 155 | 23 | 12,664 | 131 | 19 |
| Caribbean | Trinidad and Tobago | 0.799 | 63 | 5 | 1,394,973 | 153 | 20 | 5,130 | 164 | 25 | 22,607 | 110 | 17 |
| Central America | Belize | 0.72 | 103 | 20 | 390,353 | 177 | 23 | 22,966 | 147 | 21 | 2,001 | 165 | 26 |
| Central America | Costa Rica | 0.794 | 68 | 7 | 5,047,561 | 120 | 17 | 51,100 | 126 | 18 | 61,021 | 76 | 12 |
| Central America | El Salvador | 0.667 | 124 | 23 | 6,453,553 | 111 | 16 | 21,041 | 148 | 22 | 26,871 | 102 | 15 |
| Central America | Guatemala | 0.651 | 126 | 24 | 17,581,472 | 66 | 7 | 108,889 | 105 | 15 | 81,318 | 66 | 9 |
| Central America | Honduras | 0.623 | 132 | 26 | 9,746,117 | 93 | 13 | 112,492 | 101 | 13 | 24,449 | 104 | 16 |
| Central America | Nicaragua | 0.651 | 126 | 24 | 6,545,502 | 110 | 15 | 130,373 | 96 | 12 | 12,528 | 133 | 20 |
| Central America | Panama | 0.795 | 67 | 6 | 4,246,439 | 128 | 18 | 75,417 | 116 | 17 | 68,536 | 70 | 11 |
| South America | Argentina | 0.83 | 48 | 2 | 44,780,677 | 31 | 3 | 2,780,400 | 8 | 2 | 445,469 | 28 | 2 |
| South America | Bolivia | 0.703 | 114 | 21 | 11,513,100 | 80 | 9 | 1,098,581 | 27 | 5 | 42,401 | 90 | 13 |

(continued)

**Table 1** (continued)

| Region | Country | HDI | Global Rank | LA Rank | Population | Global Rank | LA Rank | Area (sq. km.) | Global Rank | LA Rank | GDP ($M) | Global Rank | LA Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| South America | Brazil | 0.761 | 79 | 9 | 211,049,527 | 6 | 1 | 8,515,767 | 5 | 1 | 1,847,020 | 9 | 1 |
| South America | Chile | 0.847 | 42 | 1 | 18,952,038 | 63 | 6 | 756,102 | 37 | 7 | 294,237 | 41 | 4 |
| South America | Colombia | 0.761 | 79 | 9 | 50,339,443 | 29 | 2 | 1,141,748 | 25 | 4 | 327,895 | 38 | 3 |
| South America | Ecuador | 0.758 | 85 | 12 | 17,373,662 | 67 | 8 | 276,841 | 73 | 9 | 107,914 | 59 | 6 |
| South America | French Guiana* | – | – | – | 282,731 | 184 | 26 | 83,534 | 114 | 16 | 5,180 | 151 | 23 |
| South America | Guyana | 0.67 | 123 | 22 | 782,766 | 164 | 21 | 214,969 | 83 | 10 | 4,121 | 154 | 24 |
| South America | Paraguay | 0.724 | 98 | 17 | 7,044,636 | 106 | 14 | 406,752 | 59 | 8 | 40,714 | 91 | 14 |
| South America | Peru | 0.759 | 82 | 11 | 32,510,453 | 43 | 4 | 1,285,216 | 19 | 3 | 228,989 | 48 | 5 |
| South America | Suriname | 0.724 | 98 | 17 | 581,372 | 171 | 22 | 163,820 | 90 | 11 | 3,774 | 155 | 25 |
| South America | Venezuela | 0.726 | 96 | 15 | 28,515,829 | 50 | 5 | 916,445 | 32 | 6 | 70,140 | 68 | 10 |

(*Sources* 2019 population figures from [30]; HDI figures from [13], area figures from [29], GDP figures from [14], †Cuba GDP for 2018 from [26], * French Guiana is still a French territory, so not all statistics are reported in the same sources - area & 2017 GDP are from (Wikipedia [32, 10], respectively) "fair". With the rise of concerns related to global warming over the past two decades, the definition of energy security has tended to include the concept of sustainability. In the most recent major evolutionary step, energy poverty issues have been discussed in the framework of energy security. Currently, a typical definition of energy security of supply could be "the continuous availability of energy in varied forms, in sufficient quantities, and at reasonable prices" [9].

Along with spatially, economically, and temporally, the concept of energy security varies with commodity. Energy security for many countries was historically concerned primarily with the supply of crude oil. Insecurity was mostly limited to extreme events that were often precipitated by geopolitics / petropolitics [23]. As price in the international oil market is an effective balancing mechanism for supply and demand, supply security also focuses on the economic damage caused by extreme price jumps. This is in direct contrast to other energy commodity markets where the distribution system must be kept in constant balance or capacity constraints exist—namely electricity (transmission wires) and natural gas (pipelines). Because of these characteristics, electricity and natural gas prices do not have the same power to balance supply and demand in the short term.

With increasing reliance on the international commodity markets for energy supply, the analysis of insecurity for fossil fuel disruptions has evolved from merely assessing the risk to energy resource delivery. The security of supply must also consider net-import dependence, the political stability of suppliers, and risks to the global shipping lanes. Increasing the number of entry points (ports and pipelines), raising the levels of stocks, and diversifying supplies are all important factors of resilience [24].

## 3 Energy Security in Latin America

In the past decade, Latin Americas' energy situation has changed rapidly. The first couple of years, mainly starting around 2011, saw the energy market transition into a sellers' market, with the expansion of newer drilling technologies, such as fracture stimulation to recover tight oil, causing wild fluctuations and steep declines in global oil prices. The early decade also witnessed OPEC joining with non-OPEC producers to strategically unite in cutting production, in response to lower prices. Around 2018, the share of liquified natural gas (LNG) in the power generation mix began to grow, at the expense of coal and oil. Moving into 2020, the outlook for gas and oil is bleak and fraught with risk, as most major global economies are transitioning away from fossil fuels to meet international climate change objectives.

The concepts of sustainability and low carbon technologies have entered the mainstream in the industrial and power generation sectors of developed economies. The share of renewable energy in developing countries is also increasing, driven by technological innovations such as electric transportation, energy storage, and electricity smart grid solutions to reduce electricity waste. This trend has shifted the focus of developing economies away from using inexpensive conventional sources of energy to boost economic development, to attempting to maintain the balance with global climate commitments, on the trajectory of green growth or green economy [15]. Price is no longer the only factor driving the transition to alternative energy sources, securing future demand for clean energy, expanding employment opportunities, and implementing a structural economic shift in industrial development have all become critical goals for countries investing in developing secure domestic energy supply. Latin American nations are currently experiencing these transitions.

The past decade also saw changes in the regional export market; for example, Latin America's role in providing energy security to China and India has increased. As well as increasing supply diversity for China and India, this trend is reducing Latin America's dependence on the Americas region export market. Along with the growing population and increasing domestic energy demand, this trend signals a major structural shift in Latin America's energy security. To understand why this is, and the dynamics of Latin America's energy security, let's take a step back to understand fundamental aspects underlying the foundation of most of Latin America's energy policy decisions.

### *3.1 Resource Nationalism and Energy Security*

The concept of *resource nationalism* emerged during the liberal period of the nineteenth century in Latin America. Under the policy of resource nationalism, the state controls all natural resources within its territory on behalf of the people, using them to advance political, social, and economic objectives [18]. Resources cannot be privatised, the government can use them as the state sees fit. Energy policies in Latin America are based on the two key objectives of resource nationalism (leading to export) and energy security (preferring domestic consumption), and policymakers balance between them by considering the long-term strategic goals of earning export revenues vis-à-vis meeting domestic energy requirements. It is imperative to understand that through exports driven by resource nationalism, Latin America's oil and gas resources can earn revenues, which in turn can create socioeconomic gains for the country (infrastructure, health care, etc.). Of course, then domestic energy demand must be met some other way. If this balance is achieved, then energy supply can be secure and stable.

Consider also that export revenues have the potential to be leveraged, increasing along with global market trends, generating additional social benefits. However, this potential comes with the risk of governmental corruption and dishonesty, as public servants purloin additional export revenues, rather than distributing them to society. When this happens, resource nationalism leads to the natural resources neither meeting domestic energy demand, nor contributing to socioeconomic development through exports. Further, this kind of corruption can lead to undue exploitation and irreversible damage to the environment. The allocation of natural resources should maximize societal benefits through sustainable development, and if this objective is not met, the nationalism of resources can create instability. The recent protests by indigenous groups, claiming subsurface rights and not desiring exploitation of the natural resources in exchange for revenues, are an example of the tension that resource nationalism can cause [21].

In Latin American energy policy, the counter-balance to resource nationalism—energy security—leans away from export, and more towards domestic consumption. Indeed, relying on territorial oil and gas reserves to meet domestic energy demand also protects the national economy from shocks in the international energy markets caused by changes in energy revenues and supply allocation. As in many countries, increasing domestic energy demand can threaten to deplete the countries' natural resources. To protect their share in the global energy export markets, Latin American countries are experiencing pressure to more heavily adopt alternative sources of energy to meet domestic energy demands. However, the highly-subsidized fuel costs in most Latin American markets pose significant challenges. Removing established fuel subsidies to level the playing field is also risky. Thus, the oil and gas exporting Latin American countries find it challenging to meet the transition objectives of creating alternative sources of energy and supporting the global climate change agenda, because the public is unwilling to forego subsidized energy for the nation's long-term benefit [20].

According to a World Bank report, nearly 80% of the population in Latin America lives in urban areas, and this proportion is expected to increase in the coming years. The majority of energy—mostly focused in these urban areas—is consumed for transportation, buildings, public lighting, waste management, and potable water needs. The sprawling urban region of Rio de Janeiro, for example, consumes 60% more energy for public lighting than New York [25]. Such rampant urbanization and energy consumption can seriously impact energy export revenues, and lead to social unrest. Recall, for example, the 1989 rioting in Venezuela, primarily Caracas, when the government attempted to raise the price of gasoline to meet an export revenue shortfall (NY [27]. December 2010 saw the eruption of similar riots in Bolivia over the revocation of gasoline subsidies [31].

Indeed, Latin American countries have experienced much energy-related conflict. No matter the level of conflict—regional, national, or local—they may prove to be an immense risk opposing realization of the potential economic development funded by resource nationalism revenues. Indeed, if not addressed promptly and effectively, they may threaten the stability of democratic governance.

A key observation highlighted by the Latin American experience is that an energy-exporting country pursuing energy security with heavily subsidised domestic fuel prices runs the risk of damaging the socioeconomic value of resource nationalism. Heavy fuel subsidies tend to increase domestic demand, increase consumption of local fuel, more rapidly deplete domestic reserves, and ultimately reduce fuel export revenues. Failing the balancing act of resource nationalism vs. energy security leads to the paradox that neither objective is achieved. This is currently the most important challenge faced by energy-exporting Latin American countries.

### 3.2 Pricing and Subsidies

A special concern in Latin American energy policy is pricing and subsidies, largely due to the negative impact they can have on achieving the long-term goals of sustainable economic development. Once put in place, energy subsidies are notoriously difficult to reverse, and yet oppose the development of consistent energy policies. Energy fuel subsidies interfere with market efficiency, discourage innovation and investment, distort demand, don't always favour the most impoverished of society, and disincentivize the integration of renewable technologies.

Latin American governments generally subsidize fuel prices highly. Residents of Venezuela, for example, enjoy some of the world's lowest gasoline prices, though at great expense to the public coffers. In 2010, fuel subsidies accounted for 8.3 and 6.7% of Venezuelan and Ecuadoran national GDPs, respectively [2]. According to the IEA [19], the price of gasoline in Venezuela in 2017 had dropped to $0.6 per litre. This means that, with the collapse of the Venezuelan Bolívar, gasoline and diesel was essentially free. Furthermore, subsidies are both high and lack transparency in some countries, their social costs and sources of financing are unclear, and some opponents claim they disproportionately benefit the affluent. The presence of these subsidies favour cheaper fossil fuels, and discourage the transition to the more costly renewable energy sources.

Hence comes the fundamental problem with fossil fuel subsidies, vis-à-vis long-term sustainability: energy subsidies obstruct the development of renewable energy sources, unless renewable energy is also subsidized. A nation that relies on heavily-subsidized domestic energy prices will find it very difficult to successfully promote investment in renewable energy without slowing economic development or diverting funds that would otherwise meet other social needs.

### 3.3 Regional Energy Conflicts

The history of Latin America has been rife with armed conflict, with energy and natural resources a frequent theme. Regional conflicts are typically considered to be geopolitical. These conflicts may be related to the use of energy—usually oil—resources as a tool for engendering political alliances across borders. They can also spring from long-term unresolved geographical friction, hindering cooperation among neighbouring countries on energy topics [31].

Perhaps the most challenging recent cross-border regional conflict in Latin America is one that has its origins in the War of the Pacific in the 1880s [31]. This war resulted in Chile expropriating Bolivia's access to the Pacific Ocean, leaving the country landlocked. Since then, Bolivia has maintained their historic claims to the pacific coastline, a complaint which gained further popular support in 2002. This was caused by a proposal to liquefy and export newly-discovered Bolivian gas reserves through a Chilean port. This would make Bolivia South America's first LNG exporter:

a lucrative achievement for the region's poorest country. With such economic potential at stake, the underlying grievance erupted into the so-called "Gas War"—violent uprisings which resulted in the death of dozens and ousted two Bolivian presidents (Gonzalo Sánchez de Lozada in 2003 and his successor, Carlos Mesa, in 2005). Due to the situation and political instability, the project to export Bolivia's gas stalled, and a similar project was awarded to Peru. Peru became Latin America's first LNG exporter in 2010 [31].

### *3.4 Local Energy Resource Inequality Conflicts*

National and local disputes, while varying in many details and dynamics, share two common high-level triggers. The first is widespread economic inequality coupled with marginalization of certain societal groups. Secondly, conflicts are often precipitated by inadequate and / or inappropriate management of natural resource revenues by the state. The former issues of inequality and marginalization have been improving across the region, with many Latin American countries increasing wealth redistribution and improved access to education. Opponents claim that the wealth redistribution remains minimal, and that the quality of education received by the poor is very low. These perceptions of persistent socioeconomic inequality despite increasing revenues generated by natural resources foments social instability, and are at the heart of energy-related conflicts in Latin America [31].

National-level disputes generally stem from disagreements over the distribution of natural resources and / or their revenues, often between different ethnic and economic groups. Local conflicts emerge within areas of energy resource development; it is these local conflicts that typically build on the persistent economic inequalities, weak institutional frameworks, and inconsistent application of the rule of law.

At the same time that producing conventional oil reserves has become more difficult, largely untapped hydrocarbon reserves in the Amazon basin has become the focal point of international interest. Several new hydroelectric power generation projects are also in various stages of progress, a product of the South American Regional Infrastructure Integration Initiative, designed to promote regional energy cooperation. The emergence of potentially valuable energy resources in areas inhabited by indigenous tribes—people who are becoming increasingly effective at voicing their grievances—is spawning a proliferation of local conflicts. Resolving local conflicts that are based on energy resources can be especially difficult. This is due to the fact that they involve a variety of stakeholders, the issues are complex, and applicable legal frameworks can be particularly obtuse and intricate.

## 4 Ensuring Security of Energy Supply and Demand

The uneven distribution of energy supplies among countries has led to significant vulnerabilities globally. To mitigate the risks of supply, energy security policy across countries has largely been framed around the four As: *availability*, *accessibility*, *affordability*, and *acceptability* [3]:

- Availability—Availability covers the physical existence of an energy source in the nation, including both proven / unproven and conventional / unconventional resources. The concept of reserves assesses the availability of fossil fuel sources and does not apply to renewable energy sources, which only depends on geographical conditions.
- Accessibility—Availability of a resource does not necessarily lead to accessibility. Factors such as infrastructure, intermittency, geopolitics, environment condition (deforestation for laying pipelines), economics, trade policies, transportation, technological development etc. can act as barriers, and play a pivotal role in deciding which energy source is used to meet demands.
- Acceptability—Acceptability usually focuses on non-technical concerns such as high levels of greenhouse gas (GHG) emissions, the perception of loss of scenic beauty due to windmills, safety fears from nuclear plants, the impact of biofuel on land use, etc. These factors can influence the energy policies of a nation due to potential political and social consequences, and hence threaten energy security.
- Affordability—Investments, subsidies, and availability of an energy source can influence the cost of energy. For example, renewable energy generally remains unaffordable if subsidies are not granted, the infrastructure for energy fuel transport (such as special ports and containers for liquid natural gas) impacts price, and transmission of electricity through 'smart' grids requires investments: all these developments are to secure energy supply, yet impact affordability. Subsidies help individuals afford energy consumption, but hampers the development of alternative fuel sources, and reduces public revenues. Alternatively, directing subsidies from fossil fuel prices towards encouraging the deployment of renewable energy sources can make clean energy affordable.

Some authors [6, 7] suggest that these four factors alone are insufficient to address security questions. To supplement the four As, Hughes [12] introduced the four Rs. To clarify the concept of energy security, the author explains that a new methodology should be introduced based on the four dimensions of *review*, *reduce*, *replace*, and *restrict*:

- Review—This entails assessing the situation and gaps in energy security. The supply of energy needs to meet demand, so the most important factor is to secure supply. Importing countries should review their suppliers (geopolitics), and the sufficiency of requisite infrastructure. For example, for importing liquefied natural gas, special ports and containers are required for transportation; investing in this infrastructure would have a positive impact on energy security.

- Reduce—There are three major ways to reduce energy demand—energy conservation, energy efficiency, and increased energy prices. Energy conservation can be achieved in many ways, but conservation is an act of virtue rather than a practical activity [12]. Conservation cannot be an exclusive route to reduce energy, but can be pursued simultaneously by adopting efficiency and pricing measures. Energy reduction through efficiency is generally achieved through technological development, replacing incandescent bulbs with LEDs, for example. Substantial progress has been made in this area in the past decade, encouraged by programs such as Energy Star. Increasing energy prices while implementing government policies that encourage reduction can also reduce demand [12]. Efforts to reduce energy consumption need to be targeted towards insecure sources of supply, i.e., fossil fuels, and public policies can encourage shifting of demand to more secure sources of energy.
- Replace—Diversification of the energy mix, shifting from insecure sources to secure sources can substantially improve the security of supply. An energy mix with a mixture of non-renewable and renewable sources, both domestic and imported, may be ideal.
- Restrict—With the replacement of demand from insecure sources of energy to secure ones, policies can be developed to restrict meeting future demand with secure sources, i.e., alternative sources. It can be difficult, but with energy mix policies, such measures can be achieved. For example, renewable energy can be used as a source of power during the daytime, and non-renewable energy predominantly consumed to meet (typically lower) night-time demand.

Taken together, the 4 Rs and 4As cover all aspects needed to effectively assess the security of energy supply and develop risk mitigation strategies.

At both the national and global levels the concerns for energy security can vary, ranging from supply disruptions due to the forces of nature (earthquakes, hurricanes, etc.), to supply disruptions due to geopolitical conflicts or acts of terrorism. Dependence on foreign oil supplies introduces additional risks to supply, such as those regarding political issues with trade deals. The 1973 oil embargo against the United States, in which suppliers curtailed oil delivery to the United States over the government's support of Israel, is a perfect example of this type of risk. Oil cartels can also threaten the supply of energy for countries, either by increasing prices or reducing exports. Despite all these risks, there are several possible risk mitigations through which a country (either importing or exporting) can secure energy supply; here are a few examples:

- Alternative sources of fuel in the energy mix—The use of renewables and other alternative fuels for domestic supply can potentially reduce reliance on imports. For exporting countries, it can free reserves from domestic consumption, leaving them for export, resulting in increased foreign earnings.
- Effective growth forecasting—Developing efficient future energy scenarios and long-term energy demand forecasts based on economic development, infrastructure development, and planned investment can help ensure the availability of sufficient fuel resources at reasonable prices.

- Energy pricing—Correctly pricing energy domestically is essential to ensure affordability and prevent energy poverty in importing countries. On the other hand, energy must not be so heavily subsidized that it encourages wasteful over-consumption.
- Investment and financial mechanisms for continuous development — Infrastructure and technological innovation and development can promote advanced measures to secure energy reserves and reduce emissions, in addition to contributing to economic development.
- Climate change targets—Setting reasonable climate change objectives nationally can steer a country in developing less energy-intensive industries, which in turn can create job opportunities and develop innovative practices. Boosting research and development industries to enhance alternative sources of energy supply can lead to more efficient use of current sources of energy and reduce reliance on imports.
- Reassess the current economic status, transportation and urban infrastructure, industries, environment policy, and promote innovation—A country would benefit from integrating energy policies with other economic sectors to promote socioeconomic welfare. According to Krarti et al. [16], mandated improvements in energy efficiency across industries and the construction sector will have knock-on effects, improving the well-being of residents.
- Supply diversification—Relying on a single market for energy import and export multiplies the risks to energy security and their severities. For example, oil fields in the middle east are prime targets for sabotage, due to their nations' extreme reliance on the oil. Many countries also hold strategic petroleum reserves as a buffer against supply risk. All member nations of the International Energy Agency, for example, hold a minimum of approximately 3 months of their imports [8, 18].
- Decarbonization of the energy system—Governments can develop policies and financial tools within the institutional framework to incentivise the industrial sector to promote the uptake of energy-efficient technologies and renewable energy projects, and to develop innovative ways to reduce dependency on fossil fuel whilst maintaining economic development. Decarbonization decouples economic welfare from energy generation, and is the most sustainable and long-term energy security risk mitigation measure.

## 5 Environmental Security

Environmental security can be classified as a normative concept, as it is not limited to a single state or sovereign. Though environmental concerns most strongly impact the environmental security of the nation causing them, they are truly international in nature. Global warming is affecting ecosystems in unprecedented ways; the consequences of climate change occur everywhere and are globally interconnected. Unlike some other forms of pollution, emissions of greenhouse gases have a global impact. Whether they are emitted in Asia, Africa, Europe, or the Americas, they rapidly disperse across the globe. In addition, even local effects of climate change can become global. The generation and consumption of energy is a perfect example of this—consider the well-documented spread across the Pacific Ocean of pollution from China to the United States.

Global environmental problems are the sum of local environmental problems. Thus, ensuring environmental security is an international obligation, with a multi-level approach that requires extensive collaboration between countries. The common goals to which all are reaching—ensuring the security of food, water, and the natural habitat—should also be balanced against securing economic development and energy supply within each sovereign domain. The history of international climate change collaboration bears out that this is a balancing act that requires much effort.

The principal forum for international climate change action has been the United Nations Framework Convention on Climate Change (UNFCCC). The objective of the UNFCCC is to join all nations in commitment to reduce greenhouse gas emissions and mitigate the resultant anthropogenic climate impacts. The UNFCCC established the principle of common but differentiated responsibilities and respective capabilities. This principle recognizes that as nations vary in both their contribution to anthropogenic climate change and economic capacity to combat it, so should their mitigation obligations. Notably, it encourages international collaboration and technology transfer between developed and emerging economies. Under the auspices of the UNFCCC, the Conference of Parties (COP) is an annual meeting, in which all nations are invited to participate in the efforts to resolve the existential issues of climate change mitigation. The dialogue regarding potential greenhouse gas emissions reduction activities forms the foundation of an evolving global collaboration around mitigating anthropogenic climate change. The path of the UNFCCC's evolution can be summarized broadly from the 1997 Kyoto Protocol to the 2015 Paris Agreement, as evidenced by their paradigmatic differences. Broadly, the UNFCCC's paradigm of collaborative engagement shifted from a top-down to a bottom-up approach.

### *5.1 Environmental Threat*

Overall, Latin American countries do not emit large volumes of greenhouse gases. There are three primary reasons for this: lightly-industrialized economies, limited public transportation infrastructure, and the large share of hydroelectric power in the region's energy mix. Rather than direct emissions, Latin America's greatest contribution to climate change is deforestation, which degrades the earth's capacity to absorb $CO_2$.

Rampant deforestation in South America is a global issue; between 2001 and 2010, the forest cover was reduced by over 260,000 square kilometres, as shown in Fig. 2 [1]. Brazil alone lost almost 150,000 sq. km. forest cover in the first decade of this century. The waterfall charts in Fig. 2 show for each country, and the entire continent, the gross area of forest added (left green column), gross area reduced (yellow middle


**Fig. 2** South American Deforestation by Country 2001—2010, in Square Kilometres (*Source* data from [1])

column), and the net reduction (red) or addition (green) in the right column of each chart. Four countries experienced a combined net gain of approximately 23,700 sq. km. of forest (French Guiana, Guyana, Suriname, Venezuela). All the others saw net deforestation.

While the rate of deforestation in the Amazon rain forest has decreased, the forest is still shrinking. According to data gathered by the Instituto Nacional de Pesquisas Espaciais (INPE, or National Institute of Space Research) in Brazil, the Brazilian Amazon alone has lost over 60,000 square kilometres between 2011 and 2019 [5]. Deforestation is a serious environmental threat with far-reaching global consequences. According to American thinktank The Sustainability Laboratory, a square kilometre of young rain forest can absorb 60,000 tons of $C0_2$. [17] Hence, the combines South American forest coverage losses for 2001—2010 and Brazilian losses from 2011—2019, could have absorbed up to almost **12.2 billion tons of $CO_2$**!

Regional energy policies have begun to address the climate challenges facing Latin American countries. These initiatives have been mostly focused on hydroelectric power (though much curtailed from its peak) and energy efficiency. As previously mentioned, other renewable forms of power generation are also gaining momentum, as they reduce both $CO_2$ emissions and fossil fuel dependence, and can provide additional socioeconomic benefits such as jobs. While these technologies are still relatively expensive for the region, and difficult to effectively promote without subsidies, costs have recently begun to decline significantly. Furthermore, there has been active discussion suggesting that international financing mechanisms could be made available to allow developing countries to invest more heavily in renewable energy [20].

**Table 2** 2019 Human Development Index and ranking for Latin American countries

| | Rank | HDI | | Rank | HDI |
|---|---|---|---|---|---|
| Chile | 42 | 0.847 | Venezuela | 96 | 0.726 |
| Argentina | 48 | 0.830 | Paraguay | 98 | 0.724 |
| Uruguay | 57 | 0.808 | Suriname | 98 | 0.724 |
| Panama | 67 | 0.795 | Belize | 103 | 0.720 |
| Costa Rica | 68 | 0.794 | Bolivia | 114 | 0.703 |
| Cuba | 72 | 0.778 | Guyana | 123 | 0.670 |
| Brazil | 79 | 0.761 | El Salvador | 124 | 0.667 |
| Colombia | 79 | 0.761 | Guatemala | 126 | 0.651 |
| Peru | 82 | 0.759 | Nicaragua | 126 | 0.651 |
| Ecuador | 85 | 0.758 | Honduras | 132 | 0.623 |
| Dominican Republic | 89 | 0.745 | Haiti | 169 | 0.503 |

(*Source* [13])

## 5.2 *Human Development Index*

Narrowing down environmental security concerns to the national level, there are several challenges that are commonly faced across Latin American countries. The most widely-used metric for environment security is the Human Development Index (HDI). The HDI values and global rankings for all 22 Latin American countries are recorded in Table 2 [13].

According to the United Nations Development Programme 2019 HDI rankings, the positions of Latin American countries vary widely. The most developed Latin American countries are Chile (0.847) and Argentina, which occupy the 42nd and 48th ranks, respectively; both categorized as "Very High Human Development". Both the countries have suffered under harsh dictatorships in the past, but strengthened their economies and improved their HDI rankings through several strategic initiatives. Haiti is the least developed with an HDI of 0.503, ranked 169$^{th}$ out of 189 countries; endemic corruption and violence has led to poor development. The devastating earthquake in 2009 further hindered social progress. Venezuela is the twelfth most developed country in the region, lagging behind Brazil, Peru, and Colombia.

## 5.3 *Energy Access*

Energy access is an important measure of energy poverty. Latin America is closing on universal access to electricity; in 2017 the electrification rate in Latin America was approximately 98% [28], p. 20). However, there appears to be a significant challenge in providing clean fuel and technologies for cooking, with a high percentage of the region still cooking with polluting stove and fuel combinations. Lack of access to clean cooking fuels and technologies is one of the most significant contributors to poor health, environmental degradation, and climate change in low- and middle-income countries. It is also a contributor to women's workloads, a barrier to women's market employment, and hinders gender equality. The use of inefficient stoves or open fires paired with wood, charcoal, coal, animal dung, or crop waste is a major source of air pollution in and around the home.

Several countries in Latin America are paving the way for a transition away from combusting inefficient solid fuels for cooking. Ecuador is currently working to transition households from LPG to renewably-sourced electricity for cooking. Likewise, clean cooking has been a priority of the Peruvian government for several years, and Peru is beginning to see substantial improvement. Importantly, authorities are specifically working to increase the availability of clean gaseous fuels in rural areas, and are harnessing alternative mechanisms currently in place, such as the power distribution infrastructure - to facilitate the distribution of gaseous fuels in these areas. Across all regions, there is greater access to clean energy in urban areas than in rural areas. Extending the infrastructure for the reliable and affordable distribution of cleaner cooking fuels in the rural areas will positively impact many lives: particularly as these households already face many other challenges in accessing services for basic needs.

## 5.4 Energy Efficiency

The absolute levels of energy intensity in Latin American countries are less than the global average, reflecting differences in economic structure, energy supply, and access. A key factor contributing to this better-than-average performance is that many Latin American countries have made concerted efforts, through public policy, to drive economic development by increasing energy efficiency.

## 5.5 Renewable Energy

With the many waterways and elevation changes in South America, renewable energy in the form of hydroelectricity has long been an important source of power in Latin America. According to BP's Statistical Review of World Energy 2019 [4], approximately 29% of 2018 primary energy consumption in Latin America was from hydroelectricity and other renewable sources. While this is nearly double the overall global share, it is not guaranteed to last. Despite substantial differences among Latin American countries in terms of policies, energy mixtures, and energy trade dynamics, there are similarities in the incentives for, and threats against, renewable energy.

Brazil and Colombia are, and will continue to be, producers and exporters of significant volumes of oil. Argentina has been depleting its oil reserves over the past decades and ceased exporting some time ago. However, development of the shale oil & gas from the newly-discovered Vaca Muerta field may allow Argentina to join them again in the near future [20]. Chile is largely dependent on energy imports, producing only minimal volumes of oil and gas. Overall, hydrocarbon production in Latin America will continue to grow in importance, potentially threatening renewable energy. However, for the time being, renewable energy continues to gain importance, especially for generating electricity.

While hydropower is the most important source of renewable energy, its importance has been slowly declining. According to IRENA, hydroelectricity accounted for approximately 95% of Latin America's renewable energy mix in 2000, but this had dropped to nearly 80% by 2015. The rate of hydroelectric capacity additions has been slowing for several environmental reasons, including droughts, deforestation, and impacts upon aquatic life. Further, the potential displacement of indigenous groups has hindered and obstructed further hydropower development. At the same time, other renewable technologies—namely solar, wind, and biomass—are ascendant. This shift is due to the perceived social, environmental, and economic advantages of these technologies [20].

## 6 Energy Generation and Consumption

The energy generation and consumption statistics in this section are sourced from the British Petroleum [4] statistical review of world energy report. Primary energy consumption in Latin America is largely driven by Brazil, Argentina, and Venezuela. In 2018, these three countries alone accounted for approximately 63% of the total consumption (Brazil = 42%, Argentina = 12%, Venezuela = 9%). From 2008 to 2018, the region's energy consumption increased by almost 17%, from just over 600 million tonnes of oil equivalent (MTOE) in 2008, to just over 700 MTOE in 2018. Most of this was experienced in a 3-year 13% growth spurt between 2009 and 2012. To put this seemingly gluttonous decade in perspective, it was actually a long slow recovery; consumption plummeted by nearly 12.5% in a single year from 2007 to 2008. Peru's energy consumption increased the most—at almost 63%, while Venezuela reduced energy demand by nearly 24%. Latin American energy consumption growth was essentially flat in 2018, posting a minimal increase of 0.31%. These trends are displayed visually in Fig. 3, and the data is shown in Table 3.

When primary energy consumption is normalized per capita, and interesting observation emerges. Per capita, Trinidad and Tobago's energy consumption is almost an order of magnitude higher than that of any other Latin American nation. In 2018, this value was approximately 466 gigajoules/capita, with the next highest being Chile (92.3) and Venezuela (84). Most of the region's countries have experienced per capita growth in energy consumption between 2008 and 2018. Notably, Peru's per capita consumption increased by 43%, from 24.3 to 34.7 gigajoules/capita. Trinidad and Tobago's high per capita consumption decreased by nearly 8%, while Venezuela experienced a dramatic decrease of almost 34%, from 126 to 84 gigajoules per

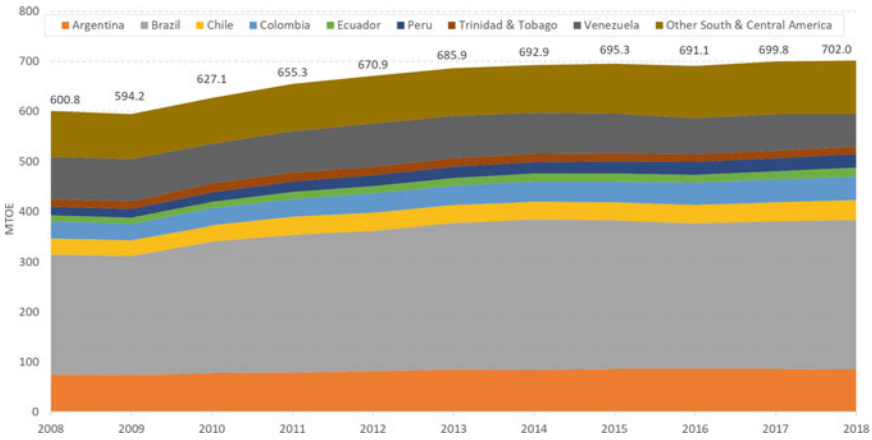


**Fig. 3** Primary energy consumption in Latin America by country, in million tonnes of oil equivalent (*Source* data from [4])

person. Figure 4 plots the 2018 per capita consumption, along with some of the notable changes from 2008.

Perhaps the most interesting view of Latin America's energy generation and consumption is by fuel / source, shown for 2018 in Table 4. The overall regional energy mix for 2018 is also visualized in Figs. 5 and 6. Renewable, including hydro-electricity, accounted for nearly 29% of energy consumed throughout the region in 2018. However, 315 MTOE of energy consumed—approximately 45%—came from oil combustion.

Figure 6 displays the same data, but now disaggregated to the country level. This perspective shows how the energy mix varies across the region overall. Trinidad and Tobago, for example, generate most—nearly 85%–of their energy demand by burning natural gas. No other Latin American country is so undiversified. Ecuador's energy mix is almost as homogenous, they are mostly reliant on oil (69%), meeting most of the remaining demand with hydroelectric power. Venezuela's energy mix is remarkably evenly distributed: natural gas (44%), oil (30%), and hydroelectricity (25%). Of the approximately 5% of the region's energy demand met by coal, most is burned in Brazil (15.9 MTOE), Chile (7.7 MTOE), and Columbia (5.9 MTOE). Chile meets almost one fifth of the country's energy demand with coal. With the exception of Trinidad and Tobago, all countries have some hydroelectric power meeting baseload demand. Brazil and Chile are the leaders of non-hydro renewables, with 8% and 9% of their demand, respectively, met renewably. Together, they generate approximately 27 MTOE of Latin American renewable energy. While approximately 71% of Latin American energy is generated from fossil fuels overall, this varies substantially by country. Slightly more than 60% of Brazil's energy is generated from fossil fuels; this number climbs to 100% for Trinidad and Tobago.

**Table 3** Primary energy consumption in Latin America

| | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2018 (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Argentina | 74.7 | 73.3 | 77.2 | 78.7 | 81.0 | 84.5 | 84.1 | 86.1 | 85.9 | 86.1 | 85.1 | 12.12 |
| Brazil | 239.9 | 238.6 | 263.1 | 275.8 | 281.3 | 292.4 | 299.4 | 295.9 | 289.4 | 293.9 | 297.6 | 42.39 |
| Chile | 32.2 | 31.5 | 31.7 | 34.5 | 35.3 | 35.7 | 35.1 | 35.9 | 37.7 | 38.3 | 40.1 | 5.71 |
| Colombia | 33.3 | 31.8 | 34.1 | 35.7 | 38.3 | 38.9 | 41.0 | 41.3 | 44.2 | 45.5 | 46.9 | 6.68 |
| Ecuador | 12.1 | 11.9 | 13.2 | 14.0 | 14.8 | 15.3 | 16.1 | 16.1 | 16.0 | 16.7 | 17.6 | 2.51 |
| Peru | 16.6 | 17.0 | 18.8 | 20.9 | 21.3 | 21.9 | 22.6 | 24.2 | 25.5 | 25.4 | 27.0 | 3.85 |
| Trinidad & Tobago | 15.9 | 16.0 | 17.5 | 17.6 | 16.7 | 17.2 | 16.8 | 16.9 | 15.4 | 15.2 | 15.3 | 2.18 |
| Venezuela | 84.6 | 84.4 | 79.7 | 83.4 | 86.9 | 84.9 | 82.1 | 79.3 | 72.3 | 73.6 | 64.6 | 9.20 |
| Others | 91.6 | 89.6 | 91.8 | 94.6 | 95.1 | 95.1 | 95.7 | 99.5 | 104.6 | 105.1 | 107.8 | 15.36 |
| Total | 600.8 | 594.2 | 627.1 | 655.3 | 670.9 | 685.9 | 692.9 | 695.3 | 691.1 | 699.8 | 702.0 | |
| Total Growth (%) | −12.5 | −1.1 | 5.2 | 4.3 | 2.3 | 2.2 | 1.0 | 0.3 | −0.6 | 1.2 | 0.3 | |

(*Source* British [4]

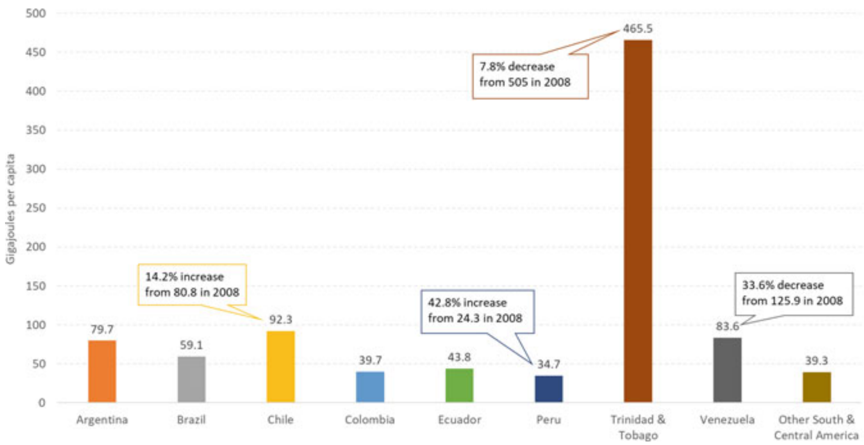


**Fig. 4** Primary energy consumption per capita in gigajoules per capita (*Source* data from [4])

**Table 4** 2018 Primary energy consumption per source in MTOE

| | Oil | Natural gas | Coal | Nuclear energy | Hydro-electricity | Other renewables | Total |
|---|---|---|---|---|---|---|---|
| Argentina | 30.1 | 41.9 | 1.2 | 1.6 | 9.4 | 0.9 | 85.1 |
| Brazil | 135.9 | 30.9 | 15.9 | 3.5 | 87.7 | 23.6 | 297.6 |
| Chile | 18.1 | 5.5 | 7.7 | 0 | 5.2 | 3.5 | 40.1 |
| Colombia | 16.6 | 11.2 | 5.9 | 0 | 12.8 | 0.5 | 46.9 |
| Ecuador | 12.2 | 0.6 | 0 | 0 | 4.7 | 0.1 | 17.6 |
| Peru | 12.4 | 6.1 | 0.9 | 0 | 7 | 0.7 | 27 |
| Trinidad & Tobago | 2.1 | 13.2 | 0 | 0 | 0 | 0 | 15.3 |
| Venezuela | 19.5 | 28.7 | 0.1 | 0 | 16.3 | 0 | 64.6 |
| Others | 68.3 | 6.8 | 4.3 | 0 | 22.3 | 6.1 | 107.8 |
| Total | 315.2 | 144.9 | 36 | 5.1 | 165.4 | 35.4 | 702 |
| Total Share (%) | 44.9 | 20.6 | 5.1 | 0.7 | 23.6 | 5.0 | |

(*Source* [4])

## 7 Energy-Environment Nexus in the Context of Latin American Countries

Based on the data discussed in Sect. 6, Latin American energy generation can be characterized as highly sourced from fossil fuels, though with a substantial portion of renewable energy. There is still much that could be done, however, to bolster the share of renewables. The large proportion of fossil fuels in the energy mix (approximately 71% in 2018) across the region certainly helps meet the rising demand in these countries cheaply, but at a significant long-term cost. As rapid economic

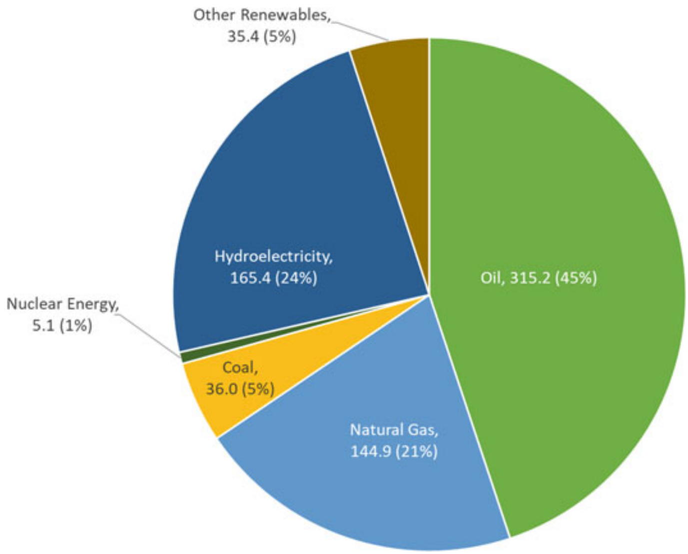


**Fig. 5.** 2018 Total Latin American energy mix in MTOE (*Source* data from [4])

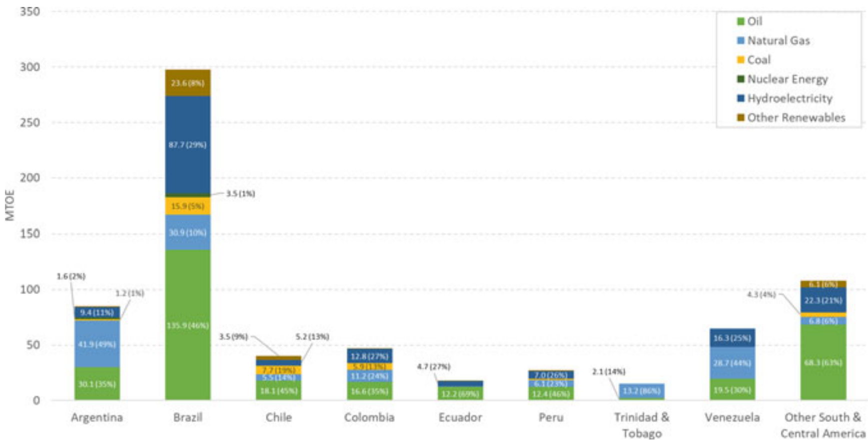


**Fig. 6.** 2018 Latin American energy mix by country in MTOE (*Source* data from [4])

development drives energy consumption even higher, the increased demand should be met with additional renewable energy capacity and energy efficiency initiatives. However, most Latin American countries are still in the early stages of developing policies to promote this paradigm shift. Accordingly, Latin America's dependence on fossil fuels will continue, and so will the subsequent greenhouse gas emissions and environmental degradation. According to the Economic Commission for Latin

America and the Caribbean, emissions from the usage of land for various purposes had risen to the level of 3.2 gigatons $CO_2$ equivalent by the year 2015 in [11].

Increases in fossil fuel extraction or imports to boost rapid industrial activities or accelerate economic development are not providing the desired socioeconomic benefits. On the contrary, some of the economic gains are offset by environmental damage. This is the paradox in which Latin America finds itself. Economic development should boost socioeconomic welfare and improve people's lives. Instead, the negative environmental externalities harm society: local flora and fauna are menaced, natural resources are depleted, and shorelines in low-lying regions are threatened. The current strategy to drive economic development is not sustainable.

A recent research study which analysed the economics-energy-environment nexus in Latin American countries determined that rapid urban development and economic development in Latin America and Caribbean countries has engendered positive socioeconomic effects. However, it is also increasing the demand for transportation, public utilities, and other services. These developments are putting additional pressure on Latin America's environment and natural resources [11].

## 8 Conclusion

When economic development is achieved through the over-consumption of fossil fuels, some of the gains are offset by environmental damage, reducing the quality of life. There is an urgent need for policymakers globally to take concerted action that will encourage sustainable economic development. Latin American countries face several particular challenges in driving sustainable economic development. This chapter has documented these challenges, in the areas of environmental security and energy security.

Latin American countries have a few distinct advancements and advantages, and are ahead of other countries. For example, the facts that only 2% of their population does not have access to electricity, and that nearly 30% of energy is generated renewably. The past decade also saw positive developments in the regional export market; for example, Latin America's role in providing energy security to China and India has increased, reducing regional dependence on the Americas region export market. Along with the growing population and increasing domestic energy demand, this trend signals a major structural shift in Latin America's energy security.

Overall, Latin American countries do not emit large volumes of greenhouse gases. There are three primary reasons for this: lightly-industrialized economies, limited public transportation infrastructure, and the large share of hydroelectric power in the region's energy mix. Rather than direct emissions, Latin America's greatest contribution to climate change is deforestation, which degrades the earth's capacity to absorb $CO_2$.

The resource nationalism philosophy—by which government controls natural resources on behalf of the population—has shown definite benefits. However, fuel price subsidies are a substantial hindrance to sustainable economic progress. Heavy fuel subsidies tend to increase domestic demand, increase consumption of local fuel, more rapidly deplete domestic reserves, and ultimately reduce fuel export revenues. A key observation that can be gleaned from the Latin American experience is that an energy-exporting country pursuing energy security with heavily subsidised domestic fuel prices runs the risk of damaging the socioeconomic value of resource nationalism. Failing the balancing act of resource nationalism vs. energy security leads to the paradox that neither objective is achieved. This is currently the most important challenge faced by energy-exporting Latin American countries.

Furthermore, as rapid economic development drives energy consumption even higher, the increased demand should be met with additional renewable energy capacity and energy efficiency initiatives. However, most Latin American countries are still in the early stages of developing policies to promote this paradigm shift. The data analysed in the study point to the conclusion that Latin America's dependence on fossil fuels will continue, and so will the subsequent greenhouse gas emissions and environmental degradation.

As discussed in this chapter, there are several possible risk mitigation strategies through which a country (either importing or exporting) in Latin America can ensure energy and environmental security while maintaining economic development, such as: enhancing the share of alternative sources of fuel in the energy mix, energy pricing, long-term supply and demand forecasting, development of investment and financial mechanisms, commitment to international climate change targets, diversification of supply to new markets, and adoption of low carbon policy in the energy system and across all economic sectors.

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# Use of Solid Recovered Fuels to Address Energy and Environmental Problems in Argentina

**L. V. Sosa, S. L. Galván, S. M. Lusich, and R. O. Bielsa**

**Abstract** In most megacities of Latin America and the Caribbean, the population and economic growth, the inefficient use of resources and energy, and the high levels of carbon dioxide emissions have led to due to unsustainable solid waste management and inequities in the access to sanitation services and energy access, and thus to several negative consequences like air and water pollution. One of these megacities is the Metropolitan Region of Buenos Aires (RMBA), Argentina, where the main treatment of solid waste is its final disposal in landfills. Thus, its recycling rates are low and its energy use is even lower. In industrialized countries, the production of Solid Recovered Fuel (SRF) is a common practice. In contrast, in Argentina, SRF is produced by only one commercial and industrial waste (C&IW) treatment center for the cement industry. This chapter describes the production and quality of this SRF and the characteristics of the waste streams that are currently sent to landfill that could be incorporated into that production. In addition, the potential uses of SRF in the RMBA to replace natural gas are analyzed in three possible scenarios. The results for scenario 1 showed a current production of 32 t per month of Class II SRF, which allows a monthly replacement of 33,722 $m^3$ of natural gas in the cement industry. The results for scenario 2 showed that 177.4 t per month of Class III SRF could be added and generate 210.97 MWh per month of electricity, replacing 86920.5 $m^3$ per month of natural gas. Finally, the results of scenario 3 showed that the incorporation of the co-generation of electricity and heat for industrial use could replace 172379.23 $m^3$ per month of natural gas with SRF.

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# 1 Introduction

Megacities demand large amounts of material and energy resources, and, at the same time, generate large amounts of solid waste as a result of their intense industrial and service activities. Thus, waste management and coverage of energy demand, as well as the reduction of their associated impacts, are major challenges for the authorities, especially in emerging countries. Although metropolitan cities and regions in Latin America and the Caribbean (LAC) present common problems and challenges, the intensity of specific aspects related to sustainability changes from one city to another. In this introduction we discuss the main sustainability issues and challenges that have arisen about energy and environment in LAC and particularly in Argentina, and then present the detailed objectives of this study.

## *1.1 Energy and Environmental Scenario in Argentina*

Argentina is located in the south of the American continent, with an extensive territory of 2.7 million $km^2$ and a great diversity of landscapes and resources. The population in 2019 was of 44,940 million, with 91% located in urban areas [9]. The main urban region is Buenos Aires city and its surroundings, an area known as the Buenos Aires Metropolitan Region (RMBA).

Despite having one of the highest human development indexes in LAC, Argentina presents a fast-growing level of poverty and poverty-related risks due to the impacts of the successive economic and financial crises. Thus, the last twenty years have shown a strong suburban and mostly peri-urban growth with precariousness and segregation in urban areas. As a result of this expansion and the lack of public and private investment, the most important natural (man-made) risk is the environmental degradation of the main water bodies, where the implementation of technical solutions is extremely slow.

Argentina's energy sources are heterogeneous [14], with its main sources being oil and gas, which make a little over 84% of the total. In 2018, most of the local purchase came from hydrocarbons, 53.2% being natural gas, 31% oil and 1.5% coal. As for the potential production of greenhouse gases, the energy industry is responsible for most of the nation's emissions, with 53% of the total.

In 2018, fossil fuels provided 63% of Argentina's electricity production, the remaining being nuclear, hydroelectric and, to a lesser extent, renewable energy (Fig. 1a). As regards the electric energy coming from non-conventional renewable sources, eolic energy leads the way. The electricity transit system features almost 14,800 km of high-voltage power lines and close to 20,000 km of trunk distribution frame, which, combined, make up the "Sistema Argentino Interconectado Nacional" (National Interconnected System).

In order to diversify the energy sources, Argentina has implemented new regulations, whose goal is to achieve a contribution from renewable energy of 20% of the

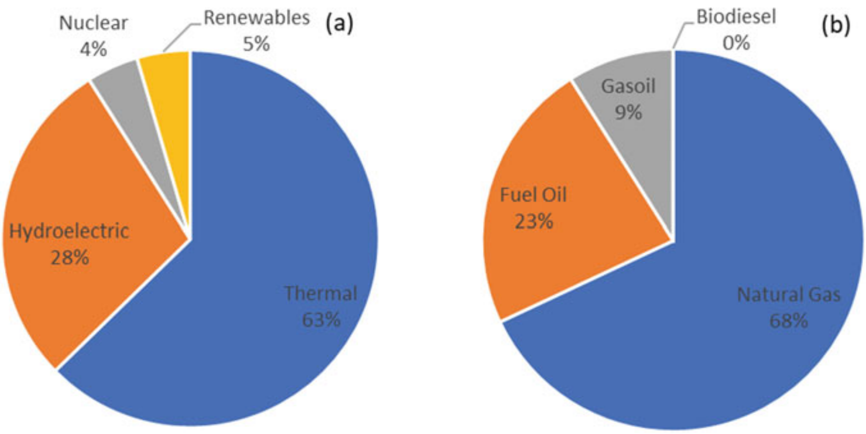



**Fig. 1** **a** Argentina's electric power matrix 2018; **b** distribution of the fuels consumed by the thermoelectric plants located in the Metropolitan Region of Buenos Aires, Argentina, 2018

national total electricity consumption by 2025. Considering the high dependence of the energy matrix of Argentina on fossil fuels, this goal is extremely challenging.

In 2017, 83.6% of Argentina's thermoelectric production was generated from natural gas. In this sense, in the RMBA, there is a sum of 6,754,390 MW installed thermoelectric power, equivalent to 20% of the power installed at a national level. Data from 2016 indicated that this power generated 29562006.5 MWh, equivalent to 23% of the gross generation at the nation's level. Only two of the thermoelectric plants of the RMBA use alternative fuels (landfill gas), representing 0.02% of the power installed. The rest of the thermoelectric plants of the RMBA consume other fuels, distributed as shown in Fig. 1b.

As in other countries of LAC, Argentina's energy consumption is very sensitive to changes in its economies, and economic growth is reflected as an exponential growth in energy consumption [13]. The RMBA consumes 37% of the national electricity, which is consistent with the fact that more than 40% of the country's population and industries are in this area [3]. Data from the Argentine Ministry of Energy and Mining indicated that, in 2016, residential and commercial electricity consumption was 68%, whereas industrial electricity consumption was 22%. On the other hand, in 2017, the consumption of natural gas destined to industrial activity in the RMBA reached 7% of the consumption at national level, equivalent to 560,149,000 $m^3$ per year. Among natural gas-consuming industries, Portland cement plants, which, together, consume 8% of the industrial consumption [5], are interesting to study. However, it should be clarified that these plants are located outside the RMBA. In 2016, annual electricity consumption per capita was of 2.99 MWh, showing an increase of 25% between 1993 and 2012, meaning a mismatch regarding the GDP.

Although energy is vital for socioeconomic development, its production and consumption have impacts on the environment, with air pollution and greenhouse gas emissions being the most significant ones. Thus, using energy efficiently and separating economic development from energy consumption become essential for sustainable development. Argentina's industrial development is still limited, and is an agriculture-based country, with an extensive area destined to agriculture and livestock, which means a heavy pressure on water resources and soil. Data from 2018 showed that about 70% of the land is under water stress and 57% shows negative trends in the quantity and quality of greenery, pointing towards degradation of the land [14].

The agro-industrial model implemented in Argentina has intensive use of agrochemicals. This contaminates both the soil and the water and is one of the main causes of the loss of native forests, which, between 2007 and 2018, decreased by 10%, mainly due to soybean cultivation. Argentina's 2016 greenhouse gas emission inventory shows that this activity is the second to contribute 37% of the emissions, reaching a total of 364 $MtCO_{2eq}$.

Similar to that observed with the energy services (electricity and natural gas), the access to health services such as clean water and sanitation and solid waste management is very unequal and limited. This is especially true for the areas surrounding the main urban centers, mainly due to the lack of investments in infrastructure. For example, while 80% of the national population has main water supply and 50% have sewers, only 12% of the effluents generated receive adequate treatment [14].

Argentina, like other countries from LAC, faces complex challenges regarding waste management. According to data from the UN Environment, in 2018, 541,000 tons of municipal (urban) solid waste (MSW) were generated daily in LAC, and it is estimated that this value will increase by 25% by 2050 [12]. These data also indicated that 90% of the MSW generated was ultimately destined to landfill and that about 145,000 tons per day went to open-pit dumps or burning. With regards to the energy valorization of waste, only technologies for the use of landfill gas or agricultural waste for biogas production have been implemented.

Although both Argentina and Brazil have some projects regarding energy recovery, these projects are not yet in operation, and neither of these two countries has "waste-to-energy" plants, i.e. plants that convert MSW into electricity and/or heat for industrial processing or heating systems [8]. In industrialized countries, "waste-to-energy" plants are widely implemented, with 589 plants in operation in Europe and 82 plants in the USA [22]. However, these plants involve high investment and operating costs and are thus difficult to implement in developing countries.

In the RMBA, the main treatment of solid waste (both MSW and commercial and industrial waste (C&IW)) is the final disposal in landfills. However, the lack of land for new landfills has led to several crises in the management of MSW and to the adoption of new laws that oblige C&IW generators to manage C&IW separately from MSW. In this context, energy recovery from waste through the production of Solid Recovered Fuel (SRF) has become a sustainable option to reduce the amount of MSW destined to final disposal in landfills. In addition, in Argentina, there is a current growing demand for SRF by the cement industry, which makes SRF production an interesting option to replace fossil fuels, especially natural gas, and simultaneously reduce the amount of MSW destined to final disposal in landfills.

SRF production is considered a component of energy recovery from waste that plays a double role: it provides a safe waste disposal service (reducing its volume and weight and destroying contaminants) and participates in the production of energy [2]. Thus, the transformation of waste into energy can create synergies between waste management and energy and climate policies [7]. SRF can be prepared from different types of non-hazardous waste, including sewage sludge, wood waste, high calorific fractions from mechanical–physical and/or mechanical–biological treatment plants, and calorific fractions from household and commercial waste, through specific treatment to be utilized for energy recovery in the combustion in cement kilns or the co-generation of electric energy or heat [11].

The benefits of SRF production depend on the quality of the material used. Some researchers as Nasrullah et al. [11] have concluded that waste streams rejected from material recovery facilities (MRFs) have more quality for SRF production than those rejected from mechanical biological treatment plants. Specifically, C&IW has shown good potential to be used as SRF through mechanical treatment and stream thermal conversion technologies with little retrofitting [10].

### *1.2 Objective and Scope of the Study*

In order to design solutions to the crisis in the management of solid waste in the RMBA and to assess the possibilities of diversifying the energy matrix, the aim of this research work was to comprehensively study SRF production, based on an in-depth evaluation and detailed characterization of the input and output streams of the waste materials produced in an SRF production plant located in the RMBA. The SRF studied was produced from the C&IW generated by the commercial and industrial sectors (shopping malls, offices, warehouses, logistics companies, manufacturing organizations, retail outlets, etc.) and institutions (educational institutions, medical centers, government offices, etc.) located in this region. This C&IW consists mainly of paper and cardboards, plastic, textile, wood, rubber, metal and inert material (stones and glass). Other C&IW streams that are not currently used by this plant to produce SRF were also characterized to verify their potential for such use and thus avoid sending them to landfills.

This research work considered the aforementioned plant as a case study and was guided by the following three questions: (1) Which is the quality of the SRF produced? (2) Which new waste streams could be used to increase the SRF production? and (3) Which are the potential uses of this SRF in the RMBA?

As regards the uses of the SRF and to assess the feasibility of diversifying the region's energy matrix, we here investigated three scenarios applicable to the RMBA:

Scenario 1: the use of SRF to replace the use of natural gas in the co-processing in the cement industry (current use).

Scenario 2: the thermal valorization of SRF for the generation of electricity intended for residential consumption.

Scenario 3: the thermal valorization of SRF for the generation of electrical power and heat for industrial use.

The results of this study are expected to provide basic information for an informed discussion of the goals of recycling and recovery of solid waste materials and energy in the RMBA and to help plant managers, local governments and other cities in Latin America to design strategies for Solid Waste Management.

## 2 Methodology

### *2.1 C&IW in the Study Area*

The RMBA is a typical megacity of Latin America, with its center in the Autonomous City of Buenos Aires, covering an area of 13,947 $km^2$, with an estimated population of more than 20 million in 2017 [9]. Its geographic gross product represents 40% of the national GDP. It has 40% of the country's industries, with plants for the manufacture of cars, food, bovine leather, textiles and paper and cardboard as well as shopping malls and large supermarkets that are considered generators of C&IW.

Until 2013, this waste was managed together with the MSW, but, since then, new regulations, which oblige C&IW generators to separate the waste at source for recycling and to manage their waste privately with authorized operators, have been implemented. This led C&IW generators to stop using the municipal services, and this in turn led to the creation of new companies for the collection, recycling and treatment of the C&IW. Although there are no certain statistics of the proportion of C&IW that was included in the MSW before the regulations changed in 2013, it has been estimated at about 700,000 tons per year [4]. The main treatments of C&IW in the RMBA currently include its recycling and final disposal in sanitary landfills.

Local governments promote C&IW recycling through the installation of plants operated by urban recyclers that provide free treatment for the C&IW sent there. Despite this incentive, the recycling of C&IW is very limited (2.2% according to the [8]). Therefore, more than 90% of the C&IW is still destined to final disposal in landfills. The operations authorized in the RMBA for the treatment of C&IW include energy recovery through SRF production. However, at the time of this publication, there was only one SRF production plant starting with C&IW, and the SRF produced is entirely intended for co-processing in cement plants. Currently, this SRF plant uses only the C&IW from a single waste stream from only 28 generators, which allows the plant to have no operational problems. Since this proportion of C&IW is still low (approximately 3% wt), it could be increased to expand the production of SRF and thus reduce the impacts of the final disposal. In addition, some SRF end users want to know the C&IW streams used in its production, as well as the feasibility of meeting the increases in SRF demand for their installations (Fig. 2).

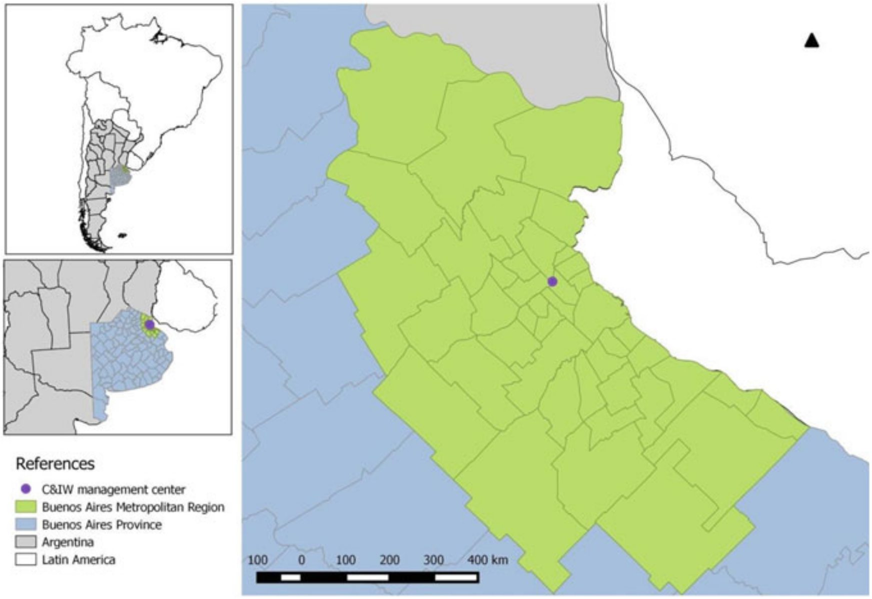



**Fig. 2** RMBA and location of the only C&IW management center with an SRF production plant

## *2.2 Description of the C&IW Management Center Considered as a Case Study*

The center belongs to a private firm that receives about 1,200 tons of C&IW per day from industrial and commercial generators and has an authorized SRF plant and landfill. This center is also linked to an external MRF operated by urban recyclers. The C&IW reaching the plant is weighed and visually inspected, and its documentation (traceability) is controlled according to the regulations. Part of the C&IW is derived directly to the production of SRF, part to the MRF, and the remaining part to the sanitary landfill. The SRF production plant has the capacity to process 15 tons of C&IW per hour, using waste streams consisting mainly of wastepaper, cardboard, non-recyclable wood, plastic labels, and some non-chlorinated plastics. The stages in SRF production are separation of bulky C&IW, primary shredding to less than 100 mm, removal of ferrous metals (magnetic separation), secondary shredding to less than 50 mm, classification by sizes (sieving), compaction and packing, quality control and dispatch to cement plants (Fig. 3).

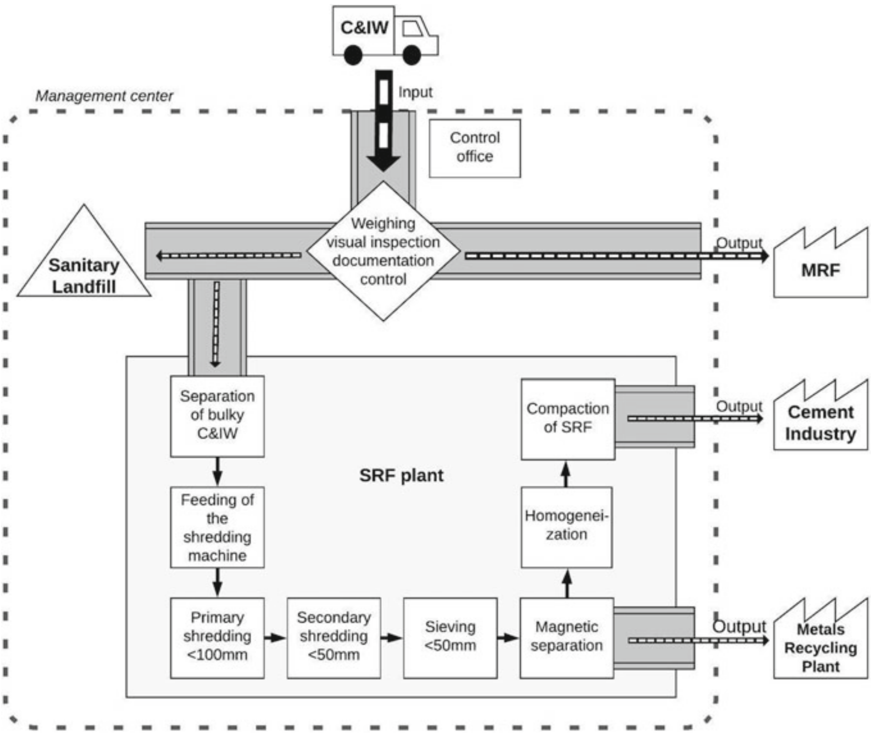



**Fig. 3** Scheme of the C&IW management center of our case study

## *2.3 Field Work*

The C&IW and SRF characterization study here described was conducted between October and November 2017. All the C&IW entering the facility was identified and the following information was recorded: date of arrival, collecting company, weight of the C&IW (in kg), type or principal component of the C&IW according to the cargo manifest, generator, and destination of the C&IW assigned by the operator of the center (SRF plant, MRF, or final disposal). In addition, the truck's contents were visually inspected and photographically recorded at the unloading point.

## *2.4 Sampling and Analytical Methods*

SRF and C&IW streams of the treatment center were sampled at different points. SRF samples were taken at the pre-compact point from a static batch and in accordance with the EN 15442 standard [21], whereas the C&IW streams were collected at two points: at the weighing point and at the discharge point in the landfill, applying an adaptation of the EN 15442 standard. Only two batches of SRF were produced during the field work.

Samples of wet leather, textiles (synthetic fibers), hard plastic, soft plastic, dry wood, rubber and foam material were collected, labeled and preserved in airtight plastic bags and then prepared for laboratory analysis according to standardized methods.

## 2.5 Sample Preparation and Laboratory Analysis

At the laboratory, both SRF and C&IW samples were prepared using different mills and sieves to reduce their particle size to 1 mm in accordance with the EN 15443 standard [16]. The physical and chemical parameters measured and standard determination methods used were: moisture content (% by weight), in accordance with the EN 15414-3 standard [17]; ash content (% by weight), in accordance with the UNE-EN 15403 standard [18]; chlorine content (% by weight) on a dry and wet basis in accordance with the EPA 9253 [6] and UNE-EN 15408 standards [19]; and higher and lower calorific power (i.e., net calorific value, NCV) at constant dry-basis volume (MJ $kg^{-1}$), in accordance with the UNE-EN 15400 standard [20]. In addition, the contents of metals and trace elements (arsenic, cadmium, cobalt, copper, chromium, mercury, lead, nickel and zinc) were determined by digestion in a microwave oven in external laboratories, in accordance with the EPA 3051 standard and EPA 6020 detection method, and elements (carbon, hydrogen, nitrogen and sulfur) were analyzed in accordance with the ASTM D5373 standard. Next, the elemental analysis of streams was used to calculate the estimated NCV by using Eq. 1 proposed by Tchobanoglous et al. [15] to compare with the results obtained with laboratory analyses:

$$NCV\,(\text{MJ/kg}) = (80.56 * C + 338.89 * (H - O/8) + 22.22 * S + 5.86 * N)/239 \quad (1)$$

where C, H, O, S and N correspond to the contents (% weight) of each chemical element in the respective samples.

## 2.6 Compositional Analysis of SRF

In addition, the composition (% by weight) of the SRF was estimated following a procedure adapted to the ASTM 5231/92 standard [1], combining manual and mechanical classification, using sieves.

### 2.7 Estimation of Replacement of Natural Gas with SRF in Alternative Scenarios

To estimate the replacement of natural gas with SRF, both with the one currently produced ($SRF_C$) and the one that can be produced ($SRF_P$), we propose the following three possible scenarios:

Scenario 1: Current scenario, i.e. co-processing of $SRF_C$ in cement kilns.
Scenario 2: Co-processing of SRF C in cement kilns plus use of $SRF_P$ in thermal valorization plants for production of electricity intended for the residential public service.
Scenario 3: Co-processing of $SRF_C$ in cement kilns plus use of $SRF_P$ in thermal valorization plants for production of electricity and heat intended for industrial demands.

In the calculation of natural gas replacements in each scenario, to calculate the total energy susceptible to be obtained from $SRF_C$ and $SRF_P$, we discounted the own consumption of SRF of the production plant. The energy expenditure of sending the rejected C&IW to landfill was not considered as in the treatment center. The energy used in the transport of C&IW from the generators to the treatment center was neither considered, as the treatment center receives the waste from around 300 generators located at different points in the RMBA and no data are available on their location so as to estimate the distance traveled between the generation points and the treatment center. For the use of $SRF_C$ in cement kilns, natural gas savings were counted only as regards the gas specifically used in the kiln. Similarly, for the use of $SRF_P$ in the thermal valorization, we considered only the savings on natural gas used in the combustion process for steam production, taking into account its corresponding efficiencies if used only for electricity generation (scenario 2) or for the co-generation of electricity and heat (scenario 3). In all cases, for the comparisons, we considered a natural gas with a calorific power of 38.94 $MJm^{-3}$, corresponding to that used in Argentina [5], and the statistical data on fuel consumption of the official agencies, the Electric Wholesale Market Management Company of Argentina (CAMMESA), the Argentine Ministry of Energy, and the National Gas Regulatory Body (ENARGAS).

For the calculation of the consumption of the SRF plant, we also considered the consumption of its machinery, namely the primary shredder, the secondary shredder, the compactor, the conveyor belts and the front loader shovel. Based on their respective powers and considering an 8-hour working day for 22 days per month, we also estimated the average energy consumption of the SRF production plant.

For the thermal valorization of the $SRF_P$, we considered that the technology applied is grate combustion, which, according to the German Environment Agency [2], is the most widely applied waste incineration technique. This can be used to produce electricity and/or heat, taking advantage of 82% of the energy contained in the waste for the generation of steam. This steam is used for the generation of electricity and part can be either lost as heat or used in other industrial processes. Figure 4 shows the energy balance of this type of plant.

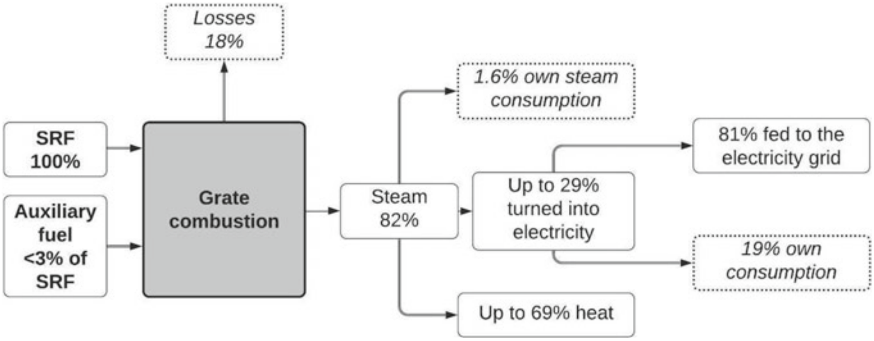



**Fig. 4** Energy balance of grate combustion of SRF

Electricity production was estimated from Eq. 2 (adapted from [24]):

$$EP\left(\frac{\text{kWh}}{\text{month}}\right) = \sum_{i=1}^{i=n} M_i * NCV_i * \frac{\eta_{ec}}{3600} \quad (2)$$

where EP is the electricity production per month; $M_i$ is the monthly dry mass of waste streams, $NCV_i$ is the lower calorific power of the waste streams to be incorporated into the production of SRF; $\eta_{ec}$ is the efficiency of the electricity generation plant; and 3600 is the conversion factor from MJ to KWh.

## 3 Results

### *3.1 SRF Production and Quality*

During the field work, a total of 22,000 tons of C&IW reaching the management center were recorded and distributed as follows: 3% was destined to the SRF plant, approximately 6% was destined to MRFs, and the rest was sent to landfill.

As explained in the Methodology section, two of the SRF samples produced in this plant during the field work (samples 10-10 and 26-10) were chosen to analyze their waste components in the laboratory for their proximate analysis. The results of the laboratory analysis of the components of SRF (Table 1) showed a high NCV (dry basis) of the SRF 10-10 sample (20.95 MJ $kg^{-1}$). This high heating value of SRF was due to the high mass fraction of plastics in it (more than 20%). The two samples showed mercury contents of less than 0.001 mg $kg^{-1}$ or 0.03 mg $MJ^{-1}$ (Table 1). The high heating value of SRF and its chlorine and mercury contents met the quality specifications for a Class II SRF in agreement with the European Committee for Standardization (CEN) [23]. In the component analysis, the SRF 10-10 sample showed higher content of dry wood (49 wt%) and less plastic than the

**Table 1** Results of the laboratory analysis of the components of SRF of samples 10-10 and 26-10

| Sample ID | Moisture content (wt%) | Ash content (wt%) | Net calorific value (NCV) dry basis (MJ $kg^{-1}$) | Chlorine dry basis (wt%) | Metals and trace elements (mg/kg) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | As | Cd | Co | Cu | Cr | Hg | Pb | Ni | Zn |
| SRF 10-10 | 5.00 ± 0.15 | 4.48 ± 0.11 | 20.95 ± 0.14 | 0.57 ± 0.12 | 0.009 | 0.005 | 0.01 | 0.30 | 0.18 | <0.001 | 0.23 | 0.06 | 56.4 |
| SRF 26-10 | 3.10 ± 0.22 | 2.86 ± 0.19 | 17.89 ± 2.71 | 0.24 ± 0.05 | 0.06 | 0.008 | 0.02 | 0.69 | 0.22 | <0.001 | 0.18 | 0.11 | 0.6 |

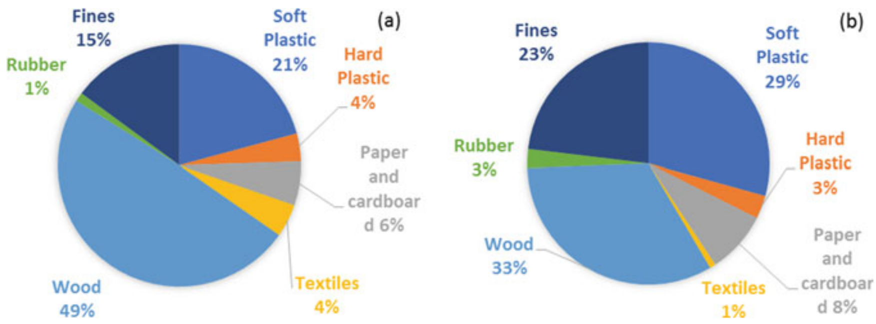



**Fig. 5** Results of the mass compositional analysis of SRF 10-10 (**a**) and SRF 26-10 (**b**)

SRF 26-10 sample. This may explain why the SRF 10-10 sample had higher chlorine content.

The values of ash and moisture content were low for the two SRF samples (Table 1).

The waste components of SRF included: paper & cardboard, hard plastic, soft plastic, textile, wood, rubber, foam and fines. Hard plastic and soft plastic were separated based on their physical/apparent hardness and softness: soft plastic consisted mainly of plastic bags and plastic labels and hard plastic consisted of hard plastic material (waste components) (Fig. 5).

## *3.2 Potential for SRF from New Waste Streams*

C&IW streams that were considered with potential to produce SRF were prepared and analyzed to verify whether their chemical and thermochemical characteristics make them SRF-safe. Results are shown in Table 2. C&IW samples were also analyzed to determine their elemental composition (ultimate analysis) (Fig. 6). Based on the results of the elemental analysis and by applying Eq. 1, we estimated the NCV and compared it with the values measured experimentally (Fig. 6).

These results showed that the C&IW stream identified as W002, corresponding to cowhide from a tanning industry, contains chromium in an amount that exceeds the limits recommended for heat treatment of waste. The results also showed high cadmium content (86.6 mg/kg) in the C&IW stream called P010 of plastics in relation to the SRF recommendations of Waste & Resources Action Program (WRAP) [23]. This content of contaminants and the high moisture percentages of the W002 and P010 streams make these two samples not suitable for SRF production. Regarding samples P004 and P015, although their chemical and thermochemical characteristics make them suitable for SRF production, they are materials that are sporadically sent to the treatment center, so they were not taken into account for the formulation of SRFp.

**Table 2** Results of the thermodynamic and chemical characteristics of C&IW samples

| Sample ID | Main components | Moisture content (wt%) | Ash content (wt%) | Net calorific value (NCV) dry basis (MJ $kg^{-1}$) | Chlorine dry basis (wt%) | Metals and trace elements (mg/kg) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | As | Cd | Co | Cu | Cr | Hg | Pb | Ni | Zn |
| W002 | Wet leather | 23.30 ± 7.90 | 5.62 ± 0.06 | 12.00 ± 0.63 | 1.36 ± 0.06 | 0.008 | 0.356 | <0.01 | 1.61 | 1339.5 | <0.001 | 0.06 | 0.16 | 5.0 |
| P004 | Textile (synthetic fibers) | 3.90 ± 0.40 | 27.30 ± 2.55 | 29.00 ± 1.99 | 0.50 ± 0.11 | 0.051 | 0.181 | <0.01 | 4.36 | 2.70 | <0.001 | 4.71 | 0.71 | 30.3 |
| P006 | Textile (synthetic fibers) | 2.00 ± 0.20 | 0.52 ± 0.06 | 19.40 ± 0.29 | 0.19 ± 0.003 | <0.002 | 0.005 | <0.01 | 3.23 | 2.61 | <0.001 | 0.73 | 0.90 | 4.0 |
| P008 | Rubber and foam material | 0.49 ± 0.06 | 4.69 ± 1.05 | 20.20 ± 0.67 | 0.26 ± 0.07 | 0.035 | 0.075 | 0.15 | 164 | 3.56 | <0.001 | 1.25 | 1.74 | 1560 |
| P010 | Hard plastic | 12.80 ± 3.60 | 3.88 ± 0.55 | 25.70 ± 0.56 | 1.06 ± 0.03 | <0.002 | 86.400 | 8.34 | 18.2 | 3.01 | <0.001 | 2.41 | 1.30 | 24.9 |
| P014 | Textile (synthetic fibers) | 3.15 ± 0.03 | 2.08 ± 0.15 | 18.63 ± 0.06 | 0.17 ± 0.02 | <0.002 | 0.095 | 9.55 | 1270 | 14.80 | <0.001 | 5.38 | 5.39 | 347.0 |
| P015 | Dry wood | 4.10 ± 1.20 | 6.33 ± 0.12 | 16.60 ± 0.30 | 0.30 ± 0.05 | 0.899 | 0.205 | 2.11 | 18.60 | 21.70 | <0.001 | 14.30 | 10.30 | 2500 |
| P018 | Rubber and foam material | 0.47 ± 0.03 | 30.50 ± 0.17 | 19.20 ± 0.32 | 0.17 ± 0.04 | 0.011 | 0.105 | 0.16 | 17.0 | 6.41 | <0.001 | 1.87 | 3.08 | 31.0 |

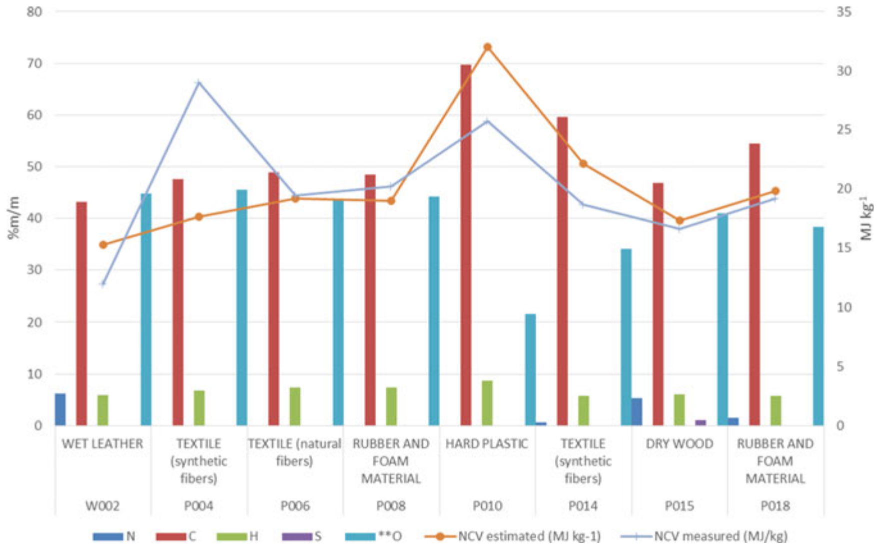



**Fig. 6** Results of the elemental analysis and values estimated with Eq. 1 and NCV measurements in C&IW samples

The potential streams that were combined to form a potential theoretical SRF (SRFp) type are listed in Table 3.

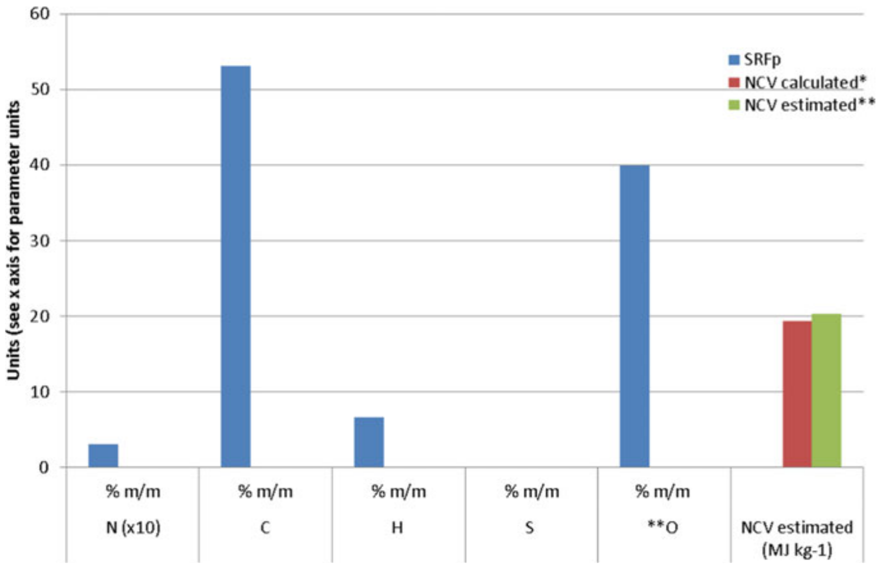
The amount of monthly input of waste (in kg) was estimated based on the records obtained during the C&IW characterization field work, and the following chemical and thermochemical characteristics of the SRFp were calculated as weighted averages based on the experimental results of the four waste streams constituting it:

Moisture content (wt%): 0.02
Ash content (wt%): 3.33
Net calorific value (NCV) dry basis (MJ $kg^{-1}$): 19.33
Chlorine content dry basis (wt%): 0.002
Mercury content (median) (mg/MJ): <0.001.

These results show that the SRFp has characteristics that make it suitable for energy recovery, achieving a Class III quality [23]. It should be noted that the limiting

**Table 3** Main C&IW streams used to compose the SRFp and its contribution to the total energy content

| Sample ID | Main components | wt% | Contribution to total energy content (%) |
|---|---|---|---|
| P006 | Textile (synthetic fibers) | 54 | 54 |
| P008 | Rubber and foam material | 2 | 2 |
| P014 | Textile (synthetic fibers) | 37 | 35 |
| P018 | Rubber and foam material | 7 | 8 |




* Calculated based on experimental NCV from the C&IW samples composing it.

** Estimated using equation 1.

**Fig. 7** Results of the calculation of the elemental composition of the SRFp and the theoretical NCV compared with that calculated as a weighted average of the NCV measured at the laboratory

parameter to define the SRFp class is the calorific power, because the characteristics of environmental interest are well below the limits proposed in the bibliography.

The elemental composition of the SRFp was also estimated and used to calculate the estimated NCV of the SRFp with Eq. 1. This NCV was also calculated as a mass weighted average of the NCV of the C&IW experimentally measured. All the values obtained are shown in Fig. 7, where a difference of less than 10% can be seen between both calculations of the NCV of the SRFp.

## *3.3 Potential Uses of SRF: Estimation of Natural Gas Replacements*

The replacements of natural gas estimated in each scenario are presented in Fig. 8. In all cases, the consumption of the SRF production plant, which was estimated at 7.62 MJ per month, was discounted.

In Scenario 1, which continues with the current use of SRF, the 32 t daily produced are destined to the cement industry, which represents monthly savings of 33,722 $m^3$ of natural gas, equivalent to 1% of the demand for natural gas in the region.

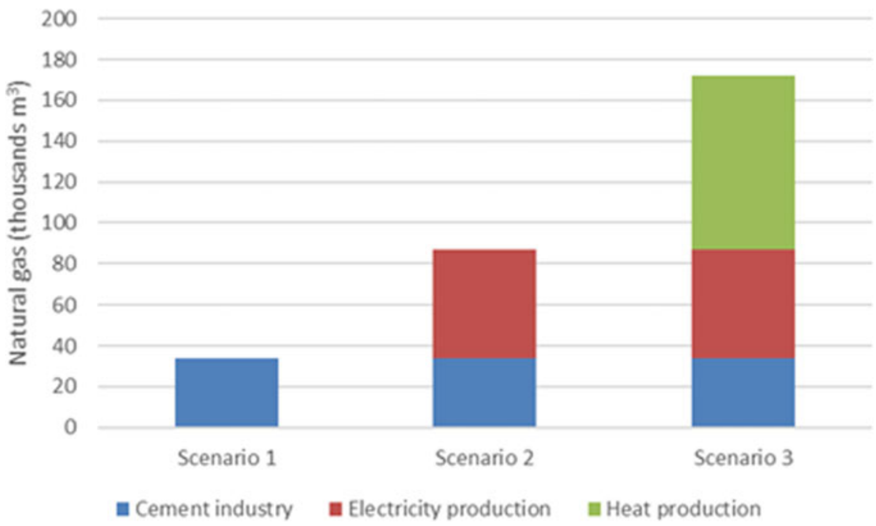



**Fig. 8** Replacement of natural gas (per month) by use of SRF for each scenario

Scenario 2, which continues with the current use of SRF but adds the electricity generation from the SRFp, shows a production of 177.4 t of SRFp per month, which could generate 210.97 MWh, equivalent to 1% of the residential electricity demand in the region. This use represents monthly savings of 53,198.5 $m^3$ of natural gas. Thus, in this scenario, a total of 86,920.5 $m^3$ of natural gas would be replaced by SRF.

In scenario 3, which proposes to add the thermal valorization of the SRFp to generate vapor and electricity for industrial use, adds the generation of: (a) 210.97 MWh of electricity per month, which could cover 3% of the region's industrial electricity demand; and (b) heat in the shape of steam, which could replace 85,459.53 $m^3$ of natural gas per month for industrial use with $SRF_P$ (1% of demand). Considering the three advantages of SRF (both $SRF_C$ and $SRF_P$) in this scenario, a total monthly replacement of 172,379.23 $m^3$ of natural gas per SRF would be achieved.

## 4 Discussion

The treatment center here evaluated receives C&IW streams from large generators and, according to their characteristics, gives them three possible destinations: material recovery, SRF production, or landfill disposal. According to the data collected during our fieldwork, less than 10% of the material received by the treatment center is recovered in the form of fuel or recycling, while more than 90% is disposed of in landfills. These recovery values are far from those achieved by other SRF production plants in other countries, which exceed 60% of the material received by the plant

[11]. It should be considered that, in Argentina, particularly in the RMBA, this is an incipient technology. However, the growing interest in high-quality alternative fuels by certain industries in the region is an incentive to make improvements to the treatment center to increase its production.

Our results showed that the SRF currently produced by the plant has characteristics that allow classifying it as Class II: high energy content and low moisture values [23]. These values make this SRF a desirable and highly efficient fuel for use, especially when compared with those reported by Nasrullah et al. [11] for SRF obtained from waste from MSW plants in Finland, and with those reported by Lupa et al. [10] for SRF obtained from C&IW and MSW in United Kingdom (moisture content above 20% wt on average).

In line with that found by Nasrullah et al. [11], in the present study, we verified that the quality of the input waste is extremely important to obtain a high-quality SRF, even more important than the production process itself.

Based on this field study and the analyses of the C&IW currently sent to landfill, we found that SRF production can be at least five-fold higher, reaching a Class III SRF, suitable for thermal valorization. This is based on the fact that the samples analyzed present appropriate thermochemical characteristics for use in the production of SRF. However, if characteristics of environmental interest are considered, some C&IW streams yielded values that exceed the limits recommended in the bibliography for their energy valorization [23]. Taking into account the calorific power of each C&IW stream (Table 2), streams P004 (29 MJ $kg^{-1}$), P008 (20.2 MJ $kg^{-1}$) and P010 (25.7 MJ $kg^{-1}$) showed the greatest calorific power. However, sample P010 had a high cadmium value (86.4 mg $kg^{-1}$), while samples P004 and P015 were not considered for the SRFp because they were from infrequent generators. However, if a continuous flow of waste could be ensured, they could be incorporated into the production of SRF.

In this way, the results obtained indicate that the C&IW streams identified as P006, P008, P014, and P018 are suitable to produce a Class III SRFp, which is suitable for thermal valorization to generate either electricity (as in scenario 2) or both heat and electricity (as in scenario 3). The main material of formulated SRFp is textiles (synthetic fibers), which also provide 89% of the energy content. It should be clarified that these textiles are mainly synthetic fabrics based on polypropylene fibers and therefore their NCV is greater than 18 MJ $kg^{-1}$.

The chemical and thermochemical characteristics of the C&IW streams evaluated in this study showed values similar to those of others reported in industrialized countries [11]. We verified that the materials with the greatest energy input were hard plastics (with NCV of more than 30 MJ $kg^{-1}$), and that those with the lowest energy inputs were those obtained from wood. We also noted that naturally occurring textiles had lower NCV than synthetic textiles because the former contain lower carbon percentages.

Since, in Argentina, textiles made of both natural and synthetic fibers are difficult to recycle due to technological limitations or lack of demand for recycled materials, it is estimated that the energy recovery of these materials is a valid alternative to their final disposal in landfill. Most synthetic textiles come from car assembly plants (car mats, insulating materials, etc.) and from disposable towel and diaper industries (i.e. nonwoven fabrics). These generators of the RMBA apply zero landfill policies to their waste, so their valorization as SRF is also positively considered by them.

The analysis of the scenarios here proposed to consider the impacts of the increase in SRF production in the region by using C&IW streams that are usually sent to landfill shows that the replacement of natural gas by SRF for the generation of electricity and heat is considerably high relative to the current use (Fig. 7), although still small relative to the demand for natural gas (about 1%). Both scenarios 2 and 3 require the installation of energy recovery plants in the region, which are currently not available because of the high investment and operating costs required and the low costs of landfills. It is thus expected that new regulations to support these new technologies, which allow energy to be recovered from waste, will be introduced in the coming years.

## 5 Conclusions

The management of C&IW of the RMBA poses an environmental problem that must be comprehensively addressed by seeking the recovery of materials and energy to reduce the environmental impacts of the current management, which is based mainly on the final disposal in landfills. These wastes can be recycled in material recovery plants and the waste fractions of these treatments can be used to produce SRF by mechanical treatment. This process recovers energy from waste fractions in the form of SRF and allows recovering ferrous metals and preventing their final disposal in landfills.

This chapter described a field study conducted at a C&IW management center in the RMBA, Argentina, where only 10% of the waste input is recovered in the form of SRF. This allows obtaining a Class II SRF that has increasing demand in Argentina's cement industry to replace the use of natural gas. This C&IW consists mainly of paper and cardboard, plastics, woods, natural and synthetic textiles, leather, and rubber. C&IW streams that are not currently used for SRF were characterized to verify whether SRF production can be increased and scenarios of possible SRF uses were analyzed. The results indicated that natural and synthetic textile streams and synthetic rubbers and foams have sufficient quantity and quality to produce SRFp that meets the requirements of a Class III SRF according to the CEN classification. This SRF is suitable for thermal valorization to generate steam and electricity.

Finally, we estimated the percentage of energy demand that could be met with C&IW that could be used to produce SRF. In this way, the production of the SRF plant can be increased by 500%, reducing the amounts of C&IW sent to landfill. In addition, this extra production of SRF would cover 2% of the energy demand of the RMBA, thus collaborating to achieve the goals of incorporating renewable energy sources, established by Argentina's national regulations.

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# Broader Dimensions of Energy and Environmental Security

# Energy and Environment: Sustainable Development Goals and Global Policy Landscape

**Liliana N. Proskuryakova and Irina Loginova**

**Abstract** The global challenges faced by the humankind encompass access to clean and affordable energy for all, shifting to the green development path and tackling the consequences of climate change. Success in addressing the related goals relies on the concerted efforts of society at large, whereby researchers may offer new solutions and media could raise awareness and organize public discussions. This chapter examines the policy landscape created for addressing the global energy and environment goals, as defined in the international documents. Moreover, the chapter analyses attention given to these goals by researchers, business and media. More specifically, the chapter focuses on goals set in the legally binding universal agreements and conventions formulated and adopted by the United Nations: "Transforming our world: the 2030 Agenda for Sustainable Development" (SDGs or SG), the Paris Agreement (PA), the "Future We Want" Resolution (FWW), and the Johannesburg Plan of Implementation (JPI). Research methods include policy analysis and the smart big data analysis of thousands of publications on the topic. The authors highlight controversial policy issues, as well as relatively low attention to global energy challenges on behalf of mass media. Researchers address these challenges much more often, however, focus primarily on a few SDGs. The outcomes underline further steps to be taken by global and national policymakers.

**Keywords** Energy research · Energy technology · Energy policy · Grand challenges · Energy goals · Universal agreement · Global energy targets

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## 1 Introduction

Energy-related grand challenges are defined in international declarations and action plans. This chapter analyses the legally binding universal agreements adopted at the United Nations. One of the most well-known documents is the UN General Assembly Resolution that set the Sustainable Development Goals (SDGs) in September 2015. The SDGs for 2015–2030, replacing the Millennium Development Goals (2000–2015), became the new agenda and a plan of action "for people, planet and prosperity" [1]. Energy issues are in the focus of SDG7 "Ensure access to affordable, reliable, sustainable and modern energy for all", while a number of other SDGs also tackle sustainable generation, distribution and use of energy and natural resources [2–4].

Agreements and conventions that focus on climate change and sustainable development also state energy-related goals. The Paris Agreement has become a key document to prevent and mitigate climate change for developed and developing countries [5]. This document has multiple implications for the energy industry, including the advancement of renewable and low-carbon energy technologies [6, 7], the sustainable use of fossil fuels and large hydropower plants [8], and increased energy efficiency [9].

The Johannesburg Declaration and Plan of Implementation, agreed at the World Summit on Sustainable Development, identify global challenges and specific timetable to address some of them, as well as underline the continuous international oversight on sustainability agreements. "The Future We Want", the outcome document adopted at Rio +20, focuses on green growth and the interface between environment and economy [10]. Although the understanding and interpretation of the outlined challenges fuel discussions [11], the extent to which these challenges are picked up and operationalized by researchers, businesses, and media remains unclear.

Grand energy challenges go beyond the public good. They could be very relevant for business, in particular, in the application of closed-loop technologies, construction of own energy generation facilities and introduction of various sustainability frameworks [12, 13]. The business could also channel support to resolution of grand challenges as part of the corporate social responsibility and charity programs, such as the funding for energy education and energy efficiency projects from the Bill and Melinda Gates Foundation.

Solutions for grand energy challenges require the concerted efforts of society at large. People should also have a say in the implementation of these solutions. Media plays a crucial role in both of these processes through awareness rising and forming people's opinions and attitudes, as well as communicating energy-related research to non-expert audience [14, 15].

The possibility to address grand challenges through science has increasingly attracted the attention of researchers over the last decade [16]. The researchers have approached this task from conceptual [17, 18] and thematic perspectives [19, 20]. Scientific research could offer new solutions to grand challenges [17].

This chapter answers two questions. Which energy challenges, as defined in the international documents, are addressed by the media and researchers? What are the differences in approaching them by these three groups of stakeholders (business media, news media, and researchers)?

## 2 Grand Energy and Environmental Challenges as Reflected in International Agreements

The selection of grand energy challenges started from identifying energy-related universal documents, such as key energy, climate and environment-related United Nations agreements and conventions. The following documents were selected for analysis:

- Resolution A/RES/70/1 adopted by the General Assembly on 25 September 2015 "Transforming our world: the 2030 Agenda for Sustainable Development" that assert the Sustainable Development Goals [21];
- Resolution A/RES/66/206 adopted by the General Assembly on 22 December 2011 "Promotion of new and renewable sources of energy" [22];
- Resolution A/RES/66/228 adopted by the General Assembly on 27 July 2012 "The Future We Want" adopted after the United Nations Conference on Sustainable Development, Rio +20 [23];
- Agreements taken by the World Summit on Sustainable Development, including Johannesburg Declaration (A/CONF.199/20) [24] and Johannesburg Plan of Implementation [25];
- United Nations Convention on Climate Change (United Nations, 1992, FCCC/INFORMAL/84) [26];
- The Paris Agreement (adopted by the United Nations, 2015, FCCC/CP/2015/10/Add.1 [27];
- Documents related to Earth Summit + 5;
- Agreements taken by the United Nations Conference on Environment and Development;
- Other major agreements.

After revision of the selected documents it was decided to focus on four of them: the "Transforming our world: the 2030 Agenda for Sustainable Development" (SDGs), the Paris Agreement (PA), the "Future We Want" Resolution (FWW), and the Johannesburg Plan of Implementation (JPI). These documents were selected due to their direct relationship to energy issues and their coverage in sufficient detail (i.e. 2-page documents were not considered).

Sustainable Development Goals, and SDG7 in particular, have been scrutinized by researchers. They have commented on the contribution of particular types of energy [28, 29] to achieving the SDG7, the related strategies for particular regions [30] countries [31], or localities [32].

The wide application of renewable energy sources contributes to addressing many global energy and climate challenges. Researchers also note considerable environmental and societal trade-offs, including biomass preferences in rural areas and biodiversity concerns regarding certain types of renewables [33]. Before new energy technologies enter the market, related technologies should be assessed for environmental impact over competitors [34]. Long-lived energy technologies are parts of interlocking networks and usually require more time to diffuse and co-develop with other technologies in the network. These network effects represent high entry barriers even for more advanced products. Therefore, policy measures to promote greater technological diversity and lower entry barriers for new infrastructures are needed to accelerate global decarbonisation [35].

Poverty alleviation through access to energy and other natural resources is relevant to SDG1. Despite the numerous initiatives for promoting energy access in poor countries (i.e. Power Africa, SE4All), African countries might not be able to achieve universal energy access by 2030. One reason is that these actions need to account for income, cultural, gender, and other specific features of the target region. For instance, programs in Sub-Saharan Africa should focus on enhancing rural electrification rather than merely increasing generation capacity [30]. In particular, good prospects are noted for application of well-developed photovoltaic (PV) technologies coupled with local capacity building [36]. To attain this goal, development aid should be complemented with energy industry and institutional reforms, as well as integrated with climate change mitigation initiatives. Importantly, policies should be coherent not only at the level of objectives, but also at the level of associated instruments and implementation practices in areas such as resource efficiency [37].

Electrification is one of the main trends in the growing global energy consumption. Its impact on the transport sector (electric-based mobility: electric vehicles, hybrid engine cars, and electric drive trains), energy consumption in households (smart house solutions), working environment, and leisure activities is immense. This means that the global regulatory regimes of the post-2015 development agenda of Rio20+ United Nations Conference on Sustainable Development should be adapted to electricity generation preferential technologies under the SDGs. The researchers conclude that priority should be given to electric energy storage (including pumped hydroelectric storage) that support the expansion of renewable electrification [38].

Waste-to-energy (WTE) technologies contribute to sustainable urban waste management reflected in SDG11 [39] and to attaining SDG7. Over the past years, waste incineration technologies have gradually increased their environmental and economic indicators. Other waste processing solutions, like anaerobic digestion, gasification, and pyrolysis have made it possible to obtain a wide range of products for energy generation. For this reason, expanding WTE technologies contributes to both waste disposal and renewable energy expansion. For instance, many developed countries, including Switzerland, Sweden, and Germany implement strategies for economically beneficial use of biomethane that contributes to clean, safe and a friendly environment for citizens.

An important element of energy systems for the poor, relevant for remote rural communities in developing countries where grid extension is often expensive, is decentralized biomass-based generation facilities connected with mini-grids. Technical and financial feasibility studies of decentralized electrification based on agricultural waste gasification show good prospects for these solutions [40]. Another element of energy system for the poor is the relationship between renewables and living conditions of poor rural households in developing countries [41]. The researchers offer comprehensive policy recommendations to foster the diffusion of affordable renewable solutions at the local and global level [42].

Biofuels have the potential to play a significant role in attaining SDGs 1, 7 and 13. However, researchers note several potential barriers to large-scale production of the first and second-generation biofuels that include emissions and competition with agriculture for land use. Third and fourth generation biofuel producers are capable of overcoming these difficulties by applying novel biology, carbon capture and bioconversion technologies to provide larger volumes of clean fuel [28].

Responsible energy consumption and production (SDG12) imply that companies follow industrial ecology principles according to which a firm exists as part of the social-ecological system. Through combining internal competencies and external drivers a company could improve its resource productivity and, thus, increase competitiveness. Other concepts that contribute to attaining this SDG are the Sustainable Value framework and Eco-Synergy approach. Researchers also outline three areas where the industrial ecology, business strategy, and sustainable development merge making SDGs relevant for business: strategic positioning, efficient use of energy and resources, mitigation of and adaptation to climate change [43].

Air pollution is a pressing sustainability concern inscribed in SDG11. Measures to improve air quality also help provide 'clean energy for all', achieve climate change targets, introduce waste management, and other components of sustainable development. Within these areas, researchers address comprehensive policies for attaining three interrelated SDGs. Scenarios should be designed for attaining these goals in a comprehensive manner that will allow for cross-fertilization and benefit [44].

Some of the world's largest polluters and carbon dioxide ($CO_2$) emitters are actively introducing environmental and climate policy measures. For instance, China has developed smart solutions to reduce the dependence on power generation from coal and to halve the related emissions in the next five years. These include new $CO_2$ and greenhouse gas 2030 emission targets to decrease dependence on fossil fuels, wide introduction of electric vehicles, energy efficient technologies, and interactive air quality index monitoring systems [45]. In addition to climate mitigation measures, environmental policies have a positive effect on technological innovation in the energy industry, including the traditional fossil fuel-based generation.

Energy-efficient and green buildings can also contribute to meeting SDG11 and SDG13. However, the implementation of stimulating measures in construction is constrained by socioeconomic and technical barriers. The most important drivers identified by researchers include stable regulatory framework, standardization, low transaction costs, and the price of energy [46]. Proper timing of their introduction through policy measures also matters, as well as careful targeting at either investors or inhabitants.

The ocean plays a significant role in regulating global climate and is has the potential to provide an increasing amount of clean energy. The adoption of SDG14 gives new stimulus to international efforts geared to the protection of marine environment and the sustainable use of marine resources for the benefit of present and future generations. SDG14 provides the basis for monitoring the achievement of international milestones for all maritime zones including areas in international jurisdiction and establishment of integrated, coherent and transparent governance framework at the national level [47].

Studies involving partial equilibrium energy system modelling and life cycle assessment (LCA) estimate environmental and human health impacts of energy system transformation pathways that are directly related to Article 125 of the 'Future We Want' Resolution. More precisely, the most substantial damage to the environment and human health is caused by coal production, use, and disposal; oil use by transport and industry; and energy crops cultivation and use. The energy transformation policy that takes into account climate change mitigation measures contributes to several SDGs by achieving positive side-effects for the environment and human health, while challenges to water and land use should be addressed through nexus solutions [48].

Technological and behavioural changes, orchestrated together, may contribute to simultaneous achievement of energy-related sustainability objectives set by the international agreements. These interlinked objectives cover poverty eradication, assuring universal access to safe and affordable energy sources, preventing and mitigating climate change, safeguarding biodiversity and decreasing air pollution. To this end, researchers have identified different strategies that preview major transformations of energy systems, agriculture, transport and other sectors that go beyond the existing policies [49].

The interrelation of all grand energy challenges provides a favourable background for future studies and policies to tackle them. For instance, SDG17 related to global partnerships and SDG13 on climate action represent enablers for the other goals, and the SDG3 related to human health is subject to impact from all the SDGs [50]. SDG1 is complimentary to most of the other goals, while SDG12 is the goal most commonly associated with trade-offs. Changes in freshwater resources caused by climate change can either increase the trade-offs with SDGs 3, 15, and 9, or influence negatively the complementarities with SDGs 1, 3, 4, and 17. The highest synergies were identified for SDGs 2, 3, 7, and 14 [2]. Climate issues are addressed by SDG13 and the Paris Agreement. Health impacts from energy use are addressed by several SDGs and 'The Future We Want' Resolution. A similar interlinkage in attaining these SDGs should be mirrored in the global and national efforts of major stakeholders – governments, business and the media.

## 3 Policy Approaches to Attaining the Energy Goals

Policies to address global energy challenges are developed by a variety of international organizations and country groupings: International Energy Agency [51], World Energy Council [52], Organization for Security and Cooperation in Europe [53], Organization for Economic Cooperation and Development [54], G8 [55], and other. The main policy approaches are based on fair and competitive market-based tools, including:

- The development of legal and regulatory frameworks that sustain the obligation to uphold contracts and generate sustainable international investments;
- The organization of dialogue with stakeholders, in particular, related to the supply and demand security;
- The diversification of energy supply sources, transportation routes and means of transport;
- Promotion of energy saving and energy efficiency;
- Environmental and climate regulations related to the energy development (extraction), deployment and use technologies;
- Promotion of transparency and good governance principles in the energy industry;
- International collaboration related to the energy emergency response and protection of critical energy infrastructure;
- International collaboration for addressing the energy challenges in the poor developing countries;
- Exchange of best practices and capacity building related to coping with grand energy challenges.

The universal nature of international agreements analysed in this chapter pose additional requirements to relevant energy policies. This relates to achieving common targets by countries that are at very different level of development, monitoring of the progress towards these goals and agreeing on best practices. There are multiple difficulties associated with each of these three policy actions. First, poor countries often lack the resources to properly plan and execute the changes. Second, monitoring of universal agreements is highly complicated and expensive. Third, there is lack of consensus on what should be best practices that differ depending on national contexts and traditions [56].

The grand energy challenges may be solved with the help of researchers that could provide evidence for the policy tools design. However, if researchers do not address certain issues, there is an evidence gap. Therefore, policy makers should strive to support research across a range of energy challenges that will shape the future of energy. Table 1 features the highly cited research papers related to energy issues identified in the international agreements that were published in the last few years.

**Table 1** List of grand energy challenges and their aspects most covered in research

| Source (international agreement) and brief description of the grand energy challenge | Key topics covered by researchers |
|---|---|
| SDG 1 ('End poverty in all its forms everywhere') | Renewable energy technologies for the poor households, least developed and developing countries [41, 42, 57]; access to natural resources (fishing) under global warming [58]; inter-relation between energy, environment, climate change and health [59] |
| SDG5 ('Achieve gender equality and empower all women and girls') | Agroecology potential for the combined attainment of several SDGs, including gender equality [60]; gender issues related to sustainable resource use [61]; gender and health aspects of sustainable development [62] |
| SDG6 ('Ensure access to water and sanitation for all') | The inter-connection of SDG 6 with other SDGs [50]; quality of water resources [4]; water footprint related to energy generation [63]; transboundary water cooperation [64]; water contamination from shale gas extraction [65] |
| SDG7 ('Ensure access to affordable, reliable, sustainable and modern energy for all') | Energy access in specific regions [30, 42, 66], the link between research [67], |
| SDG 8 ('Promote inclusive and sustainable economic growth, employment and decent work for all') | People's well-being [68]; gender aspects of decent work and economic growth [69]; economic growth and decent work for all [70] |
| SDG9 ('Build resilient infrastructure, promote sustainable industrialization and foster innovation') | Combined cooling, heating and power microgrid [71]; bridging the digital divide [72]; policies for innovations in electricity storage [38]; innovative policies for rural electrification [66] |
| SDG11 ('Make cities inclusive, safe, resilient and sustainable') | Inequalities in urban health; integrated information ecosystem development [44]; sustainable urban land use [73] |
| SDG12 ('Sustainable consumption and production') | Food, water, and energy nexus [74]; sustainable business practices in SMEs [75]; sustainable energy system modelling [48] |
| SDG13 ('Take urgent action to combat climate change and its impacts') | Energy transition and low-carbon development [76, 77]; climate finance [78]; climate change mitigation [79] |
| SDG 14 ('Conserve and sustainably use the oceans, seas and marine resources') | General issues of SDG implementation [80]; marine biodiversity conservation [81]; ecosystem services in fisheries [82]; access to natural resources (fishing) under global warming [78] |
| SDG 15 ('Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss') | Environmental and social impacts of hydroelectric dams, landscape composition, biofuel plantings [83] |

(continued)

**Table 1** (continued)

| Source (international agreement) and brief description of the grand energy challenge | Key topics covered by researchers |
|---|---|
| SDG 17 (‘Revitalize the global partnership for sustainable development’) | Cross-sector social partnerships; the contribution of NGOs to sustainability [84] and attaining SDGs [85]; the UN global compact [13] |
| Paris agreement, article 2 | Carbon development [76, 77]; climate finance [78]; climate change mitigation [79] |
| Paris agreement, article 7 | Climate change adaptation [86], environmentally friendly vehicle technologies [87], biodiesel feedstock [88] |
| Johannesburg plan of implementation | The use of solid fuels for cooking [89]; bio-hydrogen production from waste materials [90]; energy for poor rural households [41]; adaptive management strategies in agriculture [91]; mortality from air pollution [92] |
| The future we want | The use of solid fuels for cooking [89]; bio-hydrogen production from waste materials [90]; inter-relation between energy, environment, climate change and health [59] |

## 4 Analysis of Topics Related to Energy Challenges in Research and Media Publications

For each of the energy-related targets set by SDGs and articles of “The Future We Want”, the Paris Agreement and Johannesburg Plan of Implementation (excerpts selected for analysis) a set of 2 to 25 keywords was identified. Certain keywords that are interlinked in the documents were searched together (an article or news item should contain two or three interlinked keywords). Some of the energy challenges (and relevant keywords) in the selected excerpts of the international documents under consideration are similar. However, the combination of keywords is specific to each of the excerpts.

The methodology is based on big data analysis of all research publications indexed in the Web of Science (WoS), business and news media (over 1400 e-resources in English language) with the use of proprietary software iFORA®. This software relies on a new original approach to integrating thematic clustering and analysis of dynamic patterns of terms occurrence in abstracts of research papers and media sources. The thematic clusterization algorithm is unique and differs from existing solutions. For all terms a new method for calculation of joint occurrence in research papers and media articles was offered. The selection criterion was the occurrence of two terms in one sentence or not more than two sentences apart. Thus, the borderline to account for existing interlinks among the terms was extended and allowed to take into consideration the inter-sentence connection. This is different from traditional approaches that are based on analysing joint occurrence within an entire text that yields additional groundless interlinks among the terms, or within one sentence that creates abruptions in the terms column due to very narrow context of potential interlinks. The advanced metrics was previously tested by the Higher School of Economics team with photonics [93], agriculture [94, 95], and extractive industries [96].

The sources of information for text mining in this study were selected taking into consideration previous publications on the topic [97, 98]. The 2015–2017 time period was chosen as relevant for all documents that were selected for analysis, including SDGs adopted in 2015.

The categorization of e-resources as news and business media was based on their target audience. The resources designed for the business community (i.e. websites of industrial associations), as well as corporate web-sites and other corporate e-resources were classified as business. The resources addressing general audience, as well as websites of research journals (such as nature.com) that publicize research were classified as news media.

We also performed a manual literature review search to double-check the findings. The theoretical groundwork publications were selected based on the same keywords, as those used for the big data analysis. Top cited research and review articles indexed in the Web of Science (WoS) were identified and grouped into three categories: articles, related to sustainable development (miscellaneous); articles, related to sustainable development and business relevant; articles, related to sustainable development, that are relevant for the society at large.

Figure 1 features the occurrence of energy-related grand challenges in business media. The number of energy-related grand challenges addressed by industrial, sectoral and professional publications is substantial, while most attention was given to SDGs in 2015 and 2016, i.e. shortly after their adoption. SDG 6 ('Ensure access to water and sanitation for all'), SDG7 ('Ensure access to affordable, reliable, sustainable and modern energy for all'), SDG8 ('Promote inclusive and sustainable economic growth, employment and decent work for all'), SDG9 ('Build resilient infrastructure, promote sustainable industrialization and foster innovation'), and SDG11 ('Make cities inclusive, safe, resilient and sustainable') received more attention than others. Business interest is focused on the following topics: energy innovations in specific regions (related to SDG 7) [13, 66], the link between research [67], economic growth and achieving SDGs [70], and corporate social responsibility [99].

Substantial efforts are needed to meet the SDG7: 80% of the world's 1.06 billion population without electricity live in 20 countries [13]. Indeed, integration of energy justice issues in policies targeting renewable energy should not only result in avoiding injustices but also in new business opportunities for international companies and local entrepreneurs [57]. Awareness rising and development aid need to be complemented with other measures. Similarly, there is a need for a clear business case and reconciliation of SDG7 and SDG13 targets: energy companies simultaneously need to assure access to energy, while addressing the climate concerns [13].

Energy-related and other SDGs could only be achieved with the involvement of business that could happen due to the development of relevant policy measures. One of these tools is the introduction of a sustainability framework at national level,

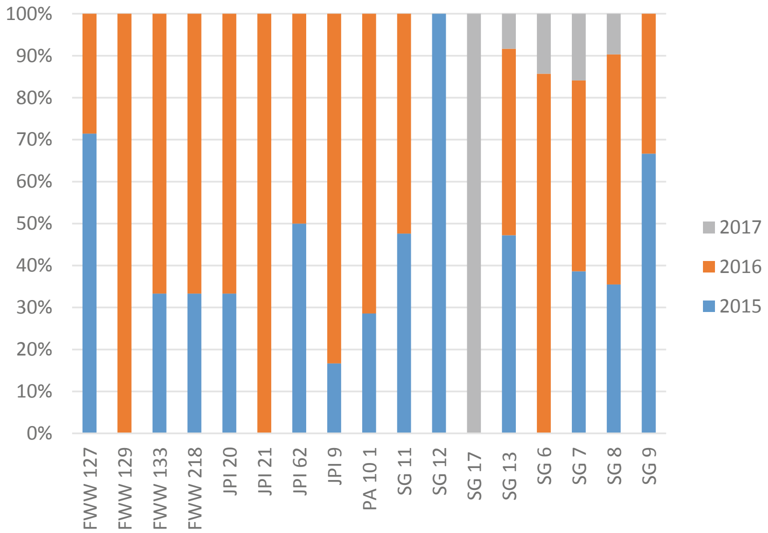


**Fig. 1** The occurrence of energy-related grand challenges in business media. *Notes* FWW—"The Future We Want" (the figure indicates the article number), JPI—Johannesburg Plan of Implementation (the figure indicates the article number); PA—Paris Agreement (the figure indicates the article number), SG—Sustainable Development Goals (the figure indicates the goal number). *Source* Intelligent Foresight Analytics (iFORA©)

i.e. the National Sustainability 3.0. These frameworks are grounded in the global sustainability challenges and assess to which extent countries, companies and civil society organizations address them. This makes global goals relevant to various actors and adjustable to their institutional context [12].

Of other challenges the most covered were articles 127 and 218 of "The Future We Want" (related to changing the energy mix to meet developmental needs, promoting sustainable modern energy services and the reduction, reuse and recycle of waste), followed by the Johannesburg Plan of Implementation articles 9 and 62, and the Paris Agreement.

The issues related to proper waste management (including hydrocarbon exploration, production and use of waste; and waste-to-energy) also appeal to business, as this approach contributes to cutting costs, resource saving and building good reputation. Companies also join forces in ecological industrial parks that are meant to coordinate efforts to reduce waste, improve environmental performance and raise economic benefits [39]. The waste topic is relevant to FWW, SDG11 and JPI.

The variety of terms related to grand energy challenges selected for this study is higher in news media compared with business media (Fig. 2). The most common are SDG7, SDG8, SDG9, SDG11, and SDG13, with the last one clearly leading amongst others. The most covered topics are related to social changes caused by application of new energy and resource technologies, such as renewable energy, water use, and

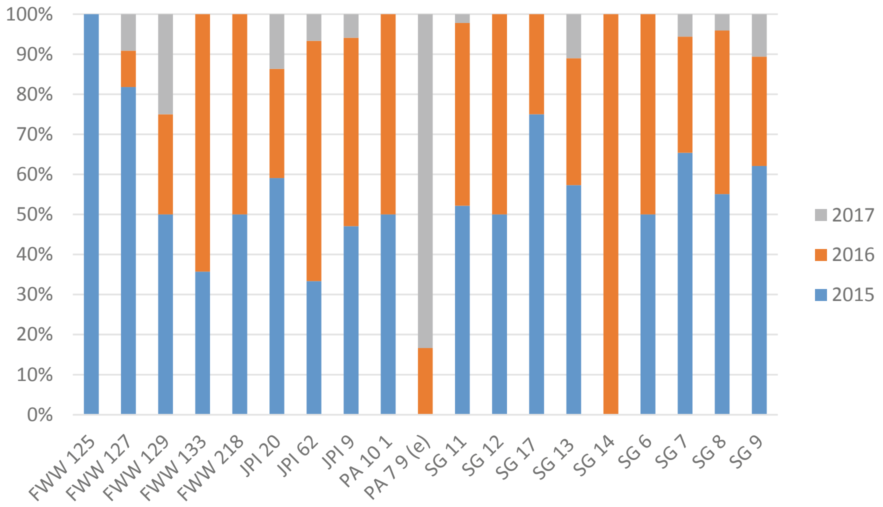


**Fig. 2** The occurrence of energy-related grand challenges in news media. *Notes* FWW—"The Future We Want" (the figure indicates the article number), JPI—Johannesburg Plan of Implementation (the figure indicates the article number); PA—Paris Agreement (the figure indicates the article number), SG—Sustainable Development Goals (the figure indicates the goal number). *Source* Intelligent Foresight Analytics (iFORA©)

climate change (related to SDG7), urban transformation analyzed through the social lens (for SDG 11), and corporate social responsibility (for SDG 8).

The most commonly addressed challenges are similar to those SDGs that are most represented in business media, with the exception of SDG13 ('Take urgent action to combat climate change and its impacts'), which is the most popular in news media. Another difference is that in business media SDG6—'Ensure access to water and sanitation for all'—yields high occurrence.

Climate change is dominating news media due to a wide array of present day and imminent future consequences that many communities already face, including health and equity implications. Researchers also mark an important role of public opinion and civil society actions, including the financial support channelled through private foundations [100], while business and government climate finance can ensure fair energy access. Media interest is also explained by a set of social effects arising from climate change mitigation actions that range from increased employment in rural areas due to renewable electrification [30] to decreasing the rates of premature deaths and disability adjusted life years [45].

The resource constraints and nexus solutions, especially in poor countries and neighbourhoods, also attract media attention. This is related to safe drinking-water impacts on people's livelihoods, well-being and health [50]. Other socially important issues are related to trade-offs between agricultural production that generated income to local (often poor) population and resource conservation (global wellbeing) [101].

The reason why SDG8 is also somewhat popular in news media lies in its substantial social implications. It addresses the "right to work, to free choice of employment, to just and favourable conditions of work and to protection against unemployment" stated in the Article 23.1 of the Universal Declaration of Human Rights and so fiercely protected by people in different countries through labour unions, peaceful demonstrations, strikes and civil disobedience actions [102]. The popularity of this SDG in both social and business media could be explained by a possibility of two-sided approach: a business view promoted by the International Organisation of Employers and a human right perspective represented by the International Trade Union Confederation and human rights NGOs [70].

Research papers (Fig. 3) cover all the energy-related grand challenges, identified for this study. Energy challenges identified in SDG8—'Promote inclusive and sustainable economic growth, employment and decent work for all'—received the highest attention from researchers. Other most researched SDGs include SDG6, and SDG11. The most popular topics here include application of emerging technologies for advancement of existing energy systems: new models and methods of ecosystems assessment (for SDG6), renewable energy technologies (for SDG7), and technologies to tackle air pollution (for SDG11).

Unlike social and business media, where the attention to most popular energy challenges was decreasing in 2015–2017, the number of research publications during the same period was increasing for most topics. Besides the mentioned SDGs, energy

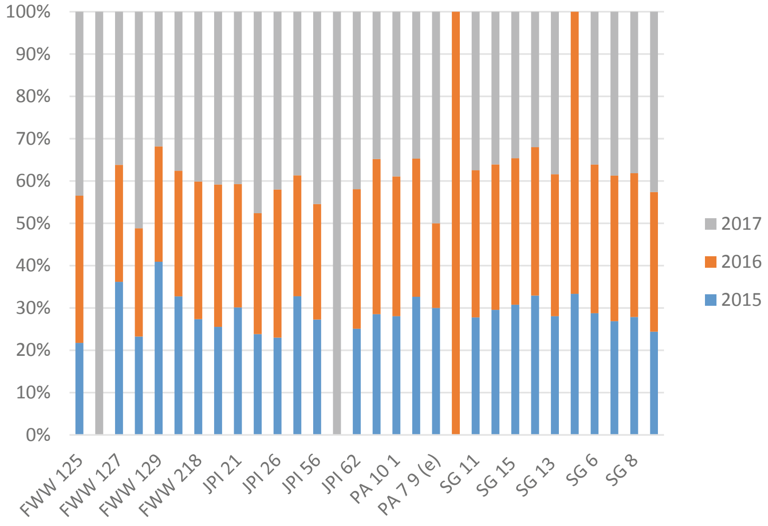


**Fig. 3** The occurrence of energy-related grand challenges in research articles (Web of Science, 2015). *Notes* FWW—"The Future We Want" (the figure indicates the article number), JPI—Johannesburg Plan of Implementation (the figure indicates the article number); PA—Paris Agreement (the figure indicates the article number), SG—Sustainable Development Goals (the figure indicates the goal number). *Source* Intelligent Foresight Analytics (iFORA©)

challenges mostly covered by research articles are related to article 218 "The Future We Want" (resource efficiency and waste management) and article 20 of the Johannesburg Plan of Implementation (focusing on a wide array of energy challenges, including technology transfer and financial tools to support energy services for the benefit of developing countries; promoting energy efficiency, affordability and accessibility; increasing the use of renewables, etc.).

Studies devoted to resource efficiency often focus on the problems and solutions associated with the water-food-energy use. For instance, the salinization of streams and rivers is caused by poor irrigation practices, salt pollution originating from road de-icers, urban runoff, domestic and industrial wastewater, and mining operations. Due to numerous causes, researchers offer different interlinked approaches to addressing this problem that relate to SDGs 2, 6, 7, 12, and 15 [4].

Energy-related targets of SDG 6, SDG7, SDG8, SDG9, SDG11, and SDG13 rank high in both research and media publications. At the same time, some topics appear to be less popular in various types of media. Of all SDGs less attention is given to SDG1 ('End poverty in all its forms everywhere'), SDG12 ('Responsible consumption and production'), SDG14 ('Conserve and sustainably use the oceans, seas and marine resources'), SDG15 ('Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss'), and SDG17 ('Revitalize the global partnership for sustainable development'). Most energy issues identified in the Johannesburg Plan of Implementation (i.e. articles 21, 22, 26, 41, 56, 59) did not receive much coverage.

Comparing the coverage of energy-relates challenges in research articles and business media, the most commonly addressed are topics related to SDG 6, SDG7, SDG8, SDG9, SDG11, and SDG13. These are followed by articles 9 ('improve access to reliable and affordable energy services for sustainable development'), 20 ('diffusion of environmentally sound technologies'), 21 ('promoting sustainable transport systems and services'), and 62 (tackling energy problems in Africa) of the Johannesburg Plan of Implementation and articles 127 ('increased use of renewable energy sources and other low emission technologies'), 133 ('sustainable transport systems'), 129 ('"Sustainable Energy for All" initiative'), and 218 ('reduce, reuse and recycle of waste') of "The Future We Want", and the Paris Agreement (article 10 related to technologies for better resilience to climate change greenhouse gas emissions reduction).

Finally, the highest attention of various media sources is given to challenges outlined in SDG 6, SDG7, SDG8, SDG9, 11, and SDG13. Further, substantial attention is also devoted to issues raised in articles 218 and 133 of "The Future We Want", articles 9 and 62 of the Johannesburg Implementation Plan and articles 10 (item 1) and 7 (item 9e related to resilience of socioeconomic and ecological systems through sustainable use of natural resources) of the Paris Agreement.

As it was shown, SDG8 has been consistently dominating the research and business media agenda. The reason is that business interest often dominates decision-making in actions that contribute to achieving SDG8 (and SDG12), i.e. introduction of resource efficient and resource saving practices. Studies suggest that the primary driver could be the economic benefit gained through reduced resource use (and respective cost-savings) along with pressure from internal and external stakeholders [99].

## 5 Conclusions

The distribution of research papers that contribute to addressing grand energy challenges identified in this study do not confirm the importance or low significance of a particular challenge. Clearly, one breakthrough study could have a more profound effect than dozens of studies proposing incremental improvements. However, the big data analysis shows the bigger picture, reflecting information and research gaps, serving as a reference point for policymakers.

The analysis of attention given by researchers, business and news media to energy-related grand challenges has revealed the 'hot' topics, gaps, and prospective areas that should be explored in greater detail. The study empowered with the big data analysis highlighted very low coverage of global energy challenges by media, while researchers scrutinize many more challenges with a focus on several SDGs. The review of selected research papers showed that unlike the media, where attention to the majority of issues has decreased over the last three years (2015–2017), researchers have increased interest to all topics. If the media covers only a selection of challenges, research papers tackle all of the energy issues identified for analysis.

The relatively low attention to most energy challenges from researchers with the exception of several SDGs also signifies that scientific studies and projects need to be reinvigorated. Specifically low coverage is noted for topics raised by article 22 (energy from waste in developing countries), 26 (energy efficient desalination), 41 (the interrelation of extreme whether phenomena with energy), 56 (the interrelation of respiratory diseases and air pollution with fuel use), 59 (affordable energy services to island developing states) of the Johannesburg Plan of Implementation, the Paris Agreement article 2(b) (climate neutral energy policy), SDG1 ('End poverty in all its forms everywhere'), and some other.

It is evident that more efforts need to be applied by global and national institutions responsible for monitoring and facilitating the implementation of international agreements to increase the visibility of energy challenges and organize more awareness rising activities in the media. Constant translation of related research outcomes into news for non-expert audience could be one way to increase the visibility of effective responses to grand energy challenges. Media could also facilitate public debates and professional discussions on topics related to SDG implementation.

The differences in coverage of energy challenges by media and research papers testify to a limited number of most popular energy challenges that are constantly addressed by journalists and scientists (i.e. SDGs 7, 8. 9, 11 and 13, FWW articles 218 and 133). The comparisons in the topics' popularity also show some complementarity of different information sources, whereby a wider array of challenges is covered by a combination of different media sources and research papers.

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# Energy and Sustainable Development from Perspective of Energy Poverty

**Meltem Ucal**

**Abstract** End of poverty, the number one Sustainable Development Goal, focuses on ending all kinds of poverty all over the world. The elimination of all forms of poverty continues to be the biggest problem facing humanity today. The most important problems that have been encountered since the beginning of the energy use are the increasing risk of deterioration of energy supply, energy production and energy poverty. The problem of energy poverty among them is widely mentioned in the literature. In general, the studies on the subject focus on how the problem is defined worldwide, its size, its consequences, the obstacles to the elimination of the problem and some solution opportunities. The term "energy poverty" can refer to two different socio-economic issues, depending on the geographical scope of its application: energy affordability in higher income and developed states; inadequate access to "modern" energy services in most low income or developing countries". Poor people pay a high price for the energy they use, either in cash or by labor. In addition, poor households spend more on energy than wealthy people, not only because their income is much smaller, but also because the fuels and equipment they use are much less efficient than modern fuels and equipment. No country has been able to diminish energy poverty to a great extent without increasing energy use. Decreasing the global inequality in energy is key to reducing income, gender and an inequality in other dimensions such as rural/urban income gaps. From this perspective, the importance of the relationship between energy poverty and sustainable development will be discussed by making comparisons by taking the country cases into consideration in the context of energy efficiency and renewable energy. The regional understanding of these concepts will also be discussed in this context.

**Keywords** Household energy use · Energy-poor households · Energy poverty · Sustainable development · Sustainable development goals · Energy efficiency · Renewable energy

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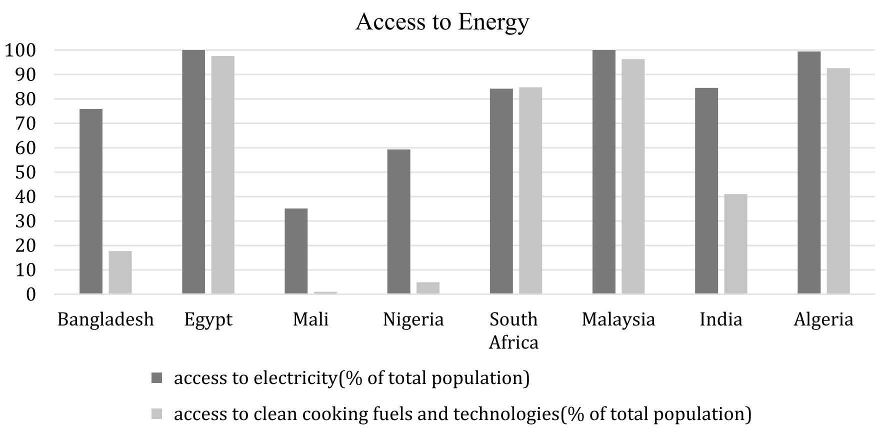
## 1 Introduction

It is widely estimated that more than 50 million households in the EU suffer from energy poverty due to energy-efficient buildings and appliances, high energy expenditure, low household income and basic household needs [1]. It was also estimated that almost 840 million people in the world have no access to electricity in 2017. Furthermore, according to these estimations, 650 million will still have no electricity access by 2030 [2]. In addition, it is notable that 3 billion people in the world have no access to clean cooking fuels [3].

Although world's energy issues are not mentioned in Millennium Development Goals (MDGs) explicitly, achieving universal access to affordable, reliable, sustainable and modern energy for all has an important place in Sustainable Development Goals (SDGs) agenda. Therefore, the seventh goal of the SDGs (Target SDG 7.1) aims to provide affordable, reliable, sustainable and modern energy access for all by 2030 as well as taking into account the direct link between household access to energy, consumption and poverty and development. While Target 7.2 highlights the importance of increasing renewable energy use by 2030, Target 7.3 emphasizes the importance of doubling the global rate of improvement in energy efficiency by this year (The United Nations Sustainable Development Goals Knowledge Platform [4].

Graph 1 shows the 2016 energy access data for selected countries, which will be discussed later as case studies.

In this graph, Mali and Nigeria are the worst ones among countries in terms of levels of access to electricity and clean cooking fuels and technologies. Generally, the countries that have improved electricity access lack access to clean cooking fuels and technologies except the case of South Africa. However, it is important to note that one should be aware of household affordability issue in the context of energy poverty instead of only looking at the accessibility issue in these countries.




**Graph 1** Access to electricity and access to clean cooking fuels (% of total population). *Source* Sustainable energy for all (SE4All) database. World Bank (2020) [5]

It is also important to look at the changes in energy intensity levels in these countries by years. Table 1 shows the relevant data below.

According to the table, South Africa has the highest energy intensity levels among other countries although the levels have not constantly increased over the years. It is seen that Nigeria follows South Africa. Mali has the lowest energy intensity levels among others however; its energy intensity level has increased up to 2.8 by 2015.

Graph 2 shows the changes in renewable energy levels in selected countries in 2010–2016 below.

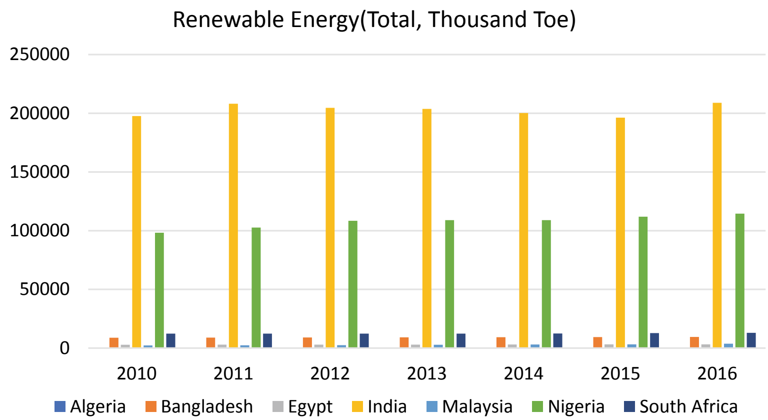
According to the results obtained from the graph above, India and Nigeria has achieved by far the highest renewable energy levels.

It is also important to look at renewable energy share of total final energy consumption (%) in selected countries. Graph 3 can be seen below.

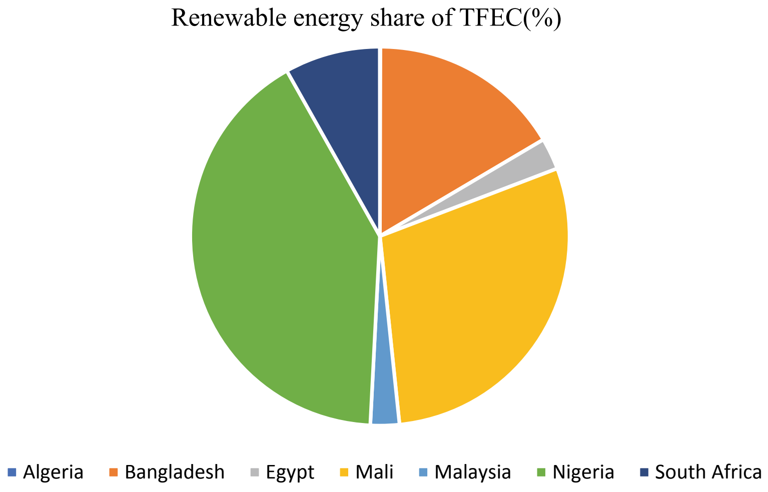
**Table 1** Energy intensity levels of primary energy (MJ/$2011 PPP GDP)

| Countries | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|---|---|---|---|---|---|---|
| Algeria | 3.6 | 3.7 | 3.9 | 3.9 | 4.1 | 4.1 |
| Bangladesh | 3.4 | 3.3 | 3.3 | 3.2 | 3.1 | 3.1 |
| Egypt | 3.7 | 3.8 | 3.8 | 3.6 | 3.7 | 3.5 |
| India | 5.4 | 5.2 | 5.2 | 5.0 | 5.0 | 4.7 |
| Malaysia | 5.2 | 5.1 | 4.9 | 5.3 | 5.1 | 4.7 |
| Mali | 2.4 | 2.3 | 2.0 | 1.9 | 2.0 | 2.8 |
| Nigeria | 6.1 | 6.2 | 6.3 | 6.0 | 5.6 | 5.7 |
| South Africa | 9.7 | 9.3 | 9.0 | 8.8 | 9.0 | 8.7 |

*Source* World development indicators database. World Bank [6]




**Graph 2** Renewable energy (Total, Thousand Toe, 2010–2016). *Source* OECD [7]




**Graph 3** Renewable energy share of total final energy consumption (%). *Source* Sustainable energy for all (SE4All) Database. World Bank [8]

According to the table, Nigeria has the largest share of renewable energy in total final energy consumption while the share of renewable energy in Egypt is quite low in 2015.

The next table will show the percentage of electricity access and access to clean cooking fuels and technologies, renewable energy consumption and energy intensity levels of primary energy in 2010–2015 in selected European Union countries.

Table 2 shows that the countries generally increase their renewable energy consumption levels every year. Also, it can be said that they have no energy accessibility issues.

Finally, Table 3 will show the percentage of population who have access to electricity and clean fuels and technologies for cooking, renewable energy consumption and energy intensity level of primary energy in selected BRICS countries, namely Brazil, Russia and China.

According to the table, Brazil, China and Russia mostly achieved universal access to electricity and clean fuels and technologies for cooking. Both Brazil and China reached high levels of renewable energy consumption.

In the following section, it will be discussed the relationship between energy poverty and sustainable development considering the importance of energy within the context of sustainable development. In the third section, it will be mentioned reasons of energy poverty and potential ways to eliminate energy poverty and achieve sustainable development. In the fourth section, it will be discussed various case study examples from different regions emphasizing the importance of transition

**Table 2** Modern energy access, energy consumption, and energy intensity level in selected European countries

| Lithuania | Access to electricity (% of total population) | Access to clean fuels and technologies for cooking (% of total population) | Renewable energy consumption(TJ) | Energy intensity level of primary energy (MJ/2011 USD PPP) |
|---|---|---|---|---|
| 2010 | 100,0 | 100,0 | 42,569.7 | 4,6 |
| 2011 | 100,0 | 100,0 | 44,837.4 | 4,5 |
| 2012 | 100,0 | 100,0 | 48,282.4 | 4,4 |
| 2013 | 100,0 | 100,0 | 51,772.4 | 4,0 |
| 2014 | 100,0 | 100,0 | 55,507.0 | 3,8 |
| 2015 | 100,0 | 100,0 | 57,858.6 | 3,9 |
| Poland | Access to electricity (% of total population) | Access to clean fuels and technologies for cooking (% of total population) | Renewable energy consumption (TJ) | Energy intensity level of primary energy (MJ/2011 USD PPP) |
| 2010 | 100,0 | 100,0 | 257,873.1 | 5,2 |
| 2011 | 100,0 | 100,0 | 276,416.4 | 4,9 |
| 2012 | 100,0 | 100,0 | 287,378.6 | 4,7 |
| 2013 | 100,0 | 100,0 | 295,061.8 | 4,6 |
| 2014 | 100,0 | 100,0 | 290,342.5 | 4,3 |
| 2015 | 100,0 | 100,0 | 302,285.7 | 4,1 |
| Czech Rep. | Access to electricity (% of total population) | Access to clean fuels and technologies for cooking (% of total population) | Renewable energy consumption (TJ) | Energy intensity level of primary energy (MJ/2011 USD PPP) |
| 2010 | 100,0 | 96,8 | 110,296.4 | 6,3 |
| 2011 | 100,0 | 96,8 | 118,405.7 | 6,0 |
| 2012 | 100,0 | 97,0 | 124,598.5 | 6,0 |
| 2013 | 100,0 | 97,1 | 134,716.0 | 5,9 |
| 2014 | 100,0 | 97,1 | 139,034.7 | 5,7 |
| 2015 | 100,0 | 97,2 | 142,773.3 | 5,5 |

*Source* Sustainable energy for all (SE4All) database. World Bank [9]

to renewable energy sources from fossil fuels. Finally, the chapter concludes with proposed policy recommendations.

**Table 3** Modern energy access, energy consumption, and energy intensity level in selected BRICS (Brazil, Russia, China) countries

| Brazil | Access to electricity (% of total population) | Access to clean fuels and technologies for cooking (% of total population) | Renewable energy consumption (TJ) | Energy intensity level of primary energy (MJ/2011 USD PPP) |
|---|---|---|---|---|
| 2010 | 93,8 | 93,7 | 3,819,419.0 | 3,9 |
| 2011 | 95,8 | 94,1 | 3,838,202.0 | 3,8 |
| 2012 | 97,0 | 94,5 | 3,798,796.0 | 3,9 |
| 2013 | 97,3 | 94,8 | 3,772,010.0 | 3,9 |
| 2014 | 97,8 | 95,1 | 3,788,991.0 | 4,0 |
| 2015 | 98,2 | 95,4 | 3,887,176.0 | 4,1 |
| *China* | Access to electricity (% of total population) | Access to clean fuels and technologies for cooking (% of total population) | Renewable energy consumption (TJ) | Energy intensity level of primary energy (MJ/2011 USD PPP) |
| 2010 | 98,0 | 54,9 | 7,871,450.0 | 8,7 |
| 2011 | 99,5 | 55,7 | 7,655,961.0 | 8,5 |
| 2012 | 99,8 | 56,4 | 8,069,989.0 | 8,2 |
| 2013 | 100,0 | 57,2 | 8,275,653.0 | 7,9 |
| 2014 | 100,0 | 57,8 | 8,744,472.0 | 7,1 |
| 2015 | 100,0 | 58,5 | 9,084,482.0 | 6,7 |
| *Russia* | Access to electricity (% of total population) | Access to clean fuels and technologies for cooking (% of total population) | Renewable energy consumption (TJ) | Energy intensity level of primary energy (MJ/2011 USD PPP) |
| 2010 | 100,0 | 97,2 | 532,164.3 | 8,7 |
| 2011 | 100,0 | 97,4 | 529,602.0 | 8,8 |
| 2012 | 100,0 | 97,6 | 536,201.0 | 8,7 |
| 2013 | 100,0 | 97,8 | 576,382.2 | 8,5 |
| 2014 | 100,0 | 98,0 | 547,443.0 | 8,3 |
| 2015 | 100,0 | 98,2 | 522,370.1 | 8,4 |

*Source* Sustainable energy for all (SE4All) database. World Bank [10]

## 2 Understanding the Relationship Between Energy Poverty and Sustainable Development

Energy is related to sustainable development because it is a source of environmental stress, it is a principal motor of macroeconomic growth and it is also a prerequisite for meeting human needs. These basic characteristics of energy easily harmonize with environmental, economic and social dimensions of sustainable development [11]. In addition, the level of economic development is closely related to the per capita energy consumption in a particular country. On one hand, energy is of utmost importance for economic and social development. It is important for any country to review their energy policy so as to ensure long-term reliability and security of energy-supply. On the other hand, local environment degradation may result from energy production. At this point, effective and sustainable energy policy comes into prominence [12]. Therefore, following current trends within the context of sustainable development and energy is important. It is understood that the current production and consumption models are not adequate since the use of resources is not efficient and this situation leads to environmental load and social inequality. Thus, it is required a paradigm shift towards sustainable economy [13]. In this context, examining the interlinkages between energy, environment and sustainable development has become essential. At first, putting energy resources that cause no environmental impact should be at the core of achieving sustainable development [14].

Energy poverty affects human health, economic development and environmental sustainability in a negative way all over the world, especially in the rural areas of Sub-Saharan Africa, South and East Asia, and Latin America in terms of access to electricity, heating and cooking. Access to affordable energy and efficient and sustainable use of modern energy sources are essential for alleviating poverty since they are critical in achieving economic and social development [15]. Examining energy technologies, business models and policies that promote sustainable development also show the importance of energy in the context of sustainable development since energy access is seen as an important precondition for socio-economic progress [16].

It must be known that modern energy services help poor people to enhance their lives in many ways. Saving extra hours for work and errands or improving communication through radios or cellular phones may become possible due to access to electricity. Using modern cook-stoves is a healthy alternative for women and children because these cooking appliances protect them from negative effects of indoor air pollution [15]. Therefore, access to clean and modern energy as well as reducing wasteful energy subsidies and curbing deadly air pollution play an important role in achieving sustainable development goals [17]. This goal also has a positive impact on other SDG goals; including gender equality, environmental protection, climate action and sustainable cities as well as health and well-being (WHO, IEA, GACC, UNDP and [18].

Renewable energy as one of the contributors to reducing energy poverty also contributes to sustainable development in the sense that it helps improve access to modern energy services and technologies for the poorest members of society. The concept of sustainable development is interested in the concerns about relationships between human society and nature. Although it is important to evaluate the exact contribution of renewable energy to the concept of sustainable development in a country-specific context, it is possible for renewable energy to contribute to a number of important sustainable development goals. These goals are divided into four categories: social and economic development, energy access, energy security, climate change mitigation and the reduction of environmental and health impacts [19, 20].

It is also possible to mention different incentives and socioeconomic sustainable development goals so as to advance renewable energy. They may also reduce energy poverty in return. According to this, renewable energy (RE) can be promoted with the help of the creation of employment opportunities and can be developed through actively promoting structural change especially in the economy of the industrialized countries. Since the associated costs of renewable energy are an important factor in order to meet increasing energy demand, an international burden-sharing regime comes into prominence. Contrary to fossil fuels, renewable energy will support the sustainable development goals to mitigate negative environmental impacts from energy systems [19]. It is also known that the use of renewable electricity leads to a reduction in carbon dioxide emissions, helps reduce costs, which are associated with fossil fuels, create jobs worldwide, helps improve standards of living in industrialized countries and improves energy security [20].

The importance of energy efficiency in the context of sustainable development should also be highlighted because reconciling economic competitiveness with sustainable development is quite possible through enhanced energy efficiency. As [21] emphasizes the importance of achieving sustainable development with the help of sustainable energy resources in his seminal work, using sustainable energy resources should be crucial in this process; however, it is also necessary to increase the efficiency of processes that utilize these resources.

Energy efficiency also helps reduce the cost of energy and increase productivity. One of the most important examples is improved residential and public sectors because they have a wide range of social, environmental and economic benefits such as energy security, job creation, poverty alleviation, improved health, and reduced greenhouse gas emissions (United Nations Development Program [UNDP] [22].

Within the context of sustainable development, energy efficiency can be examined also considering its impacts on carbon reduction, climate change, adaptation and mitigation, and employment and poverty reduction. It is also very important to substitute fossil fuels with renewable resources so as to solve many challenges associated with energy poverty [23]. For instance, energy efficiency and renewables can help reduce energy poverty by improving the quality of homes and reducing the energy cost burden and the need for subsidies to low income households in Europe [24].

In order to ensure sustainable development, it is necessary for countries to be able to use energy with maximum benefit and minimum environmental damage. It should not be forgotten that the cheapest, fastest and the most environmental-friendly way of meeting an important part of energy need is improved energy efficiency [25]. Also, the global energy system relieves the stress through the use of improved energy efficiency and cost-effective energy technologies. Therefore, the transition to low-carbon energy system from the current one is necessary to ensure access to affordable, reliable and sustainable energy for all [26].

It is crucial to understand the importance of sustainable energy access for the concept of sustainable development. If countries aim to achieve sustainable development, then they should also consider achieving access to sustainable energy for all. In other words, it is almost impossible to think these concepts apart since energy is the largest industrial sector in the world and it provides essential input to many goods and services that are provided in the economy. At this point, it is also important not to forget significant influence of energy services on productivity, health, education, food and water security, and communication services [27].

## 3 Potential Possibilities for Eliminating Energy Poverty and Achieving Reliable, Sustainable and Affordable Energy in the World

In order to eliminate energy poverty, promoting energy efficiency is essential. There are many important steps that should be taken to promote energy efficiency. It is required a complex combination of research and development activities, public and private investments in energy infrastructure, new regulations and urban planning. At this point, both national and international policies come into prominence. Achieving energy efficiency improvements may be possible through market mechanisms and new business models [26].

That being the case, it is necessary to adopt the perspective of energy efficiency and renewable energy in every nation so as to achieve an efficient, reliable and decentralized energy economy. In order to develop and apply renewable energy and its technologies, developing, promoting and harnessing the Renewable Energy (RE) resources of the country and incorporating the viable ones into the national energy mix is essential. In addition, promoting decentralized energy supply based on Renewable Energy (RE) resources in rural areas is especially important. Besides, de-emphasizing and discouraging the use of wood as fuel is also necessary. At this point, promoting the use of alternative energy sources to fuel wood, efficient methods in the use biomass energy resources, promoting biomass as an alternative energy resource especially in the rural areas and finally keeping abreast of international developments in renewable energy technologies and applications come into prominence [28].

A number of recommendations can be made for improving the potential of renewable energy, which in turn possibly leads to energy poverty reduction. These recommendations include ensuring policy coherence and stability, enhancing the penetration of renewable energy deployment, eliminating destabilizing fossil fuel subsidies, facilitating sustainable energy inclusion, undertaking local action to promote renewable energy uptake and having accurate and current energy data so as to monitor advancements in a renewable energy transition [29].

Securing a sustainable, affordable, and climate-friendly future for this generation and many to come could be possible if bringing knowledge and experience together in partnerships at all levels, establishing renewable energy targets for individual energy markets as shares of projected demand in the electricity, heat and transport sectors, phasing out fossil fuel subsidies and using taxes and regulations so as to promote market conditions in which renewable energy can compete, encouraging the expansion of renewable energy technologies for decentralized applications, which are already cost-competitive with conventional fuels, utilizing public funds to leverage and incentivize large-scale private investment in developing countries and investing in research, development, and deployment of cheaper and more efficient clean-energy technologies and adapting them for use in developing countries are achieved [30].

The importance of the expansion of generation capacity and transmission and distribution networks should also be considered in order to achieve universal electricity access within the context of sustainable development. For example, in rural areas of Sub-Saharan Africa, cost-effective off-grid systems such as mini-grids and stand-alone systems may play an important role in enhancing electricity access. At this point, public funding comes into prominence [31].

Energy conservation is essential concept for achieving sustainable development since reduced energy consumption can benefit consumers and society as a whole. Reducing emissions of greenhouse gases and other pollutants into the environment is possible through energy conservation [7]. Preventing environmental problems that result from harmful pollutant emissions may be possible through some solutions such as renewable energy technologies, switching from fossil fuels to environmentally benign energy forms, coal cleaning technologies, monitoring and evaluating energy indicators, policy integration, increasing public awareness, education and training, etc. [32].

The Sustainable Energy for All Global Action Agenda also emphasizes the importance of setting goals, developing policies and regulations and creating incentive plans, which link energy to economic development for low and middle-income countries. What industrialized countries also need to do is to prioritize efficiency and renewable energy for achieving sustainable energy in their countries. At this point, it is important to combine several sectoral action areas, which generate power and consume relatively more energy in order to achieve basic access to improved quality of life and well-being. These action areas are modern cooking appliances and fuels, distributed electricity solutions, grid infrastructure and supply efficiency, large-scale renewable power, industrial and agricultural processes, transportation and buildings and appliances [27].

The most important steps to be taken in terms of supporting sustainable development using affordable, reliable, sustainable and modern energy sources are to increase the energy efficiency in the industry, construction and transportation sectors, reduce the use of less efficient coal-fired power plants and forbid their constructions, increase the investment of renewable energy, phase out the subventions in the fossil fuel consumption, reduce the methane emission in the production of oil and gas, distribute sufficient and reasonable priced energy resources to the regions where there is no energy service, encourage energy efficiency, provide widely use of advanced energy technologies, focus on research and development activities to improve new and advanced energy technologies, encourage the use of environmental-friendly energy resources such as renewable energy, empower the energy regulations, contribute the free and open trade to the energy market and security, improve international cooperation and connections, etc. [25].

In order to advance the seventh goal of sustainable development goals (SDGs) implementation and to emphasize various possibilities for achieving sustainable energy use, SDG7 advisors make their recommendations to all stakeholders under the roof of United Nations. These recommendations are making clean-cooking solutions a top political priority, putting in place specific policies, cross-sectoral plans and public investments; closing the electricity access gap with the help of detailed action plans nationally, regionally and globally; accelerating the pace of transition towards renewable energy in transport, buildings and industry; harnessing the potential of decentralized renewable energy solutions as a key to universal energy access and empowerment of people, companies and communities; scaling up investments in energy efficiency across all sectors of the economy; doubling the financing for SDG7 globally; scaling up capacity-building and education with renewed, cross-sectoral approaches so as to develop human and institutional capacities and required skills for achieving universal access to energy and transformation of the energy sector; enhancing innovation systems, including research, development, deployment and diffusion in the design and operation of the whole energy system and finally, investing in data collection systems and data analysis so as to ensure effective monitoring of the SDG7 targets [33].

At this point, government institutions of good quality, effective government intervention and the genuine engagement of institutional stakeholders such as NGOs and civil society organizations are undeniably important on the subject of achieving the UN sustainable development goals. It is important to mention that the seventh goal of Sustainable Development Goals does not seem realistic if the institutional conditions are not good enough in a country [34].

## 4 Renewable Energy and Energy Efficiency Within the Context of Sustainable Development: Case Studies from Various Countries

The success of Bangladesh on the diffusion of renewable energy technology is evident although there are some constraints such as geophysical condition, remoteness of households, financial constraints to enhancing grid performance of electricity in the region. However, it may be better to focus on improving socio-economic conditions and alleviating the problem of increasing poverty in the rural areas since they pose significant constraints to larger penetration of renewable energy technology to provide electricity and other clean energy sources [35].

South Africa has a great potential for the solar energy radiation and wind energy. Similarly, Egypt has a great solar capacity and this means a great potential for solar thermal power generation in the country. The country has also a great source of wind energy. Nigerians mostly live in rural areas and they use fuel wood as a source of energy. Therefore, a transition to the alternative energy sources from fossil fuels is crucial in the country. Based on these data, it is not hard to say that the region can solve its energy issues especially with the help of appropriate infrastructural support [36]. There are also some problems of the supply of clean energy services to the urban and peri-urban poor in South Africa. The main problem of the majority of the poor is not access to electricity but the ability to afford it. Besides, it is necessary to identify and target the indigent by municipalities and also identify appropriate fuels for the urban poor in the region. Also, it is important to establish integrated urban energy centers to enable households to have immediate access to information and energy sources [37].

Affordable, modern energy services and alternative sustainable, renewable and efficient energy has an important role in ensuring long-term reliability and security of energy supply because non-renewable energy sources such as oil and coal cause an increase in the emission of greenhouse gases, thereby raising the issue of climate change in Malaysia. Also, non-renewable energy sources have disastrous impact on the socio-economic development in the country [12].

Denmark has a substantial potential for intermittent renewable sources however, the country unfortunately utilizes only a small share of these sources. It is important to introduce and add flexible energy technologies and design integrated energy system solutions for sustainable energy strategies so as to achieve sustainable development [38].

When it comes to the current situation of EU structural funds for sustainable energy development in the new EU member states, namely Lithuania, Poland and Czech Republic, it may be suitable to propose an integrated approach for solving market failures in achieving sustainable energy development. Dealing with energy externalities, energy affordability, and providing energy security, etc. are very important for overcoming energy market failures in these countries. Organizing institutions and implementing support measures, etc. is essential for sustainable energy development. Also, more rationality and orientation towards sustainable energy development is required for using EU Structural Funds in these states [39].

There are some constraints to/challenges of the access to clean energy sources in urban and peri-urban poor areas in Delhi, India. These are data collection issues on urban poor and on energy access on one side and the lack of effective subsidies that target the poor people, rapid expansion of urban areas, creation of slums, and inequities in the provision of basic urban services, which imply problems in urban planning processes, lack of information about access to clean energy in urban policies and finally lack of awareness and incentives to make use of clean energy sources on the other side [40]. The economic barriers to achieving renewable- based rural electrification system in India are regarded as the lack of subsidies, high initial capital costs and high transaction costs for small decentralized system. These obstacles especially affect low-income consumers in India [41].

Renewable energy can be used in the context of sustainable development so as to enhance economic development, advance energy security and energy access, and mitigate climate change in India. In order to make use of renewable energy technologies, comprehensive policies and regulation frameworks are required. In addition, explicit policies and legal procedures should be developed in order to enhance the attention of investors. The country should also focus on research and development activities (R&D) in order to overcome problems related to inadequate technology and the absence of infrastructure, which is required to establish renewable technologies.

Besides these problems, the country should also cope with the issue of unreliable connectivity to grid [42].

The demand for electricity has increased because of growing population in Algeria. Therefore, the importance of renewable energy comes into prominence in the country. Since Algeria has the relatively low share of renewable energy sources in its primary energy supply compared to the European countries, the Algerian government aims to increase the use of renewable energy technologies through specific programs that limit energy demand and enhance environmental conditions in public or private sectors [43].

Nigeria is a country with rich resources in terms of renewable energy such as hydropower, biomass, wind power, biogas, solar energy and geothermal power. However, 70 million people in Nigeria suffer from energy poverty. In other words, they have no access to clean, safe, cooking fuels and electricity and they use traditional biomass resources. The country faces various challenges such as cultural, religious and traditional issues, lack of required technology for renewable energy, inadequate funds, high cost of energy infrastructure, political factors, and low level of public awareness. Therefore, private sector participation and funding of renewable energy research is necessary. Involvement of several development partners such as the Department for International Development (DFID), United Nations Development Program (UNDP), United Nations International Children's Emergency Fund (UNICEF), and the World Bank is required for sponsorship and provision of loan for sustainable development and utilization of renewable sources. In addition, projects related to renewable energy should be implemented in accordance with activities in agriculture, small scale industrial enterprises and poverty alleviation in the country [44].

Reducing absolute poverty, enhancing gender equality and providing stability in alleviating energy poverty is very important in the Asian region. In order to alleviate energy poverty, sustainable, development-centred investment can be promoted. In order to achieve this, multi-actor partnerships between developing country governments, investors, and multilateral institutions play an important role [45].

There are some poverty problems in two Chinese provinces such as deficiency of income, malnutrition and a low energy consumption profile in terms of using firewood. Strengthening agricultural labor productivity and provision of agricultural loans can be considered as a reliable way to achieve sustainability in these provinces [46].

Research on the synergy between renewable energy and sustainable development goals (SDGs) within the context of the European Union can be quite interesting. One of the studies mentions that in order to achieve a lower renewable electricity price in the EU, SDG 8(decent work and economic growth) and SDG 12(responsible production and consumption) should be considered together [47].

Examining sustainable development goals within the context of BRICS (Brazil, Russia, India, China and South Africa) countries is also important. India aims to increase its renewable energy production by 40% in 2030 and to reduce carbon dioxide emissions intensity by 33–35%. China aims to reduce its carbon dioxide emission intensity by 60–65% with the help of solar energy capacity to be increased. Russia puts emphasis on developing sustainable renewable green energy. Among the countries, the best position arguably belongs to Brazil because the country makes benefit of renewable sources to a large extent so as to obtain its energy. South Africa falls behind these countries in terms of using renewable energy since the country still uses fossil fuels at a tremendous rate to provide its energy needs [48].

## 5 Conclusion and Discussions

Energy has a vital role in people's lives and lack of energy sources results in poor health, lower education levels, food insecurity, gender inequality, growing poverty, etc. Although electricity access has been accelerated in the least-developed and developing world in the last decade, it is important to speed up efforts to ensure access to affordable, reliable, sustainable and modern energy for all by 2030 within the context of sustainable development goals. While doing this, harnessing renewable energy sources is also necessary because climate change is one of the important warning signs that some things need to change. Since the extraction of fossil fuels contributes to the issue of global warming and lead to the problem of energy poverty, using low-carbon energy sources should be taken into consideration to achieve affordable, reliable, sustainable and modern energy for all.

In order to achieve universal access to modern energy sources, strengthening interlinkages between SDG 7 and other SDGs should not be forgotten. At this point, harnessing the potential of cross-sectoral interlinkages to maximize multiple benefits and synergies by promoting energy as an enabler for all the sustainable development goals; adopting a unified approach to achieve SDG7 along with meeting the goal of the Paris Agreement are important steps to strengthening interlinkages between the seventh goal of sustainable development goals and others. Integrating gender equality and women's empowerment into all energy actions is also necessary to improve sustainable development goals. Finally, promoting sustainable and low-carbon cities with affordable public transportation systems, prioritizing energy-efficient built environments and making use of clean energy sources for their needs are crucial steps to strengthen interlinkages between the seventh goal of SDG and other goals [33]. All of these policy proposals have an important role in fighting energy poverty because they provide a coherent and complementary approach towards the problem.

Since energy plays an important role both in people's lives and in achieving sustainable development, it would be better for relevant countries to focus on actions to be taken for eliminating energy poverty and to provide country-specific solutions that address sustainable energy for all. At this point, protecting vulnerable consumers (e.g. women, single mothers, pensioners, unemployed people, etc.) through energy subsidies is important. Also, because many people in the world (especially in the EU) have difficulty affording their energy bills, ensuring competitive market prices may help reduce the number of people who are in need. On the other hand, awareness campaigns towards households on how to use energy at homes will be helpful in terms of developing energy-saving behavior. Fostering energy efficiency and renewable energy sources and technologies also will play a significant role in energy poverty reduction. Subsequent studies are expected to help researchers and policy makers to better understand the role of energy in sustainable development and to reduce or eliminate energy poverty through the methods proposed.

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# Climate Change Adaptation and Mitigation in Sub-Saharan African Countries

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**Abstract** The impact of climate change and global warming is high on agriculture, food security, quality of life, human health, economic growth, and development in sub-Saharan African countries. Thus, there are ongoing global discussions on climate change adaptation and mitigation including the Kyoto Protocol; an international treaty which extends the 1992 United Nations Framework Convention on Climate Change (UNFCCC) that commits state parties to reduce greenhouse gas emissions caused by global warming, the 2012 Doha Amendment to the Kyoto Protocol, United Nations Development Programme climate change portfolio, United Nations Educational Scientific and Cultural Organization climate change awareness program, United Nations Environment Programme (UNEP) and other bodies efforts to reduce climate pollutants globally, Africa in particular. However, despite these

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interventions, there is little scholarly information discussing the extent to which the region's vulnerability to climate change on its economies and growing populations is addressed. Thus, this review paper examines the impacts of climate change and global warming in sub-Saharan African countries and strategies adopted to mitigate the effects on its environments and economy.

**Keywords** Climate change · Adaptation · Mitigation · Environmental protection

## 1 Introduction

Climate change poses a big challenge globally, and it is important to reduce its impact on improving the quality of life [1]. It is considered a big challenge facing society today, and it is steadily terrifying lives, and a growing body of knowledge has emphasized on the need to divert research attention towards increasing mitigation and adaptation mechanisms that will minimize its possible damaging effects [2]. The incidence of climate change has reduced development on agriculture, food security, ensuring good quality of life, human health, economic growth, and development [3]. Climate change is any alterations to the natural climate; although, the topology of the earth's climate has not been static from time. However, the current period of global warming is occurring more rapidly than in past times. Some greenhouse gas effects occur naturally in the atmosphere, while others are induced because of human activities [4], which include the burning of fossil fuels such as coal. Greenhouse gases (GHG) are the gaseous ingredients in the air that can be natural and evolution of human activities (anthropogenic). Water vapour ($H_2O$), nitrous oxide ($N_2O$), carbon dioxide ($CO_2$), methane ($CH_4$) and ozone ($O_3$) constitute the principal greenhouse gases on the planet that consume and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted on the global surface, in air and clouds [5]. However, considering the prolonged shift in annual mean values and seasonal patterns of precipitation, high temperature, and humidity leading to increased risk of floods, drought, and fire are predicted to occur in the future [6, 7, 8]. In addition, the decline in food and cash crop harvests are among some of the negative implications of climate change [9, 10, 4]. Thus, to reduce these impacts, climate change mitigation and adaptation concepts are often discussed. Mitigation measures are actions taken to curtail greenhouse gas emissions while Adaptation to climate change is a response that seeks to reduce the vulnerability of natural and human systems to climate change effects [5]. Examples of some of the mitigation measures include using fossil fuels more efficiently for industrial processes or electricity generation, switching from biomass to renewable energy, improving the insulation of buildings, and promoting reforestation in order to reduce the amount of carbon dioxide in the atmosphere [11, 12]. Other initiatives include ongoing global discussions such as the Kyoto Protocol, an international treaty that extends the 1992 United Nations Framework Convention on Climate Change (UNFCCC) that commits state parties to reduce greenhouse gas emissions caused by global warming and that caused by human-made $CO_2$ emissions and the 2012 Doha Amendment to the Kyoto Protocol, United Nations Development Programme (UNDP) climate change portfolio which has supported more than 140 countries to access funds to drive climate change initiatives since 2008, the ongoing United Nation Environment Programme (UNEP) adaptation policy aimed at food security projects in the Zambezi River Basin, Malawi, Zambia, Mozambique and the mitigation strategy aimed at supporting countries to reduce short-lived climate pollutants. Nevertheless, a large number of studies have focused on analyzing effects of climate change to cover developed countries where data are readily accessible and available although these discussions have not excluded African continent; since the latter is considered most vulnerable to climate change due to its inability to cope with the catastrophic effects of climate abnormalities. There are few studies to ascertain the extent to which the sub-Saharan African region's vulnerability to climate change variables on its economies and growing populations have been addressed. Therefore, given the threats still posed by climate change, an effective global agreement to mitigate and adapt to the impacts of climate change in Africa is pertinent [13]. Thus, the objective of this study is to review the extent of discussion on climate change, impacts on sub-Saharan African countries, mitigation and adaptation mechanisms applied to date with special focus on existing and potential future adaptation, mitigation mechanisms that can foster economic development and consequently save human lives.

## 2 Methodology

This is a review paper, and the researchers conducted a search of peer-reviewed journals indexed in the ISI Web of Science and Scopus available in Google Scholar. Reliable web resources on climate change variability, particularly those involving climate change adaptation and mitigation strategies in developing countries, were included. In addition, web resources discussing the impacts of climate change and steps taken so far to reduce these impacts in various regions were also considered.

### *2.1 Search Strategy*

Retrieved full-text articles were examined to select those to be included in the review. Full publications and web resources found not to meet the inclusion criteria were excluded. Search keywords were "Climate change" and Mitigation, "Climate Change" and Adaptation, "Climate Change" and Environmental Protection and "Climate Change" and Sub-Saharan African Countries.

### 2.2 Inclusion and Exclusion Criteria

Considered for inclusion are studies examining any form of governmental and non-governmental global interventions involving resources on international treaties, United Nations conventions to reduce greenhouse gas emissions, United Nations Development Programme on climate change, United Nations Educational Scientific and Cultural Organization and United Nations Environment Programme (UNEP) climate change awareness programmes.

## 3 Results

A total of twenty-six (26) peer-reviewed articles and seven (7) websites were consulted for this study, making a total of 33 valid resources. The conclusion and recommendation section for the study is inspired by the outcomes and recommendations provided by the recognized global bodies mentioned in Sect. 2.2 and those suggested by previous studies from all around the world, including studies conducted in sub-Saharan African countries. Thus, findings from the literature review are discussed under the following sub-headings:

### 3.1 Impacts of Climate Change in SSA

Global warming is regarded as a steady increase in the mean temperature of the planet [14]. This global condition is precipitated by the accumulation of Greenhouse Gas (GHG) emission through the burning of fossil fuels [15] and it is considered to have the major impacts on the climate through increasing temperature and reducing rainfall as witnessed in major parts of the world. The increasing temperature has led to ice melting and instability while increasing rainfall in some parts of the world has a corresponding increase in sea level, coastal overflowing, and erosion [16]. Climate change incidence has contributed to a poor harvest, and food shortage witnessed particularly in some parts of Africa (shown in Fig. 1) with estimated one out of four people malnourished and was the reason why governments of these developing nations could not provide the needed food supply for their growing population [16]. According to Isingoma [17], the effect of climate change on Africa will continue to rise due to its closeness to the equinoctial line and the consequences of these climate abnormalities are beginning to manifest in this region, and this is expected to continue if no action is taken to reduce global carbon emissions. The impacts include drought, variation in rainfall patterns, increasing temperatures, growing sea levels, and climate abnormalities. Further, the highlighted impacts have been linked to climate change, which inadvertently has negative impacts on the growth of the economy and energy security witnessed across Africa.


**Fig. 1** Climate change vulnerability in Africa (*Source* UNEP-GRIDA [18])

The population in developing countries is growing, and one of the challenges of agriculture is to meet this growth without compromising the need to conserve the local and global environment in the face of socio-economic development and global climate change. The changing climate is also responsible for resource problems beyond food instability [19], which will increase since the projected population and socio-economic is expected to double the current food requirement by the year 2050. Therefore, to meet this challenge in Africa, there is a need to double efforts towards ensuring food stability [20, 21]. The current global sea-level rise is about 0.2 m, and it is projected to rise to 1 m by the year 2100 [22]. The implication of this proportion of sea level growth in some coastal areas of countries like Nigeria, which include Port-Harcourt, Lagos, Warri, and Calabar, would indicate a metre rise in sea level thereby subjecting 3,400 $km^2$ coastal region of this region at risk of flooding. Climate change is continually impacting negatively on agriculture and food supply especially in tropical zones because greenhouse gas emissions have been projected to increase thereby putting additional 80 million people across southern Asia and Africa to some degrees of food shortage by the year 2080 [23, 24, 21]. Odjugo [25] highlighted that one of the impacts of climate change is the shift in crops cultivated in northern Nigeria since there is a reduction in the proportion of fertile land available for cultivation. Besides, while the sea advancement is encroaching on the arable land of the coastal plains, the desert incursion with accompanying accumulation of sand is depriving farmers of their agricultural farmlands and grazing pasture.

Moreover, the incessant drop in annual rainfall has started reducing the growing season, thereby causing crop failure and food shortage as water is a key driver of agricultural production and can cut production and negatively impact food security [26]. In addition, a growing number of researchers have shown that drought, desert encroachment, and coastal floods have a massive negative impact on country's ecosystem leading to environmental instability in the semi-arid region of Northern Nigeria [27, 20]. Ghana is a country of 24 Million people as of 2010, characterized by dry season and disappearing wet season. The country has an average annual temperature between 20 and 30 °C, and due to this impact; there are instances where the temperature could go higher to 18 and 40 °C in the southern and northern parts of Ghana, respectively. In Ghana, rainfall decreases from south to north, and climate change has adversely affected agricultural production and food security in the country and Africa in general. The agricultural harvest varies in Ghana, and this highlights the dynamic adaptations to increasing population and another climate variability [28]. Limited soil organic and low availability of plant constituents is the main barriers to agricultural productivity in Ghana. These barriers further aggravated by the reduction in soil's top layer through wind and water erosion. Ghana is one of the world's top producers and exporters of cocoa, and the sector has played a key role in the nation's economic development representing about 3.4% to GDP and due to the projected increase in temperature, the production is expected to decline by 2050. In addition, this adverse impact of climate change is responsible for the low output recorded in the fishery sector of the country; hence, threatening the country's ability to meet local demand, the economic and food security of the Ghanaian people. Ethiopia's socio-economic engagement is highly vulnerable to climate divergence and peaks.

Agriculture has provided great support for the Ethiopian economy resulting in about 42% GDP and 85% employment [29]. Ethiopia's agriculture is primarily rain-fed [30], meaning that harvest is sensitive to variations in rainfall. An estimated 10% of the Ethiopian population affected with food shortage even in average rainfall; this percentage of the population could barely feed their households' hence resorting to seeking food aids. Further, there was reported loss of lives associated with drought in the country, which occurred in 1984, 1974 and 1973, while the year 2002 recorded a higher number where 14.2 million people were affected, representing more than 20% of the entire population [31].

Over a period of 54 years spanning between 1951 to 2005, the country has witnessed both dry and wet climate [30]. Climate change variables would have an adverse effect on Ethiopian crop production, including vital crops such as wheat and maize. Trend analysis of annual rainfall in Ethiopia shows that rainfall remained more or less constant when averaged over the whole country while a declining trend has been observed over the Northern and Southwestern Ethiopia [5]. In addition, no fewer than 12 million people in Ethiopia, Kenya, and Somalia are short of the food supply. Rainfall has been below average since the year 1951, with the year 2010–2011 being the driest, thereby suggesting a serious cause for concern since Africa rain poses a major requirement for successful farming in this region.

In addition to the impact of climate change on agriculture in Africa, water is the main source of electricity generation in many African countries (as highlighted in Fig. 2). For instance, Nigeria has 2,062 MW installed hydropower capacity [32] representing 16% of the total installed capacity, 70% of Kenya's total installed capacity of 885 MW comes from water, 58% of Tanzania's 655 MW, 93% of Zambia's 1,786 MW, and 65% of Uganda's 580 MW [33], with water accounting for more than 90% of total power generation capacity in Ethiopia [30] while in 2007, Ghana's water level at the Akosombo dam dropped below the minimum level of 240 feet. This resulted to a decrease in the hydro generation that left the authorities with no choice than to shed the load of electricity which affected the entire country [34]; since electricity has to be rationed to about 24 h of available electricity in 48 h for the affected Ghana households [35].

In the year between 2006 and 2007, Ethiopia experienced over six months of power interruptions relating to low water levels in hydro dams caused by the incidence of drought. This resulted in power being cut from once a week's initial arrangement to 15–48 h a week [36]. Similarly, in the year between 2004 and 2006, Uganda water levels at Lake Victoria fell to 10.4 m, far below the average figure of 11.5 m; and hydropower generation dropped by over 100 MW [37] resulting in a decrease in GDP from anticipated 6.255 to 4.9% in 2005/2006 (MEMD 2006). Although thermal energy was introduced to mitigate the effect of this variable, but it proved to be a more expensive source of energy for the Ugandans. Further, in the year between 1997 and 2005, Tanzania witnessed severe drought resulting in reduced water level with a 17% drop in hydropower generation. Tanzania also experienced a major load shedding which affects individual households and commercial sectors of the economy. As observed in Uganda, thermal generation was introduced to meet the shortfall [34, 36].

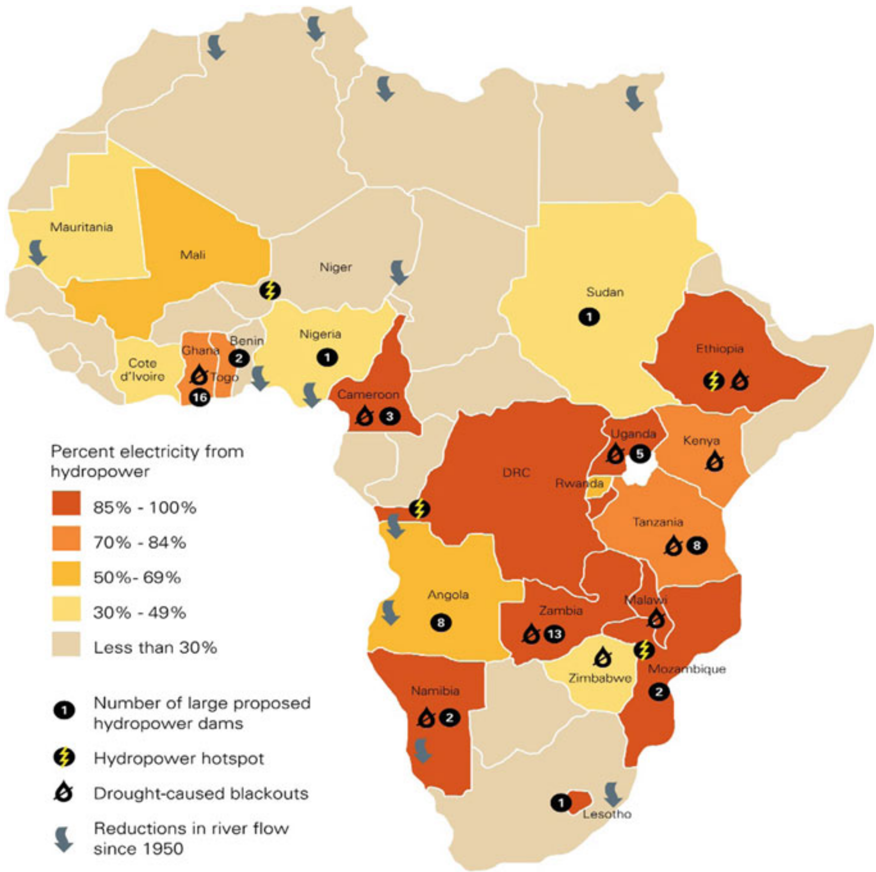


**Fig. 2** Map of Africa (*Source* internationalrivers.org)

In Kenya, the impact of drought was experienced between 1999 and 2002 affected hydropower generation in the country with generating capacity dropped by 25% in the year 2000 [36], resulting in between 1.0 and 1.5% loss in the total GDP. Additionally, the Tanzanian authorities had to replace hydropower energy with the more expensive fuel-based generation, and power ration drastically took place between the year 1999–2001. Moreover, the impact of climate change is seen across sub-Saharan African countries' human health. Schaeffer et al. [38], in their work, stressed that extreme weather variables, which include an increase in temperature, droughts, and heatwaves, have capability affect human health adversely in Africa. There is bound to be an increase in infectious disease compared to a period of no climate variability. This is supported by Lloyd et al. [39] who claimed that the incidence of malnourishment in the Sub-Saharan countries would increase by 25–90% with warming of 1.2–1.9 °C expected by the year 2050 compared to the present times. Malnutrition can impede growth in African children and bring about reduced reasoning ability, which can degenerate into dreadful disease conditions when they become adults. Climate-sensitive diseases like malaria, dengue fever can be high in poor tropical countries that have little resources to treat and prevent illness. Increases in rainfall and temperature would lead to an increase in mosquitoes, which is a carrier of malaria and the spread of dengue fever.

This is supported by Odjugo [21], and DeWeerdt [23] who stressed that implication of increasing temperature is that mosquitoes would migrate up north, and malaria will move from the tropical region to warm temperate region while the sporogony of the protozoa causing malaria accelerates from 25 days at 10 °C to 8 days at 32 °C. Further, respiratory diseases will increase the following adulteration of air quality. With this condition of limited sources and available water contaminated, there is an increased possibility of increased water-borne diseases like typhoid fever, cholera, river blindness, and guinea worm. Climate change predictions revealed that heatwaves would increase, severe, and will stay around for a longer period in the twenty-first century [40]. The increasing air pollution and repressed immunity due to climate change will result in an increased incidence of excessive death due to heat exhaustion, famine, water-related diseases, inflammatory and respiratory diseases (cough, and asthma), depression, skin cancer, and cataract. This scenario is not projected to occur only in the Mediterranean regions, but also in the temperate countries which are currently not experiencing heatwave occurrence [41]. In view of the highlighted challenges of climate variables on the African continent, understanding the impacts of climate change on Africa's socio-economic development and assured adaptation and mitigation mechanisms to curtail the adverse impacts is essential to the pursuit of sustainable development and improved climate administration.

## *3.2 Climate Change Mitigation and Adaptation*

The African continent is believed to be the most vulnerable to future climate change [29]. Intergovernmental Panel on Climate Change IPCC [5] defined adaptation to climate change as: "*Any adjustment in natural or human systems in response to actual or expected climatic stimuli or their effect, which moderates harm or exploit beneficial opportunities*". The objective of adaptation is to "reduce vulnerability to climate variables, thereby mitigating their negative impacts [17] on human lives and the environment. Climate change mitigation and adaptation (shown in Fig. 3) are the two mechanisms that have been applied lately for addressing climate change; mitigation measures are those actions that are taken to reduce greenhouse gas emissions while Adaptation measures are based on reducing vulnerability to the effects of climate change. Adaptation and mitigation present some notable differences, particularly in their objectives. Mitigation addresses the causes of climate change (accumulation of greenhouse gases in the atmosphere, whereas adaptation addresses the impacts of climate change [42].

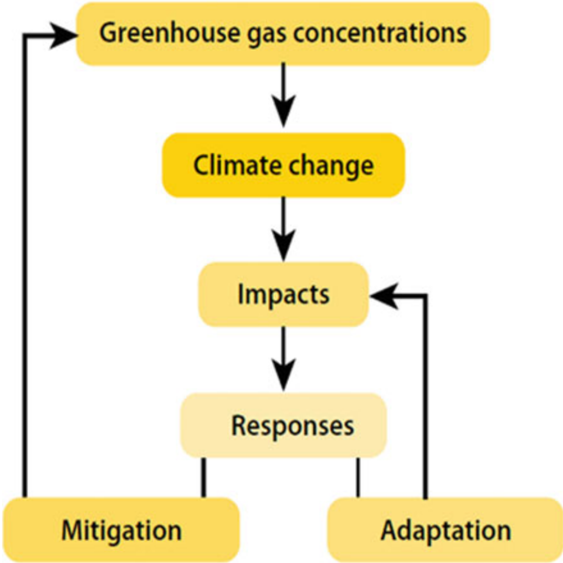


**Fig. 3** Climate change adaptation and mitigation (*Source* Locatelli [42]

The latest assessment report by IPCC [43] stressed that the current waves of global warming traced to human influence with other variables of climate change. Further, the larger proportion of GHG emissions are from the developed counties, while the actual impacts are felt in low-income countries [30]. The implication of this is the effect of climate change will be greater in developing countries than the high-income countries due to the developing economy's impoverishment and dependence on the environment for sustenance [44]. Currently, many developing countries are under considerable threat from changes in the global climate, characterized by increased severity and frequency of droughts and floods, which have forced people to leave their homes. In addition, the adverse effect from climate change puts a great strain on Africa's nation's GDP since the chuck of their revenue is generated from agriculture as this sector appeared to be the main source of employment for the African people [10]. Therefore, considering the threats posed by the effect of climate change, it becomes imperative to bring about an innovative adaptation and mitigation approaches that can promote low-carbon climate-resilient development needed to drive the socio-economic engagement of sub-Saharan Africa and the rest of the continent.

Nevertheless, there are ongoing short-term and long-term initiatives on climate change adaptation and mitigation globally and with a strong link to developing economies. The Kyoto Convention 11 December 1997 extended the 1992 United Nations Framework Convention on Climate Change (UNFCCC) that ensure parties to reduce greenhouse gas emissions and mitigate the effect of climate change globally. The only limitation to this convention is that the United States of America did not ratify this protocol, and from all indications, Canada later pulled out from the Kyoto Protocol on 12 December 2011, thereby posing a challenge to the objective.

This implication of this is that if the United States of America were to ratify the protocol, this would suggest that the US have to reduce emissions by 600 million tons in 2010 in anticipation of the 2020 targets [45]. Fourth Intergovernmental Panel on Climate Change [5] stressed that human-caused climate change that has occurred over the past 30 years had had a huge impact on physical and biological systems. The recommended adaptation and mitigation strategies by the panel include improvements of crop yields, fuel switching from coal to gas, use of electric vehicles, and control of non-emission $CO_2$ gas emission, improved technique for rice cultivation, manure management, and improved energy efficiency (shown in Table 1).

Further, the United Nations Development Programme—Global Environment Facility (UNDP-GEF) Synthesis of Experiences and Recommendations provides an overview of several successful initiatives on climate change adaptation in sub-Saharan Africa from 2000 to 2015. This initiative has supported more than 45 countries to access funds for climate change mitigation and adaptation; to the tune of US$828 million with 216 active projects. The deliverables include enhancing government policies and as well as building capacity for continuous technical support to their local communities. Nevertheless, baseline development is needed to reach targets for poverty reduction and climate action in Africa, and its success is dependent on how these projects will enhance adaptive capacity and evidence-based decision making. The Bali Action Plan [46] international collaboration provided support globally, which includes developed countries, small islands, and sub-Saharan African countries affected by drought, desertification, and floods. Adaptive measures include enhanced action on technology development and transfer to support action on climate change while mitigation efforts aimed at providing positive policy on incentives, issues emissions reduction, deforestation and forest degradation in developing countries, and mobilization of the public- and private-investment initiative, including facilitation of carbon-friendly environment.

African Union and European Union (AU-EU) Research and Innovation Partnership funding provided initiative on Climate Change and Sustainable Energy, focusing on climate action for adaptation and Mitigation towards renewable energy and energy efficiency. The first actions for the implementation of the partnership will be supported by Horizon 2020 (Estimated EUR 16 million for 2018–2020) meant for African countries. Additionally, Internal and global political must be agreed upon by both continents to address the sustainable development goals (SDG) towards a transition to low-carbon and adaptive climate economies. UNESCO—Regional Office for Eastern Africa, Kenya seeks to sensitize community in Nairobi Kenya through climate change vulnerability assessment initiated by a group of school students to form a team of Climate Change Crusaders (CCC). This is necessary to educate students and the public, especially in Nairobi, Kenya, on the adaptation approach to changing climate. Some of the adaptive measures include educating students and stakeholders on reforestation, encouraging bio fencing, planting of fruit-bearing or timber value trees, encouraging the installation of solar panels for energy use in school—mitigation strategy aimed at bringing awareness how to mitigate the incidence of climate and ensure sustainable future adaption.

**Table 1** International initiatives on adaptation and mitigation strategy for sub Saharan African countries

| Initiatives | Intervention | Adaptation | Mitigation | Remark |
|---|---|---|---|---|
| The Kyoto Convention 11 December 1997 | The debate was on the need to mitigate the effect of climate change globally | Awareness of global warming whether it is natural or human-made | It extended the 1992 United Nations Framework Convention on Climate Change (UNFCCC) that ensure parties to reduce greenhouse gas emissions | The United States of America refused to ratify this protocol, and Canada pulled out from the Kyoto Protocol on 12 December 2011, thereby posing a challenge to the objective of the protocol |
| Fourth Intergovernmental Panel on Climate Change [5] | Climate change adaptation and Mitigation dominated the discussion | Improvements in crop yields, fuel switching from coal to gas, use of electric vehicles, and control of non-emission $CO_2$ gas emission | Improved crop, improved technique for rice cultivation, livestock, encourage non-fossil fuel use, manure management, and improved energy efficiency | Human-caused warming over the last three decades has had a huge impact on physical and biological systems |
| UNDP-GEF synthesis of Experiences and Recommendations (2000 to 2015) | Provides, overview of several successful initiatives on climate change adaptation in sub-Saharan Africa from 2000 to 2015 | Enhancing government policies and as well as helping to build capacity for continuous technical support to their local communities | Baseline development is still required to reach targets for poverty reduction and climate action in Africa and to be successful, these projects will need to enhance adaptive capacity and evidence-based decision making | Supported about 45 countries to access funds for climate change mitigation and adaptation to the tune of US$828 million with 216 active projects |

(continued)

**Table 1** (continued)

| Initiatives | Intervention | Adaptation | Mitigation | Remark |
|---|---|---|---|---|
| UNESCO—Regional Office for Eastern Africa, Kenya | The students from the school form a team of Climate Change Crusaders (CCC) to carry out participatory climate change vulnerability assessment within their community | The need to educate students and the general public in Africa on an adaptation approach to changing climate | Educate students and stakeholders on Reforestation, encourage bio fencing, plant fruit-bearing or timber value trees, encourage the installation of solar panels for energy use in school | Awareness was created in the community by bringing all stakeholders in their community to discuss climate change, how to mitigate and adapt in the future |
| The Bali Action Plan [46] | International collaboration to support developed countries and small islands and the needs of sub-Saharan African countries affected by drought, desertification and floods | Enhanced action on technology development and transfer to support action on climate change mitigation and adaptation | Provide a positive policy on providing incentives on issues relating to reducing Emissions, deforestation, and forest degradation in developing countries | Mobilization of the public- and private-sector funding and investment, including facilitation of carbon-friendly investment choices |
| AU-EU Research and Innovation Partnership on Climate Change and Sustainable Energy | Africa and the EU Continent | Focus on climate action for adaptation and Mitigation, renewable energy, and energy efficiency | The first actions for the implementation of the Partnership will be supported by Horizon 2020 (Estimated EUR 16 million for 2018–2020) projected to African countries | Internal and global political commitments undertaken by both continents and address the Sustainable Development Goals in supporting a transition to low-carbon and resilient climate economies |

This is an African Union Strategy on Climate Change [47], initiative tailored towards ensuring water security and green economy for Africa. Investing in greening these sectors is likely to benefit the poor by improving livelihoods and enhancing ecosystem services. Greening the economy initiative have had impacts in countries with low carbon strategy like Rwanda and Ethiopia. Nigerian Government signed a Memorandum of Understanding on Territorial Approach to Climate Change (TACC) with UNDP in 2009 as part of its efforts to tackle environmental devastation arising from climate change. The adaptation mechanism includes identifying low-cost adaptation and mitigation measures that can promote long-term sustainability, poverty reduction, renewable energy, and energy efficiency. In Ghana, Joint UNEP-UNDP Funded by the Danish Government, recognizes that the key to successful climate change adaptation is to mainstream it into the wider national development process. There was a need to have an integrated structure and methodology to identify overlapping areas, synergies, address conflicts among the proposed sectoral adaptation options, to ensure the development of a complete and integrated national adaptation master plan. The initiative further encouraged building and strengthening the capacity of local farmers to increase agricultural production, increase awareness on climate issues, water resources conservation, and preservation, mitigating the incidence of water and airborne diseases, improving and sustaining the quality of water resources.

## 4 Conclusion and Recommendation

Evidence from the current study revealed that there are countless robust and transparent global, regional, and national initiatives aimed at mitigating effects of climate change globally, especially in developing countries. In addition, there are sufficient studies to attest to the fact that global support for climate change initiatives in sub-Saharan African countries is developing and steady. However, while continues to call for un-interrupted support for climate change mitigation and adaptation by the global and regional bodies, it is also imperative to focus research on individual adaptive and mitigating mechanisms to curb impacts of climate change on the environment. However, few sub-Saharan African countries such as Rwanda and Ethiopia have resorted to greening their environment. There are lots individuals can do to support the climate change adaptation and mitigation initiatives in their respective countries. The extent to which they respond depends on the intensity of awareness campaign instituted by the respective national governments. Some of the measures provided by UNESCO [48] Climate Change Mitigation and Adaptation Simple Guide to Schools include the use of the energy-efficient car, installing solar panels to generate electricity, and encouraging citizens to choose a green career path. Further, individuals can help by cultivating their own fruits and vegetables since this would help to remove the greenhouse gas $CO_2$ from the air. Growing our food would reduce the amount of $CO_2$ generated by fossil fuel burning vehicles, planes, ships from the air from the atmosphere.

Further, the carbon footprint is released into the air due to energy requirements minimized by replacing old luminous light bulbs for the new energy-efficient fluorescent lights (CFLs). Individuals can encourage acts of turning off lights when not needed. It is encouraged to walk or cycle instead of driving everywhere. This is common in developed countries, as most people would prefer to park their cars and walk or ride bikes to their place of work; this habit can be encouraged in Africa countries as well. The national governments should encourage paper, aluminum cans, cardboard, food cans, plastic, glass, newspapers, magazines, junk mail, phone books, and paper recycling to reduce air and water pollution on the planet. As many more nations hit by drought, people and animals in the affected parts of the world would not have clean, safe water to drink hence the need to encourage water preservation and conservation since studies highlighted that 97% of all water on the earth surface is saltwater, which is not suitable for drinking. Only 3% of the water on Earth is freshwater, and only 0.5% is available for drinking. The other 2.5% of freshwater is in ice caps, glaciers, the atmosphere, soil, or under the earth's surface too polluted for consumption. Therefore, suggesting that individuals must preserve and conserve the available clean, freshwater. Consequently, it is the responsibility of sub-Saharan African governments to teach their people more about water conservation and preservation strategy rather than limiting the responsibility only for scientists, hydrologists, foresters, wildlife managers, city planners, farmers, or mine owners.

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# Energy-Drinking Water-Health Nexus in Developing Countries

**Vikrant P. Katekar and Sandip S. Deshmukh**

**Abstract** Energy scarcity, waterborne diseases, and drinking water shortages are the three significant and fundamentally interlinked factors that are strongly influencing the social and economic growth of developing countries. The deficiency of safe drinking water contributes to many waterborne diseases, causing the demise of several people annually and hampering the growth of society. Desalination processes are often energy-intensive and expensive. Several developing countries facing energy deficiency are forced to build desalination plants to fulfill the demand for potable water. The energy required for desalination is fulfilled by importing oil, which is an additional economic burden on countries that are already paying high oil import bills. Burning a massive quantity of oil is the foremost cause of environmental degradation. The objective of this chapter is to explore the nexus among the energy, drinking water and the people's health in developing countries by using the assessment of several worldwide published reports and papers. This study identifies that community facing energy crises usually be deficient in safe drinking water services; consequently, they suffer from infirmity, which increases economic burden through the loss of work productivity. With a deficient cash reserve, the community is incapable of fulfilling the demand for energy and safe drinking water. The chapter concludes that energy, drinking water, and health nexus administration is essential for economic growth, sustainable development and energy security of developing countries.

**Keywords** Desalination · Potable water · Water scarcity · Waterborne diseases · Economic security · Renewable energy · Sustainable development goal

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## 1 Introduction

Presently the global population is facing two significant crises, energy and drinking water. Both are adversely affecting the health and economy of the community. British Petroleum Statistical Review of World Energy-2019 states that global primary energy expenditure was grown rapidly in the year 2018 by 2.9% from the year 2010; furthermore, 2.0% carbon emission growth was recorded in the year 2018 which was fastest as compared with previous seven years. United Nations World Water Development Report (WWDR 2019) says that if the deprivation of the ecosystem and unsuitable pressure on global water resources prolong at the similar rate, then 45% of international gross domestic product (global GDP) and 40% of worldwide grain production will be at high risk by 2050. It is due to rapid environmental degradation, climate change, population growth, rapid urbanization, and industrialization. Improved access to safe drinking water sources, effective water management and good governance, contribute significantly for the development of poor societies with multiple benefits such as better health, time-saving, improved economy, access to the liveliness and lots of opportunities in terms of education, employment and other sources of revenues. Safe drinking water and sanitation are fundamental civil rights, and it is the 2030 agenda for sustainable development. For prosperity and peace for people and the globe, the United Nations in 2015 gave 17 objectives known as sustainable development goals (SDGs). Goal-6 is associated with ensuring accessibility and sustainable management of water and sanitation for all. It has six targets mentioned in Table 1.

World Economic Situation and Prospects (WESP) categorize the world into three groups: developed economies, economies in transition, and developing economies. The regions for developing economies are East Asia, South Asia, Western Asia, Africa, Latin America, and the Caribbean. There are some of the prominent factors that affect the economic growth of developing nations such as human resources, natural resources, capital formation, technological advancement, social and political

**Table 1** Targets of SDG-6

| Target | Brief description |
|---|---|
| 6.1 | Everyone must get safe and affordable drinking water by 2030 |
| 6.2 | Everyone must get adequate sanitation and hygiene facility by 2030 |
| 6.3 | To improve the quality of water by reducing its pollution by 2030 |
| 6.4 | To reduce the number of populace facing water scarcity by 2030 |
| 6.5 | To execute integrated water resources administration at all levels |
| 6.6 | To safeguard and restore water-related ecology by 2020 |
| 6.A | To extend support to developing countries for water along with sanitation administration by 2030 |
| 6.B | To strengthen the involvement of local communities for water and sanitation management by 2030 |

factors [1]. Nexus is the interlinking of two or more inter-reliant factors. The nexus between mutually dependent factors such as water, food, energy, population, poverty, and health is a promising concept requisite to concretize national and regional policy competently for the development of the nation. Table 2 briefly outlines some nexus studies carried out at different geographical locations.

Usually, nationwide government and worldwide organizations have separate departments to deal with energy, water, and health. The same is valid for research also. Researchers in the field of energy, water, and health are working in separate clusters with often low interactions. Energy-Drinking water-Health nexus is not investigated, which is indispensable to accomplish the United Nations Sustainable Development Goal-6 (SDG-6). For developing countries, an effectively managed nexus approach between energy, drinking water, and health will be beneficial to deal with several activities that take place at the extremely bottom level for poor households and farmers. This communication is an effort to understand and establish an interlink between these factors for national and regional policy-making and implementation for the progress of marginalized communities in the developing countries.

For finding out the appropriate research work on energy, drinking water, and health to conduct this nexus study, the investigation was done using the title, keyword, and the abstract. Different search questions were exercised such as desalination techniques, the energy consumption of desalination technologies, environmental footprints of desalination systems, renewable energy for desalination, interlink between energy-drinking water, drinking water-health and health-energy to compile diverse sections in the chapter. The search was intended to gather research papers and reports which were illustrate the pattern of energy expenditure, potable water demand, population growth, water resource administration, drinking water supply systems and waterborne diseases in developing countries. Appropriate research papers were gathered and studied to understand the nexus between energy, drinking water and health in developing countries. Besides, special attention was given to internationally published reports from various distinguished organizations such as the UN, WHO, UNICEF dealing with energy, water, health with their policies and guidelines to discover their relevance for this nexus study. Research papers and reports were read carefully, and the most significant results of each one were noted down.

The chapter is unfolding inside the story in five more sections in addition to this section. The second section discusses the interlinking of drinking water and health. The third section concentrated on desalination systems and its energy consumption, carbon footprints as well as its economic burden on communities. The fourth section briefly describes the link between energy availability and health. The fifth section establishes the nexus between energy, drinking water and health. The last section reports the ways for nexus management.

**Table 2** Different nexus and their significant findings

| Sn | Author(s) | Type of nexus | Key findings |
|---|---|---|---|
| 1 | Ram Avatar et al.[2] | Population-Urbanization-Energy | • This nexus needs to be addressed holistically<br>• The use of science at the policy level is required<br>• The landscape ecosystem with utilization method will provide guidelines for cost–benefit study<br>• The geographical location of energy resources affects energy distribution and its cost<br>• Opportunity cost must be considered for the selection of land |
| 2 | Golam Rasul [3] | Food-Water-Energy | • Free of charge water and subsidized power is not sufficient for rural and slum development<br>• The scaffold is required for cross-sectoral management to manage the nexus challenge |
| 3 | Mangal Singh Kro [4] | Water-Poverty-Health Expenditure | • Poor people are prone to suffer from toxic substances through drinking water<br>• They cannot afford water of good quality for drinking and cooking<br>• Successful management of water resources is required to address this nexus<br>• Critical interaction of people in water management decisions and cross-sectoral with cross-scalar dynamics of water management using interdisciplinary methods is beneficial to manage this nexus |

(continued)

**Table 2** (continued)

| Sn | Author(s) | Type of nexus | Key findings |
|---|---|---|---|
| 4 | Giovanni Bidoglio et al. [5] | Water-Energy-Food-Ecosystems | • The governmental model must contain the creation and diffusion of a technology tool for nexus administration<br>• Public–private partnership is essential to develop inventive models, technologies, strategies, and policies for nexus control |
| 5 | Muhammad Wakil Shahzad et al. [6] | Energy-Water-Environment | • This nexus is vital to attain the Conference of Parties' goal, COP-21<br>• For prospect sustainability, new membrane substances are projected for water desalination<br>• Thermally driven desalination technology hybridization can increase desalination efficiency by 20–25% |
| 6 | Ibrahim et al. [7] | Water-Energy-Land-Food | • Sensitivity analysis showed a 13% decrease in nexus efficiency<br>• This nexus provides a framework for policymaking<br>• A win–win approach must be used to attain maximum nexus effectiveness<br>• Modernization of policies will augment nexus competence and sustainability |

(continued)

**Table 2** (continued)

| Sn | Author(s) | Type of nexus | Key findings |
|---|---|---|---|
| 7 | Mercure et al. [8] | Energy-Water-Food | • Global demand for agriculture commodities necessitates the growing quantity of terrain<br>• New agriculture policies avoid only direct land-use<br>• Climate change, deforestation, and change in water cycle decreases the yield of the crop |
| 8 | Mehzabeen Mannan et al. [9] | Energy-Water-Food | • Incorporation of life cycle evaluation and nexus methodology is essential to determine environmental burdens |
| 9 | Zhenyu Li et al. [10] | Water-Energy | • The utilization of ocean energy for seawater desalination will be beneficial to develop future renewable energy desalination technology |
| 10 | Julia Terrapon-Pfaff et al. [11] | Water-Energy-Food | • An organized action for integrating the water and food requirement into energy scheduling at the neighborhood level is recommended to avoid trade-offs and to improve the progress outcomes and impact of power ventures |
| 11 | Albert Wicaksono et al. [12] | Water-Energy-Food | • Optimization of resources allocation will maximize the security of resources<br>• Resources trading will be an option to fulfill the requirement without increasing domestic production |

## 2 Drinking Water and Health

Water is one of the most abundant resources on the earth, covering three-fourths of the earth's surface. However around 97% of the water on the earth is in the oceans which are highly saline, and out of remaining, two percent fresh-water is enclosed in the polar ice, and less than one percent fresh-water is reachable from groundwater, lakes, and rivers, which is used for most of the human, animal and agriculture needs [13]. Water accessibility refers to how practically drinking water is delivered to the community or individual families. All species living from the water to land necessitate water intake to avoid dehydration. Nevertheless, the consumption of contaminated water is the pathway towards the fatality. This section illustrates the inter-link between drinking water and human health.

### *2.1 Increasing Demand for Potable Water*

People mostly make use of surface water, groundwater furthermore sometimes unconventional water sources to collect the drinking water. The United Nations World Water Development Report (WWDR 2019) states that water requirements are increasing worldwide by about 1% per year from the year 1980. WWDR, 2018 states that nearly 6 billion people on the globe will suffer from safe drinking water scarcity by 2050. It is due to rising water demand, diminution in available water resources, and an increase in water pollution. Assortments of other reports at the international level show that the water crises affect most people in developing countries. Over 2 billion people living in developing countries facing high water stress, moreover, about 4 billion people experience severe water scarcity during at least one month per year. If the increase in global water demand prolongs at a similar rate until 2050, in that case, water demand will increase by 20 to 30% higher than the current level of water use [14]. Figure 1 shows an existing global overview of countries with

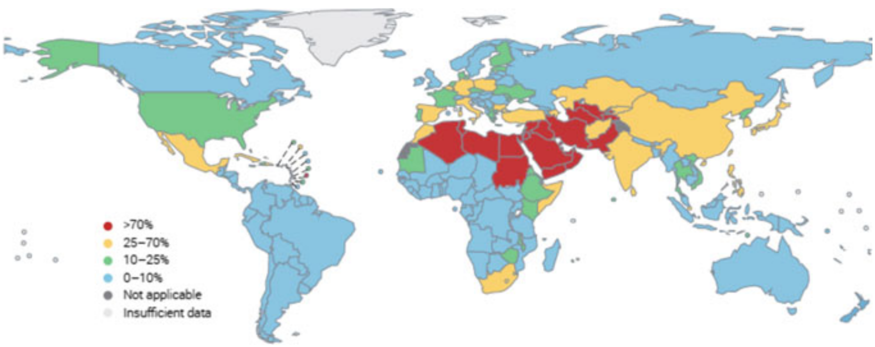



**Fig. 1** Water scarcity (*Source* WWDR 2019)

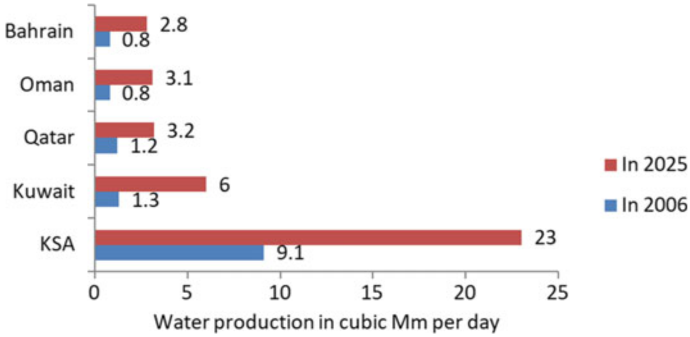



**Fig. 2** Increasing demand for potable water in developing countries [15]

water scarcity. It points out that the populace in many developing countries such as India, China, and Pakistan are facing 25–70% clean drinking water scarcity.

Currently, the global average water stress is about 11%. Thirty-one countries on the glob experience water stress between 25 to 70% and 22 countries are experiencing water stress above 70% [14]. To provide safe drinking water to more than 1 billion people living in developing countries is a challenging task. WWDR, 2019 states that in developing countries, 3 out of 10 people have no access to safe drinking water. In Sub-Saharan Africa, almost half of the people are consuming water from unprotected sources [15]. Figure 2 illustrates an increase in water demand in some developing countries. It can be easily judged that as compared with the year 2006, water demand will increase by three times in the year 2025.

Another reason for water scarcity in developing countries is that about 90% of freshwater is consumed by the agriculture sector, which increases competition between domestic, agricultural and industrial water users. Most of the developing countries are facing the difficulty of deforestation, overgrazing, and erosion. It severely affects the water cycle; they suffer from the high water runoff after heavy rain-falls, early drying of wells, ponds, and rivers. The developing countries have an urgent need to establish centralized water desalination systems to provide potable water to residents [16].

WHO/UNICEF Joint Monitoring Program (JMP) defined different water service levels for community drinking shown in Fig. 3.

Figure 4 shows global and regional drinking water coverage to different levels of water quality.

*: insufficient data

Figure 4 shows that 29% population mostly in developing countries, does not have an adequate supply of safe drinking water. Population growth is a significant factor behind increasing water demand. The world population was reached 7.6 billion as of June 2017. It is expected that it will reach about 8.6 billion by 2030 and 9.8 billion by 2050 (Fig. 5). Mostly developing countries in Africa and Asia are accounted for nearly all current population growth. Africa will be the main contributor to population growth beyond 2050 (UNDESA 2017a).

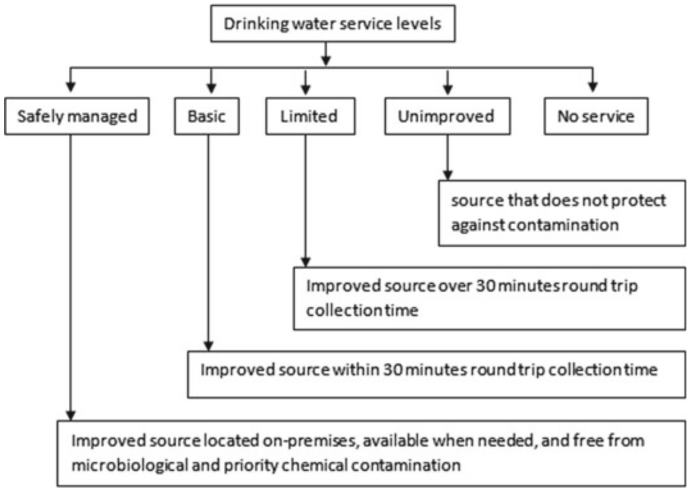
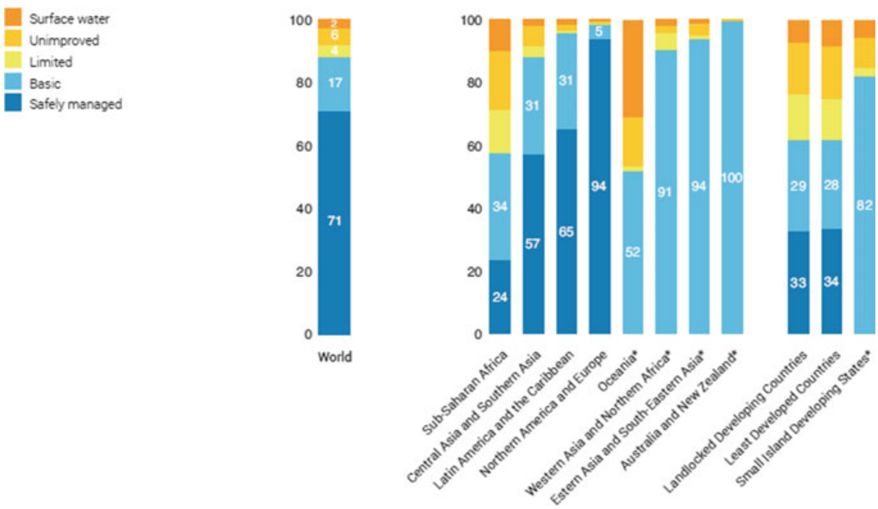



**Fig. 3** Different water service levels




*: insufficient data

**Fig. 4** Global and regional water coverage (*Source* WWDR 2019)

Many industrial products (shown in Fig. 6) require to distill water for their production. With the increase in population; the demand for these products is also increasing rapidly; subsequently, there is also an increase in demand for desalination.

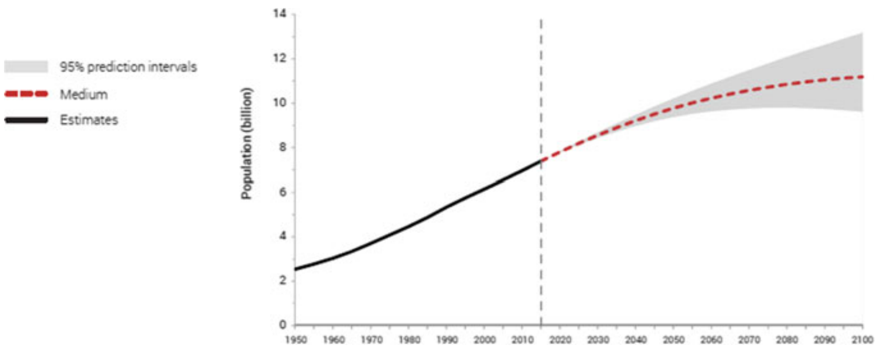



**Fig. 5** Increase in global population (*Source* UNDESA 2017a)

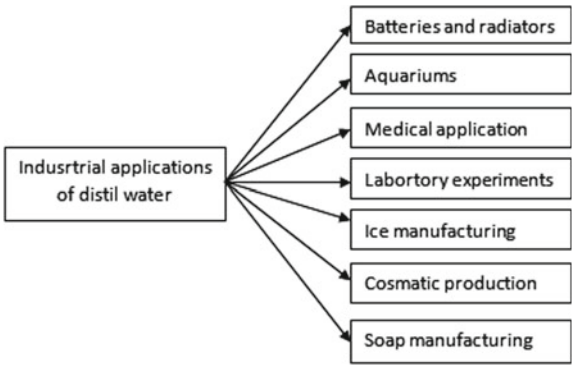



**Fig. 6** Industrial uses of distilling water

## *2.2 Significance of Drinking Water*

The major part of the human body is made up of water. The human brain is made up of 95% water; blood is 82% water and lungs are 90% water [17]. United Nations Sustainable Development Goal 6 (SDG-6) says that "Water sustains life, but safe drinking water defines civilization" [18]. To maintain good health, the Institute of Medicine advises that men must consume roughly 3.7 L, and women must consume 2.7 L of potable water per day [19]. Report of WHO, 2019 says that safe and readily available drinking water is essential for public health, whether it is used for cooking, drinking, domestic use or recreational purposes. However, high water pollution makes the task of potable water supply to the community extremely difficult. The quality of water is altered in many ways such as changes in nutrients, sedimentation and by addition of compounds such as heavy metals, non-metallic toxicants, persistent organics, and pesticides [20]. Figure 7 illustrates various types of human diseases caused by drinking contaminated water [21].

World Health Organization (WHO) states that the maximum permissible limit of salinity in drinking water is 500 ppm, and for exceptional cases, it may be up

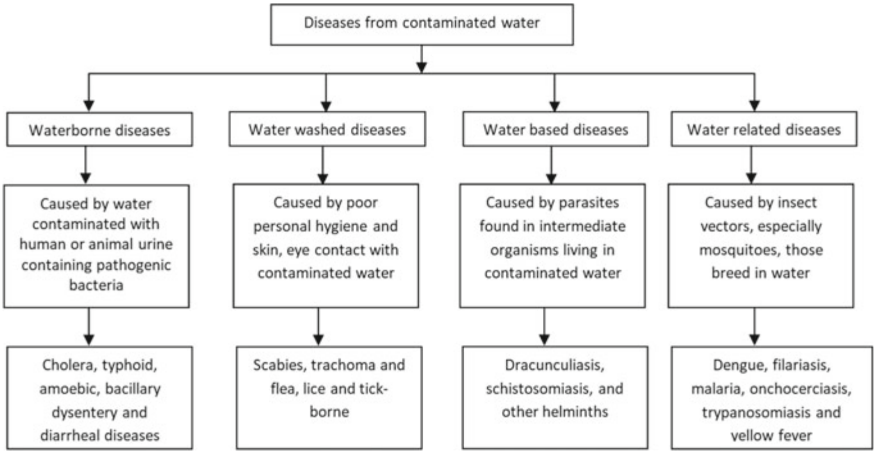



**Fig. 7** Classification of diseases due to impure water consumption [21]

to 1000 ppm. However, most of the surface or groundwater available on earth has salinity up to 10,000 ppm. The seawater usually has a salinity in the range of 35,000–45,000 ppm [13]. In addition to this, pollutants in water come in many forms such as deoxygenating materials, toxic materials and solid materials such as vehicle tires, shopping trolleys, old shoes, and plastics. These pollutants severely affect biological conditions in water and also deoxygenate the water. Such infected water transmits severe diseases. Globally, almost 900 million people have poor access to safe drinking water sources; out of that, at least 80% of people live in the rural area of developing countries [21]. In Asia and the Pacific, 29 out of 48 countries are decelerated as water-insecure due to less availability of safe drinking water and unsuitable groundwater withdrawal. In developing regions, such as South-East Asia and Africa, fluoride and arsenic are the compounds found in drinking water that are of significant concern. In India alone, 66 million people are at risk due to high fluoride content in groundwater and over 10 million people due to excess arsenic [20]. Old and poorly maintained water distribution systems also deteriorate the quality of piped drinking water below acceptable levels and create serious health risks. Almost all children in developing countries are at high risk of exposure to unsafe drinking water sources. In Sub-Saharan Africa, people living in rural areas are about 60% of the total population. Many of them remain in poverty and consume untreated water. Figure 8 shows the proportion of the global population having safe drinking water services. It shows that developing countries such as India and Pakistan have 25–50 of the population's lack of safe drinking water services.

Literature shows that about 10–15% of the population living in low and middle-income countries still drank contaminated surface or groundwater. Table 3 gives the regional distribution of the population exposed to the different levels of drinking water.

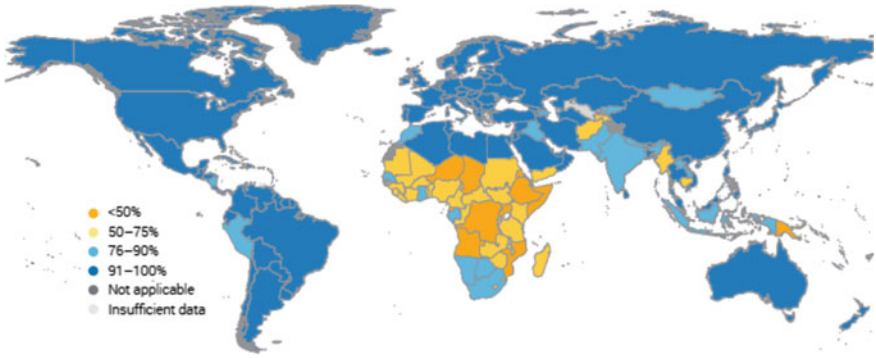



**Fig. 8** Population using safe drinking water services (*Source* WWDR 2019)

**Table 3** Distribution of the population exposed to different levels of drinking water, by region, for 2016 [22]

| Region | Percentage of population using | | | | | |
|---|---|---|---|---|---|---|
| | Piped water on-premises | | Basic drinking water, not piped on-premises | | Surface, unimproved or limited water | |
| | not filtered or boiled | filtered or boiled | not filtered or boiled | filtered or boiled | not filtered or boiled | filtered or boiled |
| Sub-saharar Africa, LMICs | 25.5 | 3.1 | 29.6 | 2.0 | 35.8 | 4.0 |
| America, LMICs | 58.3 | 82.3 | 4.6 | 1.1 | 2.9 | 0.8 |
| Eastern Mediterranean LMICs | 50.0 | 4.0 | 26.0 | 0.7 | 13.7 | 0.9 |
| Europe, LMICs | 55.6 | 20.3 | 6.9 | 4.1 | 2.5 | 1.7 |
| South-East Asia, LMICs | 24.0 | 12.7 | 38.6 | 13.0 | 7.2 | 8.5 |
| Western Pacific, LMICs | 28.5 | 50.7 | 8.8 | 8.3 | 1.6 | 2.1 |
| Total LMICs | 34.1 | 23.5 | 22.6 | 7.0 | 10.2 | 2.6 |

The Fig. 9 shows that an average percentage of the population living in developing countries using piped water on-premises but not filtered or boiled is 39.42%, Piped water on-premises and filtered or boiled is 28.08%, Basic-drinking water not piped on-premises and not filtered or boiled is 19.58%, Basic-drinking water not piped on-premises and filtered or boiled is 5.17%, surface, unimproved or limited water not filtered or boiled is 10.55%, surface, unimproved or limited water filtered or boiled is 2.94%.

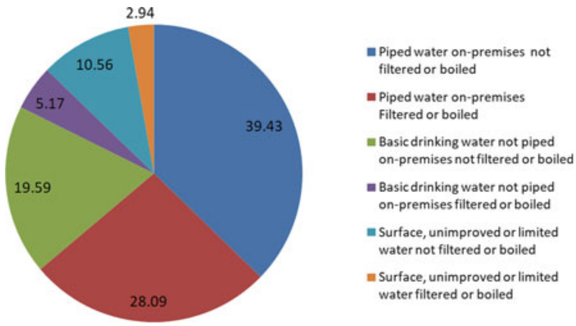



**Fig. 9** Average utilization of different water quality by the community in developing countries [22]

Due to inadequate access to safe water sources, people in Sub-Saharan Africa are facing multiple challenges such as reduced healthiness and low living conditions, undernourishment, lack of opportunity for schooling and employment. Mainly women and girls spend more than 30 min on each trip to collect water (UNICEF 2016). Fetching drinking water from long distances develops several challenges for people such as risks to physical safety, loss of time of education, business, employment, and health. People suffer from musculoskeletal injuries due to transport a heavy load over long distances. It creates social unrest, conflict, and violence. It is also a reason for the growing tendency in human immigration [14].

The human rights state that the water requisite for individual or household use must be secure and free from microbes, toxic chemicals and radiological risks that comprise a hazard to a person's healthiness. Water should be of acceptable color, odor, and taste. The World Health Organization (WHO) defines the essential requirements to ensure the safety of drinking-water given in Table 4 [23].

WHO says diarrheal diseases are the foremost grounds of illness and death in all developing countries. Annually, about 2.2 million people die from diarrhoea; 90% of these deaths are among the children [24]. It is found that in developing countries, there is a higher rate of endemic gastrointestinal disease due to pathogen concentrations in wastewater. Children have eight times low healthy life years per capita as compared with children in developed nations. In some of the poorest countries, the healthy life years are lost due to drinking of contaminated water which is 140 times greater as compared with developed countries [25]. Figure 10 shows a lack of access to potable water and deaths due to diarrheal diseases [26]. Table 5 shows regional diarrhoea burden due to consumption of impure water [22].

The availability of a safe drinking water system at residence and in the place of work improves the health of people and their productivity. An adequate safe drinking water facility in schools reduces the absentee of children and increases educational outcomes. Figure 11 shows the proportion of schools with a basic safe drinking water service by country. It shows that 25–50% of schools in a developing country like India alone do not have sufficient drinking water facilities.

**Table 4** WHO guidelines for safe drinking water [23]

| Parameter | WHO guideline value |
|---|---|
| Faecal coliform or E. coli | Not-detectable in a 100 mL sample |
| Aluminium | 0.2 mg/L[a] |
| Arsenic | 0.01 mg/L |
| Ammonia | 1.5 mg/L[a] |
| Cadmium | 0.003 mg/L |
| Arsenic | 0.01 mg/L |
| Chloride | 250 mg/L[a] |
| Colour | 15TCU[a] |
| Copper | 2 mg/L |
| Fluoride | 1.5 mg/L |
| Hydrogen Sulphide | 0.05 mg/L[a] |
| Iron | 0.3 mg/L[a] |
| Lead | 0.01 mg/L |
| Manganese | 0.1 mg/L[a] |
| Nitrate | 10 mg/L |
| Sodium | 200 mg/L[a] |
| Sulphate | 250 mg/L[a] |
| Turbidity | 5 NTU[a] |
| Total dissolved solids | 1000 mg/L[a] |
| Zinc | 3 mg/L[a] |

*Note* [a]May not be toxic but could result in consumer complaints

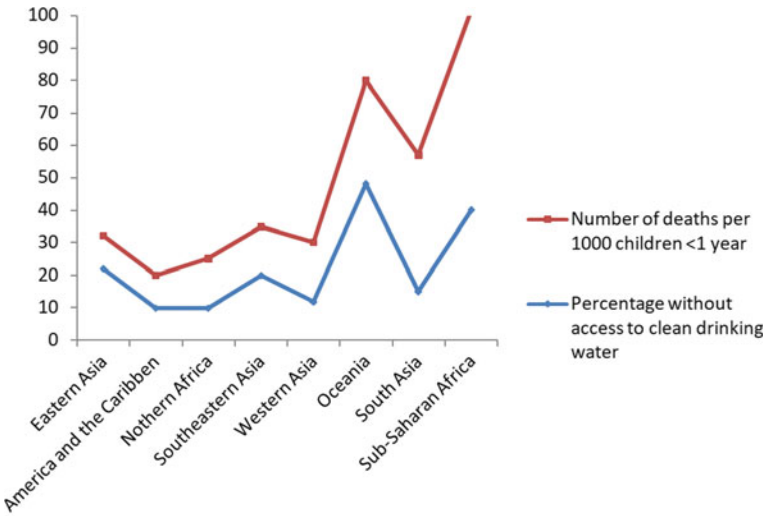



**Fig. 10** Comparison between the lack of access to potable water and deaths due to diarrheal diseases [26]

**Table 5** Diarheoes burden attributable to inadequate water by region, 2016 [22]

| Region | PAF | (95% CI) | Deaths | (95% CI) | DALYs (in 1000 s) | (95% CI) |
|---|---|---|---|---|---|---|
| Sub-Saharan Africa, LMICs | 0.40 | (0.22–0.51) | 259,073 | (140,144–330,643) | 16,837 | (9120–21,472) |
| America, LMICs | 0.27 | (0.02–0.42) | 6246 | (480–9469) | 506 | (22–776) |
| Eastern Mediterranean, LMICs | 0.39 | (0.19–0.50) | 48.947 | (24,067–63,413) | 3675 | (1778–4764) |
| Europe, LMICs | 0.20 | (0.02–0.31) | 959 | (86–1500) | 137 | (2–215) |
| South-East Asia, LMICs | 0.31 | (0.12–0.43) | 163,760 | (64,307–225,941) | 7798 | (3067–10,750) |
| Western Pacific, LMICs | 0.21 | (0.08 0.30) | 5756 | (2069 8220) | 493 | (160 725) |
| Total LMICs | 0.36 | (0.19–0.47) | 484,741 | (231,153–639,285) | 29,446 | (14,149–38,702) |

*Notes DALYs* Disability-adjusted life years. *PAF* Population attributable fraction

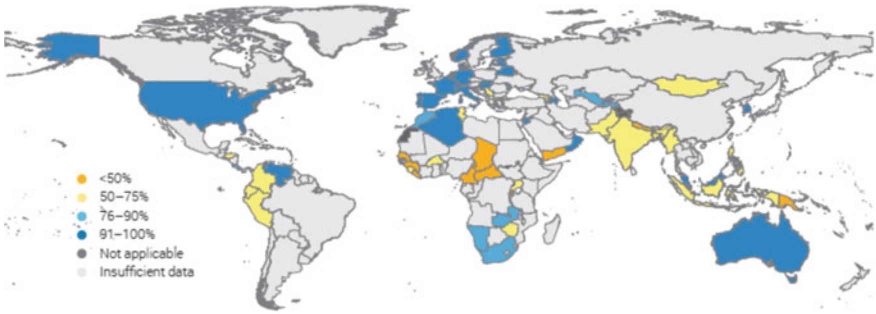



**Fig. 11** The percentage of schools having an essential drinking water service by nation (*Source* WWDR 2019)

## *2.3 Financial Burden of Water-Borne Diseases*

Everybody must be able to manage to pay for safe drinking water services. It must not depend on one's ability to obtain other basic necessitates and services, for instance, food and health. Poor living in poverty fight every day to fulfill their fundamental needs, including access to drinking water. The more significant part of people living below the international intense poverty line is in Southern Asia and Sub-Saharan Africa (World Bank 2016a). In 2013, 767 million people which is more than 10% of the global population were living under the international intense poverty line of US$ 1.90 per day, and 2.1 billion people, i.e. about 30% of the global population, were

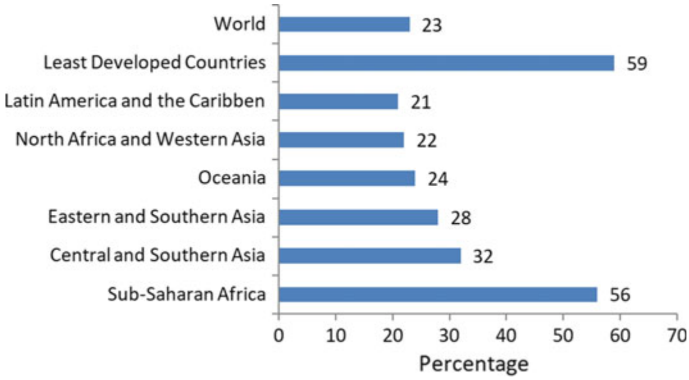



**Fig. 12** Urban population leaving in slums (*Source* World Bank 2016a)

living less than US$ 3.10 per day. Nearly 80% of the extreme poor are staying in rural and remote areas of developing countries. Poor people in developing countries such as Bangladesh, Viet Nam, Kyrgyzstan, Malawi are severely facing the problem of safe drinking water. They are forced to overexploit their natural resources to survive [24]. The problem of drinking water is not only limited to poor people living in a rural and remote area, but it is also associated with the urban population living below the poverty line in the urban slum area. Figure 12 shows the proportion of the urban population living in slums. It shows that, in the year 2016, 23% of the global population is living below the poverty line. This proportion is very high, around 59% for least developed countries and 56% for Sub-Saharan Africa.

WWDR, 2019 states that human rights laws do not support to provide essential drinking water services at free of cost, but it states that it is necessary to have a compulsion on the government to provide free services or provide sufficient subsidy to make sure that services forever remain reasonably priced for the poor. The detachment of water services for the reason that of failure to pay due to insufficient money may constitute a contravention of human rights (HRC 2014). Large people in many developing countries be inclined to live on what they earn on an everyday basis and contain no money in balance to pay for unexpected sickness. The loss of income due to illness and the incapability to pay for the medicinal treatment, many families are pushed further into the cycle of poverty [24]. There are two types of costs with human sickness: direct and indirect costs. Direct costs stand for the costs related to the utilization of the medical resource. Indirect costs associated with work loss, earnings loss, and decreased productivity from illness. Population below the poverty level in developing countries is bearing the indirect cost of illness due to water-borne diseases around US$ 0.6–1.2 per day, for low and average income families a direct cost of illness is US$ 2.3 per day, and the indirect cost of illness is in between US$ 2.3 to 4.7 per day [27].

# 3 Energy and Drinking Water

Energy is a vital element for the social and economic development of every country. All types of energy require water for their production and energy itself is required to make the water resources available for human use and agriculture. Water treatment relates to the processes used to purify, disinfect and protect the water as per guidelines of the World Health Organization (WHO). The methods of water treatment depend upon energy availability (mostly electricity) around the day; which is rarely available in many developing countries. WWDR, 2019 states that 1.1 billion people on the globe have no access to electricity; hence they are under the sever influence of drinking contaminated water. Nature-based technology for water purification is not usually suitable for a large scale as they do not assure about the quality of drinking water. This section explains various desalination technologies, its energy consumption and ill effects on the environment.

## *3.1 Water Desalination Technologies*

The challenge of providing sufficient and safe drinking water is elevating day by day due to rapid population growth, industrialization, urbanization, water pollution, and climate change. Several steps are taken by many developing countries to improve the drinking water supply such as water conservation, advancement in water collection and distribution systems, periodic repair and maintenance of water supply infrastructure. These steps improve the use of existing water resources but not increase them. The alternative method to increase the drinking water supply is water desalination and water reuse [28]. Brackish water sources include seawater, lakes, ponds, ground wells, bore wells, rivers, wastewater, industrial feed, and process water. Conversion of brackish or seawater into potable water is known as desalination. Desalination splits saline water into two parts: (a) low concentration of saltwater, i.e. product water (b) higher concentration water, i.e. brine concentrate. There are five main constituents of a desalination plant, as shown in Fig. 13 [13].

### 3.1.1 Classification of Desalination Systems

The desalination process is broadly classified as thermal or membrane desalination. Within these types, there are sub-categories shown in Fig. 14.

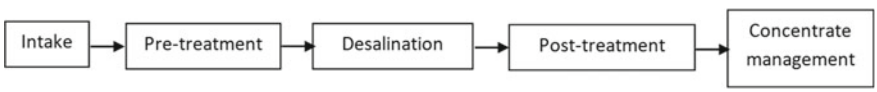



**Fig. 13** Main elements of the desalination plant

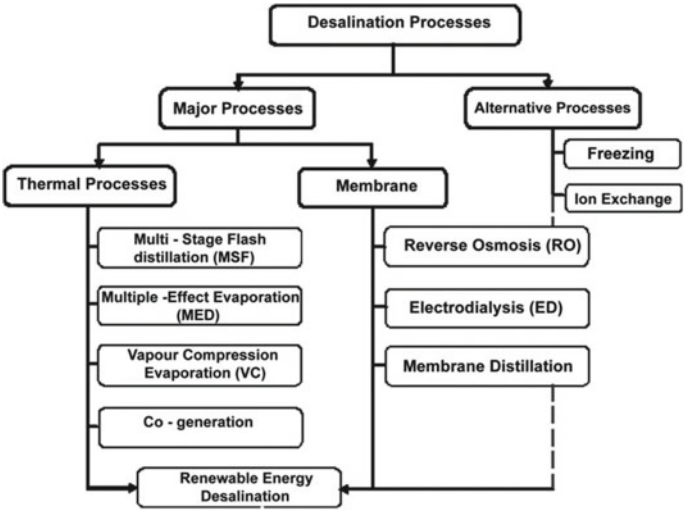
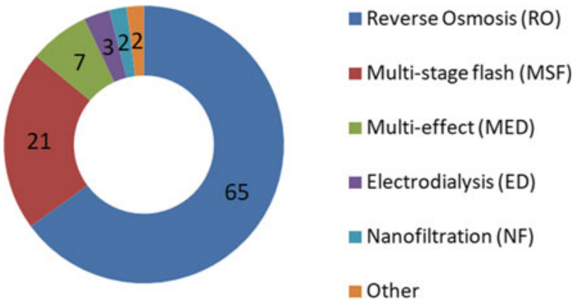



**Fig. 14** Classification of desalination systems [29]

**Fig. 15** Global installed capacity of desalination technologies in percentage [10]




The variety of commercially existing seawater desalination systems and their installed capacity in percentage is shown in Fig. 15. Multi-stage flash, multi-effect distillation as well as reverse osmosis is leading technologies used for seawater desalination. Electrodialysis and nanofiltration are typically used for brackish water distillation.

### 3.1.2 Thermal Technologies

In thermal technologies, saline water is heated, evaporated and its condensate is collected as distilled water. Thermal technologies are found to be expensive for brackish water desalination; however, they are cost-effective for seawater desalination. Thermal technologies are sub-divided into three groups (Fig. 12): Multi-Stage Flash Distillation (MSF), Multi-Effect Distillation (MED), and Vapor Compression

Distillation (VCD). In the MSF process, the feed water is first heated under high pressure and then supplied into the flash chamber where its pressure is reduced, and it is quickly vaporized. The vapor generated during this process is converted into freshwater by condensing it in the heat exchanger. In MED, a series of the evaporator is used to produce distilled water at progressively lower pressures. In VCD heat for evaporation of the water comes from the compression of vapor using a mechanical compressor. The heat rejected by the compressor during the compression is used to evaporate the saline water. The VCD units are smaller in capacity and are often used at hotels, resorts and in small industrial applications.

### 3.1.3 Membrane Technologies

Membrane technologies are classified into two groups: Electrodialysis or Electrodialysis Reversal (ED/EDR), in addition to Reverse Osmosis (RO) (Fig. 12). Electrodialysis (ED) is a voltage-driven membrane method used to desalinate the water. Electrical energy is used to remove salts through a membrane, giving fresh water as product water. In Reverse Osmosis (RO) process, saline water is forcefully passed through a semi-permeable membrane to convert it into product water and concentrated brine. RO processes are useful for desalinating both brackish water as well as seawater. A new membrane distillation process is Nanofiltration (NF). It is used for low total dissolved solids (TDS) water such as surface water and groundwater. It is mostly suitable for domestic applications.

### 3.1.4 Desalination in Developing Countries

The total number of desalination plants installed worldwide are more than 19,000 with the cumulative freshwater production capability of 95.6 million $m^3$/day. The worldwide capacity of desalination plants is probably to grow at a yearly rate of over 9% up to 2030. About 54% of the global growth is expected to occur in the developing countries of the Middle East and North Africa region. In this region desalination capacity is expected to increase from the 21 million $m^3$/d in 2007 to reach 110 million $m^3$/day by 2030. Out of this, 70% installation will be in KSA, UAE, Kuwait, Algeria, and Libya. The biggest desalination plant is set up in the city of Ras Al-Khair, KSA, which uses both membrane and thermal technology with a capacity of over 1 million $m^3$/d. It is in operation since 2013 [30]. The percentages of the desalination technology used in developing countries are 60, 27, 9, and 4% for RO, MSF, MED and ED respectively [31]. Table 6 illustrates the top five countries with their desalination capacities and type. The highest installation of desalination systems are found in Saudi Arabia (KSA) (25.6% of the total capacity) [13].

Figure 16 shows the installed desalination capacity of three leading developing countries Algeria, India, and China. It indicates that China uses more desalinated water about 4.5 $Mm^3$ per day than India and Algeria. India and China are using most of the desalinated water for industrial purposes; however, Algeria is using it mostly

**Table 6** Top five countries with installed desalination capacities [13]

| Country | Total Capacity ($m^3$/day) | % of Global production | MSF | MED | MVC | RO | ED |
|---|---|---|---|---|---|---|---|
| Saudi Arabia | 5,253,200 | 25.9 | 67.7 | 0.3 | 1.2 | 31 | 1.9 |
| United state | 3, 092,500 | 15.2 | 1.7 | 1.8 | 4.5 | 78 | 11.4 |
| United Arab Emirates | 2,164,500 | 10.7 | 10.7 | 0.4 | 3.0 | 6.5 | 0.2 |
| Kuwait | 1,538,400 | 7.6 | 7.6 | 0.7 | 0.0 | 3.4 | 0.3 |
| Japan | 745,300 | 3.6 | 3.7 | 2.0 | 0.0 | 86.4 | 6.8 |

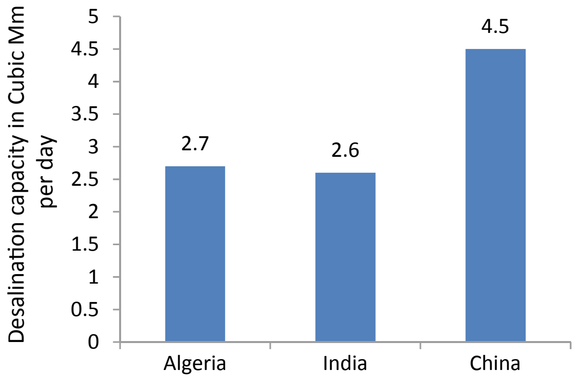



**Fig. 16** Installed desalination capacity (*Source* UNESCO-IHE 2013)

for community drinking (Fig. 17). Figure 18 shows that membrane technology is mostly used technology by these countries.

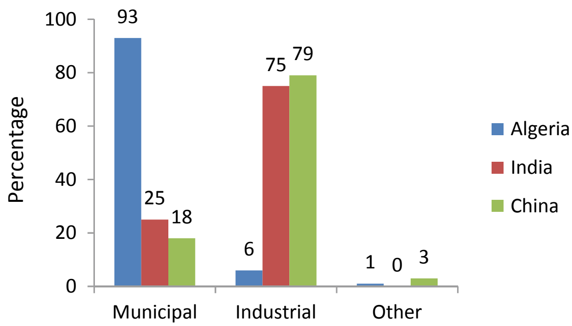



**Fig. 17** Use of water obtained from the desalination plant (*Source* UNESCO-IHE 2013)

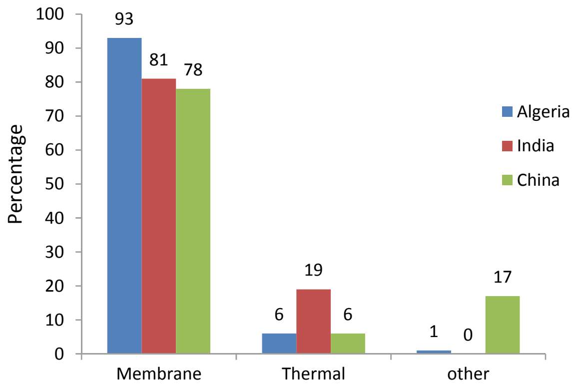



**Fig. 18** Desalination technology (*Source* UNESCO-IHE 2013)

### 3.2 *Energy Consumption and Environmental Footprint of Desalination Systems*

Desalination technologies are still more expensive and energy-intensive. Tables 7 and 8 shows the power and specific energy consumption of different desalination technologies [13]. Table 7 shows that the reverse osmosis (RO) is the most energy-efficient technology, and its added advantage is that it does not consume any thermal energy.

Desalination plants consume a considerable amount of thermal and electric energy which results in a significant emission of greenhouse gases [32]. Current seawater reverse osmosis (SWRO) desalination plants consume energy in between 3 to 4 kWh/m$^3$ and emit carbon dioxide between 1.4 and 1.8 kg per cubic meter of produced desalinated water. Another significant difficulty associated with the desalination plant is the saline water intake system. The intake process can kill a large number of fishes and other living beings in the seawater. Moreover, the discharge of desalination by-product, i.e. brine concentrate whose salinity is about twice that of seawater and the chemicals used in pre-treatment and membrane-cleaning exerts high environmental risks to living organisms when discharged to the river or seawater [28]. Table 8 shows that specific energy consumption for brackish water reverse osmosis is the lowest; however, for the multi-effect desalination process, it is highest. Forward osmosis is also emerging technology, but it consumes heat energy in addition to electric energy.

**Table 7** Power consumption of desalination technologies [13]

| Desalination technology | Total electric energy | Heat consumption |
|---|---|---|
| MSF | 3–5 kWh/m$^3$ | 250–330 kJ/Kg |
| MED/TVC | 1.5–2.5 kWh/m$^3$ | 145–390 kJ/Kg |
| MVC | 8–15 kWh/m$^3$ | – |
| RO | 2.5–7 | – |

**Table 8** Specific energy consumption of desalination technologies [33]

| Technology | Specific energy consumption (kWh/m$^3$) | | |
|---|---|---|---|
| | Electric | Thermal | Total electric equivalent |
| BWRO | 0.5–3 | – | 0.5–3 |
| SWRO | 3–6 | – | 3–6 |
| ED | 1–3.5 | – | 1–3.5 |
| EDR | 1–2 | – | 1–2 |
| MVC | 7–15 | – | 7–15 |
| FO | 0.2–0.5 | 20–150 | 10–68 |
| MD | 1.5–4 | 4–40 | 3–22 |
| MSF | 2.5–5 | 40–120 | 21–59 |
| MED | 2–2.5 | 30–120 | 15–57 |
| MEB | 2 | 60 | 30 |

*Notes BWRO* brackish water reverse osmosis; *SWRO* seawater reverse osmosis; *ED* electrodialysis; *EDR* electrodialysis reversal; *MVC* mechanical vapor compression; *FO* forward osmosis; *MD* membrane distillation; *MSF* multi-stage flash; *MED* multiple-effect distillation; *MEB* multi-effect boiling

## 3.3 Carbon Footprint

A carbon footprint is described as the quantity of carbon dioxide discharged into the atmosphere from the activities of an individual, organization, neighborhood or entire nation. It stands for global warming and climate change. The conventional desalination technologies are operating at very low thermal efficiency usually 10–15%; hence their energy consumption and environmental impact are inherently high which must be reduced to attain Conference of Parties (COP) goal-21, i.e. to maintain environment temperature below 2 °C. Several technological developments are done in the desalination sector to save energy and carbon emission. Fossil fuel operated desalination processes are the primary source of $CO_2$ emission. At present, globally installed desalination plants are contributing 76 million tons (Mt) of $CO_2$ per year. It is estimated that it will increase up to 218 million tons of $CO_2$ per year by 2040. In 2019, global $CO_2$ emission is estimated to increase up to 43.2 gigaton (Gt) per year, which is 20% higher than the year 2013 value of 36.1 Gt per year [6]. Table 9 shows that RO desalination technology has the least carbon footprints on the environment.

**Table 9** The carbon footprints of various desalination technologies [34]

| Water desalination method | Carbon footprint (kg $CO_2$) |
|---|---|
| MSF | 1.98–34.68 |
| MED | 1.19–26.94 |
| RO | 1.75–2.79 |

The energy required for surface water treatment is the lowest as water is available close to the delivery point. For groundwater treatment, it is expensive as most of the energy is utilized by the pumping process depending on groundwater depth. The energy required for brackish water treatment is also high, depending on the composition and concentration of salt. For seawater treatment, energy consumption is highest because of highly saline feed water quality. After the working life of 30 years, China's south-to-north water project is releasing about 0.179 kg $CO_2$. Similarly, UAE desalination plants are releasing 2.988 kg $CO_2$ for the multi-stage flash (MSF) method, 1.280 kg $CO_2$ for the multiple effect distillation (MED) method, and 2.562 kg $CO_2$ for the reverse osmosis (RO) method.

### *3.4 Economic Burdon of Desalination*

Energy remains a crucial problem for developing nations; hence they are frequently reviewing their energy policies at the high priority. In many developing countries, the poor are often pay high costs to energy or sometimes non-availability of energy services. Low-income families with a lack of cash reserves are unable to pay quickly for their energy expenditure. They generally prefer monthly energy service expenses. The energy price was increasing and reached to the maximum for almost all sectors of society. High energy bills and energy burden on the community hurt the economy of the nation both in the domestic sector, e.g. high contribute to energy subsidies, high energy demand due to competitiveness and external sector, e.g. trade deficit. Developing nations such as Morocco, Israel, Jordan, and Lebanon are the most energy importing nations. The high tendency of unpredictable and growing energy prices is expected to continue at a similar rate and thus increase the pressure and imbalances at the micro and macro economy levels of these countries [35].

It has estimated that nearly 0.71 kWh of energy is required for the distillation process to produce one cubic meter of freshwater from brackish water; consequently, this results in the burning of at least 1 ton of oil to produce 20 tons of desalinated water using thermal technology [36]. The International Renewable Energy Agency (IRENA) says that seawater desalination using MSF consumes typically 80.6 kWh of heat energy and 2.5–3.5 kWh of electrical energy per $m^3$ of water, while large scale RO requires 3.5–5.0 kWh of electricity per $m^3$ of water. Currently, the global production of about 95.6 million $m^3$/d of desalinated water requires the use of at least 110 TWh per year, which is equal to 0.58% of global electricity consumption. The cost of desalination is decreasing from the last few years up to US$ 0.5/m3, while its market price is in between US$ 1–2 per $m^3$; therefore, desalination is currently not affordable for many middle-income and developing countries. Table 10 shows the cost of desalination per cubic meter of water. It is found that cost reduces with an increase in desalination capacity of the plant. In thermal technologies, for the lower capacity up to 1200 $m^3$ per day, vapor compression desalination is found to be most economical whereas, for high desalination capacity, multi-effect desalination is cost-effective.

**Table 10** Cost of desalinated water in various thermal processes [13]

| Desalination process | Desalination plant capacity ($m^3$ per day) | Desalination cost per $m^3$ (US$) |
|---|---|---|
| Multi-effect distillation (MED) | <100 | 2.5–10 |
| | 12,000–55,000 | 0.95–1.95 |
| | > 91,000 | 0.52–1.01 |
| Multi-stage flash (MSF) | 23,000–528,000 | 0.52–1.75 |
| Vapour compression (VCD) | 1000–1200 | 2.01–2.66 |

**Table 11** Price of desalinated water produced using membrane plants [29]

| Feedwater | Desalination capacity ($m^3$/day) | Desalination cost per $m^3$ (US$) |
|---|---|---|
| Brackish water | <20 | 5.63–12.9 |
| | 20–1200 | 0.78–1.33 |
| | 40,000–46,000 | 0.26–0.54 |
| Seawater | <100 | 1.5–18.75 |
| | 250–1000 | 1.25–3.93 |
| | 15,000–60,000 | 0.48–1.62 |
| | 100,000–320,000 | 0.45–0.66 |

Table 11 gives the cost comparison of brackish water and seawater desalination using the reverse osmosis plant. As brackish water has lower salinity than seawater; hence its desalination is found to be cheaper. RO was found to be the most economical technology for large scale seawater desalination. MSF and MED follow this. The investment cost of a large scale RO plant is somewhere in the range of 500–1000 million dollars, depending on the size, and it can generate freshwater in the range of US$ 0.45–0.55/$m^3$ [37].

Approximately 5.2 billion people in the world have admittance to safely managed drinking water providing services. They mostly rely on piped systems, along with additional conventional, central and decentralized water supply and treatment systems. Piped water is the least costly method to transport water. However, it is not readily available to poor people, which unbalances urban slums, remote and rural areas of developing countries. If water supply from the piped network is not available, then the community has to rely on surface water, ground wells or community water supply systems, e.g. water delivery through stalls, sellers and a water truck to access the drinking water. They generally pay the high price per liter of water as compared with individuals or communities which are serviced by a water pipe network system. Water-Aid (2016) reported that underprivileged people in low- and middle-income countries could typically payout 5–25% of their income on drinking water to meet their basic needs of about 5 L per person per day and in certain parts of Madagascar and Papua New Guinea, several people pay out over half of their earnings to purchase water from salespersons. In many cases, the poor pay extra and receive less water, and it is often of poor quality.

In the Middle East and North Africa (MENA) region, drinking water demand is estimated to increase from 9 billion $m^3$ in 2010 up to 13.3 billion $m^3$ in 2030, while groundwater resources are expected to decrease day by day. As a result, desalination capacity in this region is expected to overgrow from 21 million $m^3$/day in 2007 to nearly 110 million $m^3$/day by 2030, out of which 70% growth is in Saudi Arabia, the United Arab Emirates, Kuwait, Algeria, and Libya. The total electricity demand for desalination in the MENA region is expected to increase up to 122 TWh by 2030, which is three times as compared with the requirement in the year 2007. Desalination demand is also expected to grow in the developing countries of Asia and the Caribbean region. China and India have high potential marketplaces intended for desalination due to rising population and economies with water shortage. Hence in these countries, the need for desalinated water is increasing even faster than the economy of the country; as a result, there is a proportionately increase in the energy consumption of the country [29].

## 4 Energy and Health

WHO says that better health is the key to human happiness and well-being. It makes a contribution to the economic progress of the nation as healthy people live longer, they are more productive, and they save more. In developing countries, lack of access to energy is a severe obstacle to acquiring the delivery of many essential health services, including the supply of safe drinking water. The right to drinking water does not mean the right to purchase mineral water, but it is right to consume safe drinking water even if people cannot pay its cost. Poor households use less energy than wealthier ones. Less water is boiled for drinking and other hygiene purposes which increases the possibility of water-borne diseases. Illness reduces the ability of poor people to improve their livings and increases their helplessness. It not only prevents adults from working effectively but also negatively affecting children's health and their learning ability [38]. Figure 19 shows the inter-link between the energy and health of the people.

The waterborne diseases such as diarrhoea, the contributing aspects are typically energy-associated that comprise a lack of pumping systems from clean water sources, shortage of energy or fuel to boil the water, and lack of built-up processes for water treatment or decontamination. The Fig. 20 compares access to improved water supply in rural and urban areas in selected developing countries. In most of the developing countries, it is observed that a much more significant portion of the urban population enjoys access to improved sources of water by using household piped water connection, public standpipe, borehole, protected well or spring, and rainwater harvesting. Nevertheless, rural areas are facing the problem of safe water for drinking and other

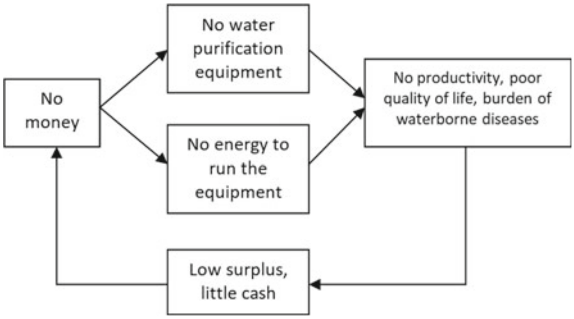



**Fig. 19** Energy-health nexus

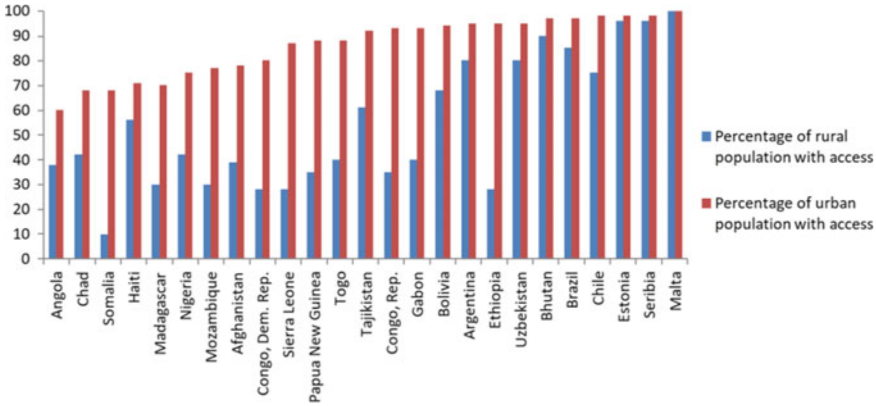



**Fig. 20** Access to an improved source of water (%) for selected developing countries [39]

purposes; consequently, 80% of all illnesses are related to impure water consumption [39].

## 5 Interdependency of Energy, Drinking Water, and Health

Literature shows that energy, drinking water and health are strongly interdependent factors. Many people in developing countries do not afford energy services; hence they use naturally available surface or groundwater without any treatment. They usually suffer from waterborne diseases and undergo loss of productivity and economy. They do not have surplus money to deal with an unforeseen health issue and enter the cycle of poverty. Many developing countries are constructing desalination plants to accomplish the demand for clean drinking water. They fulfill their energy demand by burning fossil fuel which is a major cause of local environmental

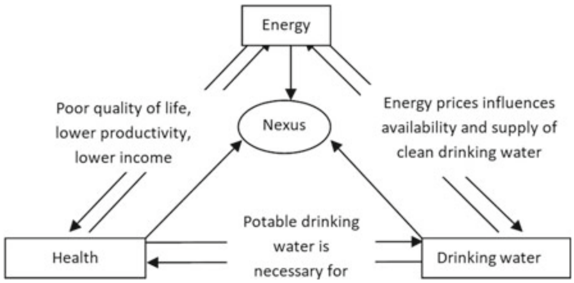



**Fig. 21** Energy-drinking water-health nexus

damage. These plants affect not only the environment but also the economy of developing countries because of the high energy expenditures. Figure 21 illustrates the interlink between energy, drinking water and health.

## 6 Managing the Energy-Drinking Water-Health Nexus

This section suggests some of the measures for the efficient nexus management of energy, drinking water, and health. The nation's health will improve, and people will prosper swiftly only when energy and safe drinking water is affordable and adequate for everyone at all levels.

### *6.1 Roll of Government and Public*

The government of many developing countries cannot always able to take complete accountability for providing safe water supply services to all general public. To ensure safe and affordable drinking water to all communities requires policy formation and implementation. Good governance involves measures and mechanisms that promote efficient policy implementation. In this context, multilevel governance and the role of a non-government organization (NGOs), active public participation is crucial for national and regional policy formulation to provide safe drinking water to all. Corruption, excessive regulation, very rigid rules, bureaucratic inertia increases the water transaction cost, discourage external investments and delay in water management reforms. Figure 22 illustrates the roadmap towards the fulfillment of SDG-6 goal using active participation of government, NGOs and local people.

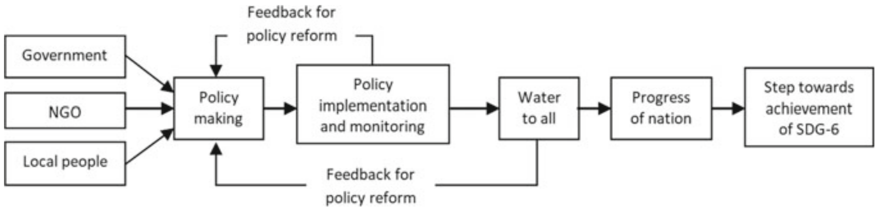



**Fig. 22** Roadmap for water management

## *6.2 Roll of Capital Investment*

People who are not connected to piped water supply systems, suffer from impure water, and they often pay more for water supply services than piped connected region. Expenditure on piped drinking water includes significant capital investments, operation, and maintenance of water supply systems. One way of increasing affordability to the ordinary family is to lower the cost of water providing the services which can be possible using technological innovation, improvement in water supply management, good governance, increasing transparency in water distribution and efficiency improvement of water desalination systems. The population density in village areas is low to justify the cost of household water connections. Supplying drinking water to groups of households rather than individual households in remote and village areas of low-income could reduce the investment cost and allow excellent and affordable water services for the poorest. Especially in developing countries, it is necessary to invest in water supply infrastructure to overcome social and economic inequalities and discriminatory nature to accomplish SDG target, which is focused on widespread and evenhanded access to protected and reasonably priced drinking water (UNGA 2015a). A decentralized wastewater treatment system is an attractive alternative with meager investment and the operational cost. It can offer more efficient solutions for rural and semi-urban areas of developing countries.

## *6.3 Roll of Good Governance*

Successful management of water resources needs to account for water quantity and water quality of resources as well as a societal dimension. Governance must ensure security and access to water in rural areas and should create opportunities for water investments. The water-related needs of small villages must be fulfilled by creating permanent water sources and infrastructure. Water allocations to large-scale users must not take place at the expense of small-scale farmers' legal needs. Educational structures, policy guidance, oversight coordination, monitoring, and evaluation are necessarily required to provide clean and sufficient drinking water to everyone. Good water governance can be done using: enhancing the efficiency of water supply

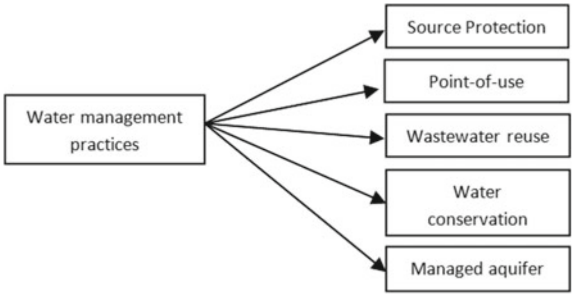



**Fig. 23** Water management practices

systems, improving accessibility, addressing the investment gap, capacity development of desalination, and awaking people about their roles and responsibilities in realizing the human rights to water. Figure 23 shows various water management practices for good water governance.

## *6.4 Cogeneration Systems*

Cogeneration is defined as the combined production of electricity and useful thermal energy from a single fossil energy source. Cogeneration concept for desalination is found to be efficient where both power and potable water are produced simultaneously. It has several benefits such as (i) low-grade waste heat is reutilized; hence, low carbon footprint (ii) reduction in cooling water demand during power production (iii) decrease in the cost of desalinated water and power consumption. Figure 24 shows that cogeneration not only improves thermal efficiency, but it also reduces environmental impact. Gas turbine cogeneration system for water desalination is found to be most attractive as it can achieve 80% overall efficiency and 25% environmental impact as compared with 57% efficiency and 35% environmental impact of single-purpose combined-cycle gas turbine power plant [6].

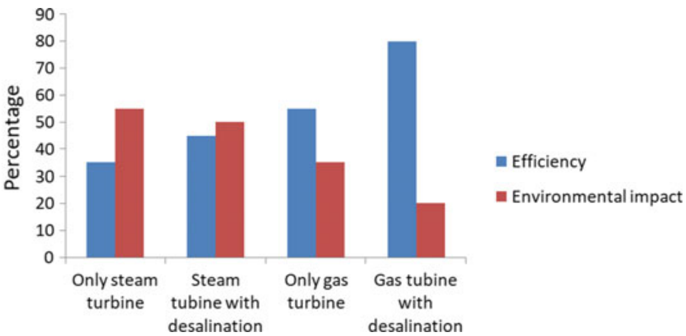



**Fig. 24** Effect of cogeneration on thermal efficiency and its environmental impact [6]

## 6.5 Use of Renewable Energy for Desalination

Renewable energy is produced from those sources which do not deplete within a human's lifetime. The typical examples are wind, solar, geothermal, biomass and hydropower. Renewable energy systems are eco-friendly and have low carbon footprints [40]. As desalination processes require a large amount of input energy to achieve separation of salts from saline water. The dramatic increase in demand for desalinated water creates a series of problems related to energy consumption and environmental carbon footprints caused by the burning of fossil fuels [41]. Figure 25 shows how the demand for energy consumption for desalination is increasing in developing countries.

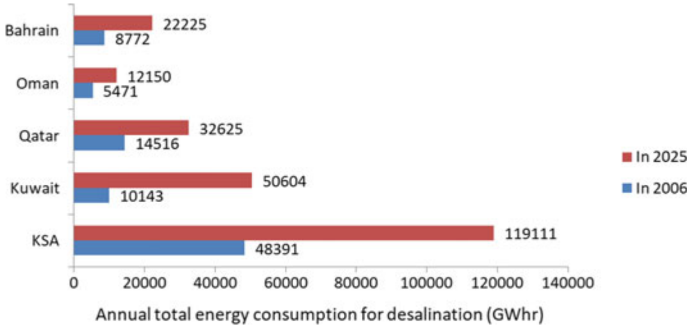



**Fig. 25** Increasing demand for energy consumption for desalination [15]

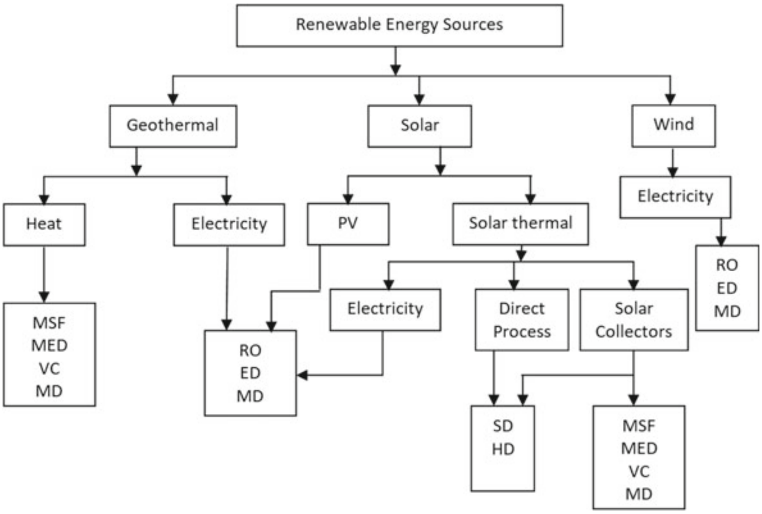



**Fig. 26** Renewable energy resources with water desalination technologies [29]

For reducing the burden of fossil fuel expenditure, renewable energy is a viable solution [42]. Production of freshwater using renewable desalination technology is a workable solution to the water scarcity problem in remote areas that lack in conventional energy sources like heat and electricity. Besides, to minimize greenhouse gas emissions, renewable energy sources could feed directly to run the desalination plant [43]. Figure 26 shows possible combinations of use of renewable energy with water desalination technologies [29].

Drinking water supply in Saudi Arabia (KSA) relies a lot on desalination. It has the biggest desalination market in the globe. The average annual direct normal solar irradiation in KSA is more than 6 kWh/m$^2$ per day, which is sufficient to run a concentrated solar power desalination system [13]. The economics of the desalination system running on renewable energy depends on the cost of renewable energy. Currently, the cost of renewable desalination is higher as compared with the cost of conventional desalination running on grid electricity or fossil fuels. However, the costs of renewable technologies are quickly decreasing day by day, and renewable desalination can now compete with conventional systems in remote regions where the cost of energy transmission and distribution is higher than the cost of energy generation. The future expected electricity cost beyond the year 2020 for most of the typical solar systems is reported to be between US$ 0.04–0.1/kWh for annual energy isolation of 2500 kW/m$^3$ [31]. The breakdown cost for SW-RO desalination showed that energy consumption is about 43% of the total water production cost as compared to 59% for the large-scale thermal desalination plant. The estimated water cost for desalination with photo-voltaic powered seawater desalination using reverse osmosis (PV/SW-RO) system is about US$ 1.21 m$^3$ while it is in between US$ 1.18–1.56 for conventional RO desalination. Table 12 shows various renewable

**Table 12** Various renewable water desalination systems with energy consumptions and cost of product [31]

| Option | Capacity m$^3$/d | Energy consumption (kWh/m$^3$) | Water cost (\$/m$^3$) |
|---|---|---|---|
| Solar stills | <0.1 | – | 1.3–6.5 |
| Solar-multiple effect | 1–100 | Thermal: 100 | 2.6–6.5 |
| Humidification | | Electrical: 1.5 | |
| Solar/CSP-multiple effect | >5,000 | Thermal: 60–70 | 2.3–2.9 |
| Distillation | | Electrical: 1.5–2 | |
| Photovoltaic-reverse osmosis | <100 | Electrical: 4–5 | 11.7–15.6 |
| Wind-reverse osmosis | 50–2,000 | Electrical: 4–5 | 6.5–9.5 (capacity <100 m$^3$/d) 6.5–9.1 2–5.2 (capacity 1000 m$^3$/d) |
| Wind-mechanical vapour compression | <100 | Electrical: 11–14 | 5.2–7.8 |

energy-driven water desalination systems with their energy consumptions and the cost of product water [29].

## 7 Conclusions

This communication explores the nexus among energy, drinking water and health in developing countries and reveals how appropriate this nexus is for economic development, environmental sustainability, and energy security. Following are the key findings of this study:

- Over 2 billion people living in developing countries facing high water stress, 3 out of 10 people have no access to safe drinking water.
- Annually, about 2.2 million people die from diarrhoea; 90% of these deaths are among the children.
- Population below the poverty level in developing countries is bearing the indirect cost of illness due to water-borne diseases around US$ 0.6 to 1.2 per day.
- Desalination technologies are still more expensive, energy-intensive and not eco-friendly.
- Multilevel governance and the role of a non-government organization (NGOs), active public participation is crucial for national and regional policy formulation to provide safe drinking water to all.
- One way of increasing affordability to the ordinary family is to lower the cost of water providing the services. It can be possible using technological innovation, improvement in water supply management, good governance, increasing transparency in water distribution and efficiency improvement of water desalination systems.
- The gas turbine cogeneration system for water desalination is found to be the most attractive method.
- Production of freshwater using renewable desalination technology is a workable solution in remote areas that lack in conventional energy sources like heat and electricity.

From the assessment, it can be concluded that in developing countries, energy, drinking water and health is a multifaceted issue of nexus that must be dealt with comprehensively. Communities facing energy crises frequently are short of safe drinking water services; as a result, they suffer from ill-health. It adds to the monetary burden on them caused by loss of work productivity and earnings. With a low cash reserve, the community is unable to fulfill the demand for energy and safe drinking water. The enhanced water supply systems and improved administration of water resources can boost up countries' economic growth and contribute significantly to poverty diminution.

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# Updating Energy Security and Environmental Policy: Energy Security Theories Revisited

**Liliana N. Proskuryakova**

**Abstract** National and corporate policymakers view energy security strategies through the lens of mainstream concepts and definitions offered by research and policy discourse. The central elements of the classical energy security concepts are based on the premises of sufficient and reliable supply of fossil fuels at affordable prices in centralized supply systems. However, these approaches offered by neorealism, neoliberalism, constructivism, and international political economy are outdated. They rarely take account of the latest changes in the energy industry and society. The chapter examines the classic energy security concepts and assesses to what extent changes in the energy industry are taken into consideration. This is done through integrative literature review, comparative analysis, identification of 'international relations' and 'energy' research discourse with the use of big data, and country case studies. The chapter offers suggestions for revision of energy security concepts through integration of future technology considerations, new energy sources, new actors and the interrelation among them, the specific features of the developing and least developed countries and their energy relations with the wealthy states. Moreover, the differences in International Relations and Energy researchers' discourse of energy security are outlined together with a rationale for the interdisciplinary approach to energy security, combining the natural and social sciences ideas and tools. The findings are illustrated with case studies of energy security policymaking in selected countries.

**Keywords** Energy security · Energy technology · Energy policy · Energy challenges · Sustainable energy

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## 1 Introduction

Energy security is one of key parameters for assuring a stable development of countries and regions. Today energy demand has been growing faster than ever, particularly in the developing countries, making energy security an integral part of national security. Energy security is also an important element and the source of interdependence in international relations [1]. There is a close interlink between energy policy (energy governance) and dominant ideologies through which groups of stakeholders debate key energy issues [2]. This interlink has major implications in the event of energy transitions that reveal how energy systems function and how they may develop in the future [3].

Energy security as perceived by international development organizations and national policies often focuses on fossil fuels, while neglecting energy equity and environmental sustainability [4]. This is particularly a problem for the developing countries. Therefore, integration of energy governance and energy security perspectives is required to understand and address the difficulties of a just energy transition in the context of the standard energy trilemma [5]. At the same time, energy policy should avoid excessive securitization of all energy issues [6].

Energy security issues emerged on the political agenda in the early 20th century [7]. However, energy security concepts were included in the research discourse only in the 1960s. Further interest of researchers in this subject had a wave-like nature, following changes in the energy markets. In recent years the energy security concept has experienced a revival, with a renewed interest from researchers, managers and policy makers [8].

The term ‘energy security’ has evolved accordingly. If in 1970s and 1980s the researchers gave the top priority to a stable supply of cheap oil, despite the restrictions and price manipulations of exporting countries [9]. Some attention was given to the need for better management of energy enterprises, including state-owned [10], and for more effective management of energy technology [11]. In the 2000s attention was paid to ensuring equal access of all social groups to safe energy sources and reducing negative impact of the energy sector on the environment [12] and climate [13].

The approaches to energy security vary depending on a discipline in which this concept is used: the theoretical analysis of energy security can be found in both social sciences and liberal arts (political science, international relations and economics), and in natural sciences (math, physics) [8]. The social scientists usually focus their energy security research either on the analysis of international (geopolitical) relations and policy analysis [14] or on discursive and contextual dimensions of politics [15, 16]. A number of studies underline the interdisciplinary approach to energy security [17, 18].

The classic approach is to assess the four key parameters of energy resources: their availability, accessibility, affordability and acceptability [19, 20], of which availability and affordability seem to be more significant in terms of impact on other elements of energy security [21]. The main energy security elements that are usually included in the definition of the term are resource nationalism [22], secure supplies of affordable energy resources, diversification of energy sources in the energy mix and through different suppliers, secure energy and fuel transportation (transit) and corresponding infrastructure, prospective geopolitical and market changes, and *threats that are caused by or have an impact on the energy supply chain* [23]. The traditional national security concepts today merge with more recent concepts of human rights and individual security, energy justice and sustainable development [24].

Dayer and Trombetta claim that energy security implies *continuous access to various forms of energy in sufficient quantity and at affordable prices* [25]. This definition is similar to the International Energy Agency's (IEA) long-term energy security understanding: *uninterrupted availability of energy sources at an affordable price*. The short-term IEA approach to energy security underlines *the availability of the energy system to react promptly to sudden changes in the supply-demand balance*. New research in energy security also takes account of environmental and social aspects [26]. Other researchers define energy security as *assuring citizens', state, societal and economic protection from energy shortages (deficit) and blackouts, provision of quality energy resources* [27]. A more compound and, at the same time, wider definition by Cherp and Jewell, states that energy security means *low vulnerability of vital energy systems* [12].

Markovska et al. argue that the top 10 energy security challenges are decarbonising the world economy; enhancing the energy efficiency and energy savings in buildings; advancing the energy technologies; moving towards energy systems based on variable renewables; electrifying the transport and some industrial processes; liberalizing and extending the energy markets; integrating energy sectors to Smart Energy Systems; making the cities and communities smart; diversifying the energy sources; and building more biorefineries [28]. There are other security concerns, including *terrorism or more mundane forms of crime, such as fraud, in management of nuclear waste* [29], and nuclear power generation more generally. This positions energy security at the interlink of three perspectives: sovereignty, robustness, and resilience, of which the last one covers technology changes [30].

These challenges listed above better reflect the relation between energy and security and should be better analysed within energy security concepts [31]. Moreover, various aspects of global competition for energy resources, wide application of renewables [32], interdependence of the economies and energy systems (infrastructure), climate change [19] and environment impact issues, as well as technological innovations [2] in the energy sector are also considered in the studies on the topic.

## 2 An Overview of Energy Security Concepts

Many researchers admit that the existing multiple understandings of energy security and underlying concepts are rather vague and contradictory [33, 34]. There are several obstacles that prevent the formulation of a single universal approach to energy security, as each nation or non-governmental actor has its own, subjective perception of the issue that may change with the evolution of social and other conditions [35, 36]. Governments and organizations may choose the energy security concept that justifies their policy and actions [37], which leads to the manipulation with the term. In this interpretation energy security can be compared to Rorschach inkblot test: you see what you want to see [33]. Due to a number of problems in the approach and understanding of energy security, energy security policy and energy security management also remain under researched [38]. This makes researchers call for reconceptualizing the process and practice of energy policy itself [2].

Despite the relatively high number of publications on energy security, there are a number of remaining research gaps. First, more future studies are required *to link the de-coupled areas of energy security, access to energy and climate change* [39]. Second, many previous studies rely on one-sided definitions of energy security focused on particular technical and economic aspects, while overlooking social and political elements such as good governance. Moreover, many energy security publications focus only on a particular sector, an individual state, or a specific technology [40]. Unlike earlier studies this chapter is not devoted to energy security of particular countries [41] and regions [42], is not focused on particular energy segment [43] or a single energy security concept [44]. The present contribution focuses on the theoretical approaches to energy security and offers outcomes that may be applied to any country and the entire industry within the realms of the four key energy security concepts.

Most publications on energy security relate to the analysis of particular countries, inter-country relations, regional and global energy security difficulties. Very few studies attempt to conceptualize energy security, analyze this phenomenon through the prism of key energy security concepts, and none attempt to revisit those concepts in a comprehensive manner in the light of new developments in the energy industry. The chapter aims at bringing more clarity to *a dizzying variety of fragmented and contradictory interpretations of energy security in scholarly and policy literature* [3] by examining and revisiting the four major theoretical approaches developed in the realm of International Relations theory [2]. The hypothesis is that energy security concepts are based on outdated security paradigms and do not reflect the meaningful energy trends that have surfaced over the last three decades [45]. As energy theories have their practical application, i.e. are used in international, national and corporate energy management and policymaking [46], neglecting the latest developments involves high costs [14]. Moreover, the transformations of energy security may transform the international system itself [43].

There four energy security concepts that dominate in the International relations theory are neorealism, neoliberalism, constructivism, and political economy. Each of these research strings offer a different view on the key energy security elements, actors, and priorities.

The energy security concepts that have traditionally focused on fossil fuels (their availability, control over these resources and their transportation routes) should also encompass various other energy resources, including the rapidly growing renewables, available in most locations. At the same time, the rapid technological changes in the energy sector could radically change the future energy outlook, and these have to be accounted for. The switch to renewables, such as solar photovoltaics, has some positive environmental and climate effects, contributes to improvements in energy security, especially in the developing world [47]. Energy future studies may be useful for understanding how to assure energy security by managing technical, economic, and policy changes related to energy supply and use [48].

Arguably the majority of researchers working on energy security look at it in the **neorealist** perspective. They focus on the energy policy of the states in the context of national interests and security, military confrontation and regional conflicts [49]. Military and forceful actions to assure energy security are among the key research subjects in neorealism [50]. Kalicki and Goldwyn view energy security only in the context of the national security. They believe that energy challenges the country faces should be better reflected in its foreign policy strategy [51]. Similarly, Kokoshin provides a typology of global energy-related political risks and looks into balancing the interests of the key world energy actors [52].

Realism is an approach to international politics that has a long historical tradition and numerous variants. It focuses on the actual state of the world, takes as given that the key actors are self-interested states, and that they interact in an anarchic setting, one in which there is no central authority to enforce order. As a result, states seek power and what emerges is a conflict-ridden world in which the balance of power is the only basis for order. The perspective has problems and limitations but few analyze international politics without focusing on the distribution of power [53].

Control over natural resources located in oceans draws increasing attention of neorealists. According to Nincic the interstate conflicts over access to fossil fuels will be inevitable as the future oil and gas reserves are situated offshore, and their extraction depends on the outcomes of the debates over the border delimitation in the global ocean [54]. Wilson considers maritime security to be the key condition for ensuring reliable energy delivery. The former should ensure addressing illegal activity and emergency situations at the territory covering over two thirds of the Earth's surface and 80% of transport routes [55].

Neorealist researchers believe that national interests should dominate energy policy, and bilateral deals should be more important than multilateral contracts. In most cases it is understood as strengthening of the state control over natural resources, primarily in resource-rich countries. Russia and Venezuela are usually cited as examples of the countries that pursue 'resource nationalism'.

Securing sufficient energy import is of paramount importance as the energy supplies are highly competitive. Multinational energy agreements similar to those existing in the European Union have their limitations, including quotas and other energy delivery obstacles, and, therefore, will subsequently become less attractive. Acting alone is better than facing the complexity of coordination where the interests of the importing states tend to prevail due to market failures [56].

A string of research focuses on structural security changes related to energy interests. Moran and Russell believe that the risk of a global military conflict is minimal despite the ongoing local conflicts [57]. In any case, the struggle for access to energy resources remains the most likely reason for escalating violence. High dependence of the world economy on oil and gas increases the risk of both local and regional confrontation that could possibly grow into a global one. Given fierce competition for energy resources and technologies among states, conflicts are inevitable and lead to boosting military capacities, complicating international cooperation. Military aspects of energy security are also noticeable in the domestic competition for energy exports rent in fossil fuel rich countries. Related problems in energy security may lead to terrorist attacks [58].

Opposite to neorealism is **neoliberalism** that focuses on international cooperation and the non-state actors. As the states are unable to control energy prices, the energy policy is made by transnational corporations, financial institutions, think tanks, mass media, and terrorist and criminal organizations that may have a significant impact on the global energy system and even disrupt regular economic activity of individual states [50].

The emergence of global energy market and the decrease in the number and intensity of conflicts decrease the likelihood of 'resource wars'. According to Fettweis the global energy system that was developed in recent decades is suitable for all major market actors regardless of their resource assets size [59]. Consequently, they are not interested in a military conflict that could destabilize the global or regional energy trade. Moreover, high costs of military operations and related political problems do not justify the takeover of oil and gas fields, as buying oil and gas at the market would be much cheaper and easier. As Goldthau and Witte point out, market forces that shape today's supply and demand, determine the volume of investments, and ultimately the future of the world energy. Institutions are of key importance in this system [60].

Neoliberals pay special attention to the role of international institutions in shaping the global energy industry [61]. Firstly, they can intervene in instances of market failures and in cases of extraordinary situations (i.e. economic problems or disasters). Such interventions happened in 1970-ies in the course of the oil crisis by the Organization of the Petroleum Exporting Countries and the International Energy Agency. Secondly, institutions, such as the International Energy Forum, improve information transparency and increase trust among global energy actors. Thirdly, the institutions (i.e. the World Trade Organization and the Energy Charter Treaty) are designed to establish rules and standards for international energy cooperation that are based on interdependence theory proposed by Keohane and Nye [62]. The market assures secure energy supply through competition, and interdependence guarantees cooperation. The reverse side or the side effect of international cooperation is energy terrorism which targets mainly energy infrastructure [63]. Further debate places 'energy security' in the context of 'securitization' phenomenon that appeared due to international relations actors' recognition of three types of challenges: assuring energy supplies; assuring secure energy extraction, transportation and consumption; and improving energy efficiency for environmental, economic and social purposes [64].

Unlike neorealists, neoliberals believe that the relationship between the energy market actors and energy security gains should not be perceived as a zero-sum game. One outcome of this cooperation that resulted in higher energy security is the global oil market. A key remaining challenge for energy security is assuring further development of liberal economy [60].

**Constructivists** offered to make person an object of security and widen the range of actors involved in assuring security for all individuals [65]. This string of research suggests that the basic features of international relations, including energy-related, are unsteady. International relations and economic well-being are created and reproduced by the actors involved. The same phenomena, including energy security threats, can be interpreted differently by different actors of international relations [66]. At the same time, assessments and rules of the game are subject to change as a result of interaction and information dissemination.

Energy problems are considered 'unstructured problems' with many uncertainties, fundamental disagreements and resistance from vested interests [67]. This suggests that top-down rationalist approach alone is not suitable and has to be replaced or complemented with others, which offer "second-best" policy mechanisms [7] or out of the box solutions, especially at the time of transition [68].

The energy security approach in constructivism underlines the need to see and pursue common interests and shared values, to sustain communications, interpersonal contacts and trust in overcoming conflicts, including energy-related ones. Constructivists believe that frames ("construction of temporarily fixed meanings by establishing chains of connotations among different linguistic elements") shape and promote specific understandings of the world, including energy policymaking, typically seen as defined by technical and economic frames [69].

**International political economy** school considers energy to be one of the secondary power structures that play a key role in supporting the four primary structures: security, finance, production, and knowledge. Today there is a competition between the four primary structures of power and the winners are often market actors, not states [70]. According to Strange, energy research requires a new, mixed approach that fully takes into account the impact of policy factors on the energy markets and, vice versa, the impact of these markets on policy [71]. The central issue here is finding the optimal balance between the state and the market that should be identified through a structural analysis of power execution in a particular society. Researchers of this school discuss international energy relations in terms of power, political rivalry, and different types of state governance in place [25].

As noted by Markusson et al., "different liberal capitalisms could be supported by different clean fossil technologies", while "illiberal or more egalitarian regimes remain possible alongside particular, perhaps radically re-envisioned, versions of clean fossil" [72].

Researchers emphasizing the geopolitical approach focus on countries struggling for access to energy resources. States establish direct or indirect control over certain fossil fuel reserves or energy transportation routes and promote the geographical diversity of energy export or import to ensure national security. Energy geopolitics proponents Pascual and Zambetakis note that the largest energy importers depend on oil (the US) and gas (the EU) imports and seek to diversify suppliers. They acknowledge the geopolitical aspects of national energy strategies and name economic reasons for politicization of world energy. The authors point to the lack of elasticity of the global oil market due to high dependence of some countries on exports and others on imports of hydrocarbons [73].

Most energy security studies are based on a combination of several theoretical concepts discussed above. Many authors acknowledge both the influence of government actors and the conflict potential embedded in the competition for access to energy resources that are typical for neorealism, as well as the significant role of international institutions and global markets that fit the neoliberal paradigm. Some of them also admit the influence of ideas that shape the perception of energy security issues, that later feed in policy decisions. For instance, Yergin identified ten principles of energy security that are important for all actors: diversification, security margin, high-quality and up-to-date information, co-operation between supplier and consumer countries, widening the influence of IEA through inclusion of China and India, stability of infrastructure and entire supply chain, well-functioning markets, energy efficiency (that also helps reduce impact on the environment), ensuring investment flow, and the advancement of new technologies [74].

The methods of this study include comparative analysis of the major energy security concepts in international relations that was performed though an integrative literature review for a mature topic—'energy security', followed by critique and reconceptualization based on the expanding knowledge base of energy systems and energy industry and a more diversified understanding of the concept [75].

The theoretical groundwork publications, mainly books, were selected for analysis of key energy security concepts in International Relations theory. Further, the analyses was limited to the contemporary debate related to energy security theory To this end, only research and review articles, books chapters, encyclopedia and editorials published in 2000–2018 were chosen through ScienceDirect, Web of Science (through big data algorithms), and Google Scholar using keywords. Of all ScienceDirect research and review articles and editorials on international relations 535 containing 'energy security' as keywords were selected. Based on analysis of these publications, four energy security concepts were chosen: neorealism, neoliberalism, political economy and constructivism [2, 76, 77].

ScienceDirect is among the largest databases that contains a good collection of publications in Social Sciences and Humanities and the Elsevier's platform of peer-reviewed scholarly literature featuring over 3 800 journals and 37 000 books. This database was accessed by corporate subscription with access to full texts.

In contrast, Web of Science (WoS) yields much less results. Out of 38 448 publications related to 'international relations' 175 contain 'energy security' as keywords (the majority of which relate to particular countries, regions or projects; many published in journals with very low visibility/impact factor). For example, out of 20 459 publications that contain 'energy security' as keyword, only two articles also contain 'neorealism', 12 'neoliberalism', three 'constructivism', and 256 'political economy'. Of these publications about two thirds relate to climate change (a growing topic in energy security studies) and country cases. The top cited 10% of WoS publications related to 'energy security' were analyzed with the use of proprietary text mining system iFORA. This was done to compare the mainstream international relations and energy research discourse on energy security. A similar systematic approach was suggested by Sovacool and Brown [78], who applied a meta-survey of existing literature to identify energy security concerns.

Although Google Scholar yields too many results for manual processing, the results are sorted by relevance (unlike in ScienceDirect), and the top selected sources contain the core theoretical contributions, mainly books and monographs. Only the top papers/books sorted by relevance were selected for review from this database, and it was possible to read/preview many books through GoogleBooks.

Further, after four mainstream energy security concepts were selected for analysis, the following keywords were applied: 'neorealism energy', 'political economy energy', 'constructivism energy' and 'neoliberalism energy'. As the high number of results suggests, the selected publications are overwhelmingly related to adjacent research areas. The high number of papers also suggested a need for automated analysis in addition to manual search and review. It is also obvious that the majority of publications that databases contain, were made in the period selected for analysis (2000–2018).

Of those publications selected in the databases by keywords, the most relevant for the scope of the study were selected for an in-depth analysis based on the focus of the paper: either a theoretical paper related to energy security or a paper that applies energy security concepts to reality.

Case-studies of the energy security policy in Germany, China and Russia are used to test the hypothesis and reflect on the interlink between energy security concepts and energy policy. The same approach has been taken by Winzer [23], who used "a stylized case study for three European countries to illustrate how the selection of conceptual boundaries … determines the outcome". The three countries selected for analysis represent the various approaches to energy security policymaking discussed below. The information base for case studies included energy policy documents and official information from government agencies, where available, as well as research papers.

Further development of energy security debates and analysis in the last two decades introduced more technology insights, as well as the concepts of resilience and flexibility [12], but the underlying theories remained unchanged. The research novelty of the present study is a revision of existing energy security concepts with a view to update them and bring in line with contemporary energy technology developments that open many more options for energy production and use. It is an attempt to marry the new technology trends and considerations (foresight) and the dominant energy security concepts.

## 3 Comparison of Theoretical Approaches to Energy Security

Modern studies of energy are often characterized by theoretical eclecticism. The differences between neorealists and neoliberalists have levelled-off. These two classical schools are successfully supplemented with alternative approaches—constructivism, international political economy, and neomarxism. With the advancement of international energy relations modern theoretical constructs will be complemented with new strings of research. Characteristics of the four theoretical approaches to energy security discussed above are summarized in Table 1.

Each of the described approaches has its advantages and limitations. Neorealism and Neoliberalism clearly assign the leading roles to either states or non-state actors, while underscoring the diversity of the modern world. In overestimating the value of either of the sectors (government or private) these theories are limiting the cooperation benefits within and across the national borders.

**Table 1** Characteristics of the theoretical approaches to energy security

| Theoretical approach/characteristics | Neorealism | Neoliberalism | Constructivism | International political economy |
|---|---|---|---|---|
| Level of issue consideration (cooperation/isolation) | The national interests dominate ("resource nationalism") Each state acts on its own, however bilateral agreements are possible Cooperation is relatively beneficial | States cooperate on energy issues Cooperation is beneficial for all actors | The main features of international relations are created and reproduced by the actors themselves The benefits of cooperation are subjective | The combined approach, that fully takes into account the impact of policy factors on the energy markets and the impact of these markets on policy The combination of state and market-driven approaches |
| Key aspects of energy security | Military confrontation and conflicts over energy resources (fossil fuels) Ensuring sufficient fossil fuel imports | Market forces determine the development of the world energy sector Ensuring secure fossil fuel supplies | Different interpretations of the problem by various players, assessments and behavior rules depend on the interactions and the information flows | Energy is a secondary power structure that ensures the four primary power structures: security, finance, production and knowledge |
| Main actors | States | Non-state actors[a] | States and non-state actors | States and non-state actors |
| National priorities | National power | Economic well-being | Depend on the interpretation of players | Depend on policy-making in a particular economy |

*Note* [a]Non-state actors include transnational companies, financial institutions, think tanks, media, terrorist organizations, and international institutions
*Source* Authors own analysis

Constructivism and International political economy seem to be more balanced in terms of key stakeholders, but they postulate the ever-changing nature of energy security decisions. While in Constructivism these depend on subjective interpretation of each of the actors, in International political economy energy security prepositions may shift due to changing political priorities. Therefore, these two approaches lack the stability and predictability of energy security considerations.

In conclusion, one may note that neither of the described classical energy security concepts covers the diversity of international energy relations that have fundamentally changed since the 1970s. These concepts presume that fossil fuels dominate the world energy balance, while renewable sources are hardly noticeable and are not a significant factor for energy security. Today it is hard to ignore that renewables are the fastest growing segment of the global energy sector and this trend is expected to continue [79]. Some countries that have previously been net exporters of fossil fuels plan switching to electricity export in the long term [80].

The ideological theoretical differences are further exacerbated by the difference in research approaches by scholars of difference scientific disciplines, and this has been acknowledged. Cherp and Jewell have identified three distinct perspectives on energy security: the 'sovereignty' perspective grounded in political science; the 'robustness' perspective grounded in natural science and engineering; and the 'resilience' perspective grounded in economics and complex systems analysis [12].

The analysis of the top 10% highly cited international relations papers (closely related to political science and integrated with policy-making), indexed in the Web of Science, performed for this study, show a great variety of areas that focus on energy security (Fig. 1). There are large nodes that are disconnected with each other, i.e. there is no cross-fertilization among papers tackling various aspects of energy security from the international relations perspective. The most read research is centered around national security, energy prices, resource curse, resource security, industrial policy, conventional weapons, and East Asia. This picture shows a marked difference with the energy security research topics discussed in energy journals (Fig. 2).

The top 10% of highly cited energy papers, indexed in the Web of Science, show us a great variety of areas that focus on energy security (Fig. 2). The top cited research papers on energy security are very disperse and cluster around the following nodes: power system, microgrid frequency, lithium-ion battery—battery management system—long life cycle, renewable energy (generation), wind speed, energy efficiency, load demand, SOC estimation, conventional technologies, flue gas, and a variety of smaller nodes. All of these nodes, that represent a gigantic picture, are interconnected. Behavioral change and deterministic approach are, perhaps, the only large node of research that links energy and international relations researchers.

Moreover, the time period from basic research findings to the development of energy applications and technologies has dramatically shortened [81]. Therefore, today's research and development may have an impact on energy markets in the short to medium term perspective [82]. Disruptive energy technologies that appear on the market are capable of introducing new energy sources that are acceptable from the socio-political, community and market perspectives [83]. These technologies include, inter alia, hydrogen energy [84], economically justifiable energy storage

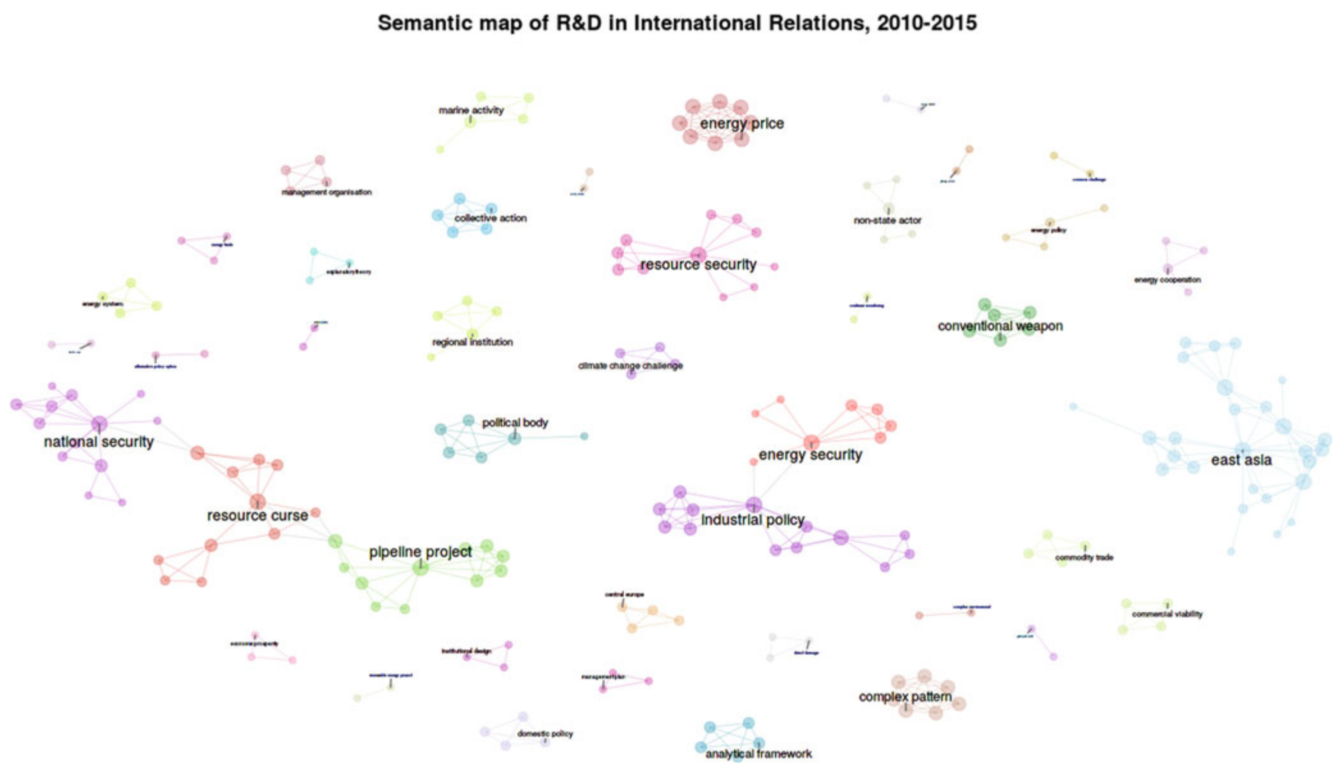


Fig. 1 Semantic map of the top cited publications in 'International relations', Web of Science, featuring energy security (2010–2015). *Source* Intelligent Foresight Analytics (iFORA©)

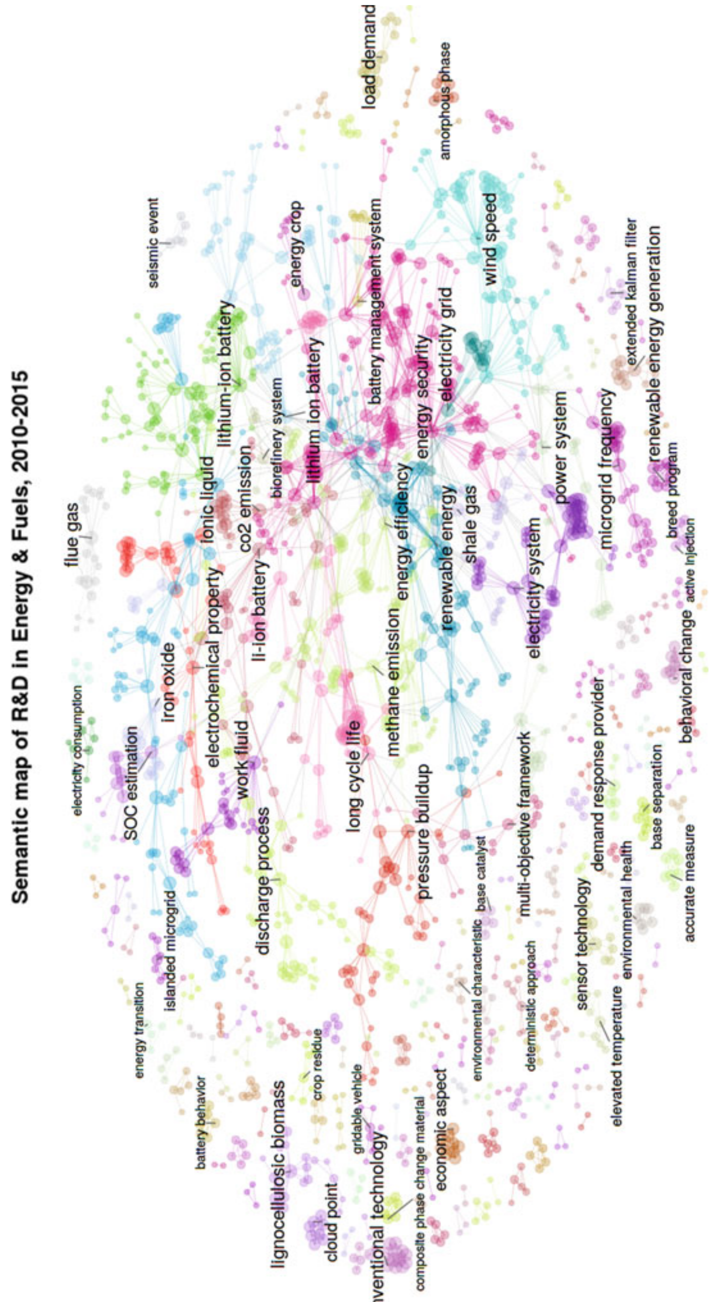


**Fig. 2** Semantic map of the top cited publications in 'Energy and Fuels', Web of Science, featuring energy security (2010–2015). *Source* Intelligent Foresight Analytics (iFORA©)

systems (at the price of US$100 per kW/hour or less) [85] and entirely new energy infrastructures.

The classic theoretic prepositions are linked with energy issues that are mostly relevant for the developed countries. At the same time, as much as 40% of the world population in developing countries still uses wood and other basic bioenergy resources, adding new elements to the energy security concept, such as access to clean fuels and technologies for cooking, and electricity [86].

Often overlooked are market forces that have significantly affected the development of world energy outlook over the past decades. This has resulted in the formation of a fluid, competitive and truly global market with free trade of large volumes of oil, gas and electricity across borders [61]. These changes lead to former net importers exporting fossil fuels, and new trade routes appearing. Some countries and regions have become self-sufficient through adding a large share of renewables in their energy mix or becoming "renewable energy research and innovation hubs as well as build up a renewable energy technology export industry" [87]. Decentralization of energy supply is led by consumers' self-generation and the establishment of micro and mini grids [88]. Deploying community-based small-scale renewable power plants in combination of low-cost energy efficiency measures also contributes to energy security and poverty reduction, specifically for rural and vulnerable households [89].

## 4 Revisiting Energy Security Concepts

As it was shown, the classic international relation concepts of energy security take into consideration a multitude of internal and external factors that are necessary for a stable operation of energy systems. However, the future energy technology shifts and breakthroughs, such as discovery and commercialization of new energy sources, radical cheapening of existing renewable energy and energy storage technologies and other uncertainties, are not taken into consideration [90]. The foresight studies usually mark such factors as 'weak signals', 'wild cards' and 'black swans' [91]. The reserve also holds true: future energy studies should incorporate a much stronger political and institutional analysis [49].

### *4.1 Energy Technology Foresight Shaping New Security Agenda*

Most of energy security concepts take into consideration the disruptions in the supplies of (predominantly fossil) energy resources, but do not take into consideration the appearance of disruptive innovations that are capable of changing the energy outlook in a few decades. The existing concepts made a certain move in this direction by attributing high importance to externalities. However, the list of externalities lacks revolutionary technological changes that may be identified, for instance, with the use of technology foresight instruments.

Energy technology foresight has become a widely used practice in most developed and certain developing countries, including the European Union, BRICS countries, and more [92]. Research and technology foresights in the energy sector are developed in the framework of foresight (forecasting) systems; science, technology and innovation policies; as well as strategic planning for informed decision-making, including the decisions on science and technology priority-setting in the energy sector [93].

The energy foresight studies differ in scope, principles of organization, and the use of outcomes. They could be implemented at international, national and corporate levels. All of the studies may be devoted to the analysis of energy security perspectives. National energy-related science and technology foresights may be used for identifying the approaches to overall security in the energy sector, as well in particular energy segments, such as the *Outlook for shale gas and tight oil development in the U.S.* by the US Energy Information Administration [94], and *Roadmap to achieve energy delivery systems cybersecurity* by the US Department of Energy [95].

The foresight studies on advanced, in particular, low-carbon energy technologies contribute not only to addressing climate change and economic development issues, but also energy security. For instance, the APEC Energy Demand and Supply Outlook [96] identified key energy policy factors of APEC member-states, including energy security, the overall economic effects necessary for energy sector development, and sustainable development. The experience of Delphi survey undertaken in the course of the first national Foresight study in Poland "The Scenarios of Technological Development of Fuel and Energy Sector for National Energy Security", implemented on the request of the Polish Ministry of Economy, was analyzed by Czaplicka-Kolarz et al. [97]. The study allowed identifying future development directions for the energy sector until 2030, a list of key energy technologies of strategic importance, as well as corresponding roadmaps for their implementation.

Shell has been developing world energy scenarios since 1990s, and already in its early reports the company was underlining that there is no alternative to sustainable development that will allow addressing multiple global challenges. In 2005 the consequences of negative and hardly foreseen events such as terrorist attacks and high-scale corruption deals (i.e. Enron case) were forecasted. In scenarios with a 40-year time horizon the company offers a fork between an absence of efficient state policy in energy efficiency (with consequent rapid depletion of natural resources and corresponding climate problems), and policy directed towards assuring energy security while minimizing environmental impact.

International Renewable Energy Agency (IRENA) approaches energy security through replacement of fossil fuel imports with renewable energy generation that will have an impact on the energy and trade balance structure. IRENA experts estimate that the G7 countries would save USD275-315 bn per year in 2012–2030 due to increasing the share of renewables in their energy balance [98]. The Agency uses some elements of foresight studies, including non-linear scenario analysis.

The reviewed examples prove that foresight studies (including science and technology foresights) often take into account energy security issues. However, the forecasted changes and breakthrough in energy research and development are not taken into consideration in the major energy security concepts, which limits their applicability. The suggested revisions of energy security concepts through integration of technology foresight are given in Table 2.

The common new elements in all energy security concepts should be the consideration of new energy sources, primarily renewables [99]. Their production, transportation and use patterns differ radically from those of fossil fuels. The countries will focus more on transmission of power, improving the speed and efficiency (minimizing losses), rather than transportation of fossil fuels by pipelines and tankers. A more equal distribution of renewables throughout the planet (as compared with hydrocarbons) will change the notions of 'resource rich' and 'resource poor' countries [87].

The competition for primary energy resources will be substituted by the competition for energy conversion and storage technologies, high-speed energy transmission systems and smart-grid solutions. This will require countries to correctly assess the global market potential and domestic capabilities, to concentrate the limited financial resources on priority R&D areas.

### *4.2 Application of Energy Security Concepts at National Level*

To test the suggestions in Table 2, three cases of national energy policy are reviewed below. It is described how Germany, China and Russia respond to their energy security challenges within the boundaries of the described energy security concepts and beyond, encompassing future energy technologies through science and technology foresight.

In Germany that is in the middle of a very ambitious energy transition, *the Energy Security of Supply Act* permits the restriction of sales, purchase or use of goods (demand restriction related to quantity and time) or permits them only for certain priority purposes. The government regulated that companies should assume individual responsibility for backup solutions to ensure supply security for their energy facilities. Companies that have fuel-switching capability would use it in the case of a gas supply emergency [100].

The security of electricity and gas supply through power grid and pipelines to the population is a core objective of the *German Energy Act (EnWG)* and it also makes up a large part of the Federal Grid Agency's (*Bundesnetzagentur*) work. The challenges of Energy Transition (*Energiewende*) and the increase in volumes of European power trade represent additional loads on the country's electricity grid and gas supply networks.

**Table 2** Suggestions on integration of technology foresight in energy security concepts

| Theoretical approach/characteristics | Neorealism | Neoliberalism | Constructivism | International political economy |
|---|---|---|---|---|
| Type of energy resources | Various types of renewables (solar, wind, geothermal, biomass, hydrogen, etc.) should be taken into consideration | | | |
| Technological advancements | Development of national champions that produce own energy technologies and equipment, and provide energy services | International cooperation in basic research (for ex. advancement of mega-science projects) that will trigger changes towards the new technological order in the world energy | Multiple-actor energy R&D programs suffer from actors' diverse interpretations of technology potential | The state sets minimal security standards for existing and future energy facilities and technologies that are observed by market actors These standards may become more stringent or loose with the appearance of new threats and new energy sources |
| Level of technology studies, including foresight | Science and technology energy foresight at national level | International foresight studies and foresights for world regions | States, companies and research centers develop their own science and technology foresights and provide for security of suggested solutions | Foresight studies are performed by various actors for pragmatic purposes—to maximize benefits (profits); the aim is to persuade partners, competitors and the market that one's vision is correct and one's products will be in demand years ahead |

(continued)

**Table 2** (continued)

| Theoretical approach/characteristics | Neorealism | Neoliberalism | Constructivism | International political economy |
|---|---|---|---|---|
| Level of technological foresight consideration | Development of national centers of excellence capable of making a breakthrough and advancing national capabilities | Foresight studies are planned with participation of international experts and consideration of best international experience | The decision to use or neglect the available science and technology studies and technologies is made by each actor independently, based on their strategic documents and priorities | The state assures permanent monitoring of energy technology trends and 'weak signals' that are early markers of substantial future changes. The national systems of energy technology monitoring and foresight are set up by states and used by other national actors |
| National priorities | Support to traditional energy sources (fossil fuels, nuclear), and advancing technologies for their use | Support to new economically and technologically feasible energy solutions that spread fast at the world market | International organizations, states, and companies set their own priorities based on own requirements and limitations | The state seeks to maximize the profit derived from energy technologies, therefore the support goes to easily scalable technologies with short pay-back period, or to technologies with high added value |

*Source* Author's own analysis

In accordance with item 13(1) and 14(1) of the EnWG the electricity distribution system operators are authorized and obliged to address any threat or breakdown in the electricity supply network through the adoption of system- and market-related measures. After assessing all pros and cons of the nuclear energy—its role in meeting the growing demand, providing a pathway towards the decarbonization of the world's major economies and environmental risks (possible nuclear accidents and radioactive waste) [101]—nuclear power stations with 8.4 GW capacity were shut down in 2011 and it was decided to decommission additional 12 GW of nuclear power by 2022 [100]. This loss of capacity will be offset by energy efficiency/energy saving, renewables, and natural gas, as well as more frequent interventions by grid operators. One major assumption behind the successful implementation of *Energiewende* is that future technologies (i.e. energy storage, smart grid, etc.) will be developed and put on the market.

Energy security is in mutual interest of all EU member-states, therefore cooperation between member-states is considered desirable. The European energy market was based on the principles of states' interdependence and energy companies' competition. Its common energy market fits into the neoliberal approach to energy security. A competitive energy market is meant to increase energy security through lower prices and costs, thereby making supplies less critical.

The German energy plans are in line with the overall European Energy Security Strategy (released in May 2014) and its targets, such as increasing energy efficiency and reaching the 2030 energy and climate goals. Another target is to increase energy generation in the EU and to diversify suppliers and routes. The biggest challenge for the EU supply security is that more than half of all energy demand is covered through imports: crude oil (over 90%) and natural gas (66%) for the amount of over EUR1 billion per day [102]. Many EU member-states, including Germany, import their energy from a single supplier, i.e. natural gas from Russia. Although Russia has proven to be a reliable partner, this dependence is potentially subject to politically or commercially motivated supply disruptions or infrastructure failure.

The EU Green Paper "Towards a European strategy for the security of energy supply", adopted by the European Commission in 2000, was developed to address the risks associated with the ever-increasing external dependence on energy [103]. In 2014 38 EU and other European countries carried out energy security stress tests where they simulated one to six months Russian natural gas supply disruption scenarios. The exercise revealed that if all countries cooperate with each other consumers would be supplied even in the worst-case scenario by redirecting energy across Europe. Thereafter, the Energy Community countries developed regional energy security preparedness plans that were adopted in 2015.

To address the technology aspects the European Energy Security Strategy is closely linked with the EU Strategic Energy Technology Plan. New energy technologies will be required to reduce the emissions by 80% until 2050, build a common smart grid, and integrate distributed renewable energy facilities in the energy system [104].

The German Federal Ministry of Education (BMBF) undertook science and technology foresight exercises to address future societal challenges, including those in the energy sphere, in 2007–2009 and 2012 [105]. Previous studies were performed by Fraunhofer ISI back in 1990-ies and also included the recommendations for national policies and possible follow-up security problems [106].

Energy security was put forward by China's policy makers in 1990s and reflected in the country's 10th Five-Year Program (FYP) (2001–2005). The goal was to optimize the energy mix while sustaining the overall energy security. The 10th FYP established the strategic petroleum reserves for emergency cases to ensure national supply security, as well as storage schemes by individual enterprises [107]. Additional way to lower heavy dependence on oil imports was to enhance domestic coal gasification and nuclear power development, as well as boosting domestic oil and gas extraction. Another goal was to diversify oil and gas imports. To this end, China aimed at import of hydrocarbons from many different suppliers, contribute to the setup of a regional energy security system and investing in overseas oil business.

The strive to mitigate economic, environmental, and climate problems associated with boosting energy consumption has become the top priority and led to multiple low-carbon policies since 2005, displaying a mixture of authoritarian and neoliberal environmentalism [108]. The key energy security challenges in the 11th FYP (2006–2010) cover increasing energy demand and energy imports, continuous increase of the strategic petroleum reserves, and enhancement of the overseas sea-lane transportation security [107]. For an increase in domestic hydrocarbon extraction, new technologies will be required for the exploration of unconventional hydrocarbon resources such as coal-bed methane and shale oil.

In the 12th FYP (2011–2015) the energy security priorities included exploration of unconventional hydrocarbons, rational energy use—energy conservation, diversification of energy supply and a more active use of renewables. Today China is leading in domestic and overseas investments in renewable energy and related technologies and dominate the renewable energy equipment manufacturing [109]. Moreover, the analysis shows that the country has more 'efficiency losses' than 'efficiency gains' resulting from carbon transfers. The situation could be changed with new policies and technologies, as well as stricter technology standards for carbon intensive productions [110].

To this end, China has performed several foresight exercises in 2002–2009 that have identified priority (critical) technologies [111]. Outcomes of these studies were integrated in the National Science and Technology Development Plans. The criteria for the selection of technologies included achieving their domestic production not least for increasing energy security [112].

In Russia the key document in energy security is the *Energy Security Doctrine of the Russian Federation*. The document treats national energy security as part of national security that includes assuring quantity (volume), quality (economic feasibility and reliability) and efficiency (logistics) of energy supply to consumers. The national energy security threats are divided into domestic economic (low level of investments, depletion of fossil fuel reserves, dependence on equipment imports, lack of energy saving gains), social-political (ethnic conflicts, labor conflicts at energy enterprises, malfunctions and terrorist acts at energy facilities), man-made (accidents at power supply facilities), natural (earthquakes, floods, hurricanes, etc.), and external economic and foreign policy (sanctions, etc.) [113]. Although the hydrocarbon receipts will shrink twofold in the national 2040 budget [114], it is planned to further increase hydrocarbon exports at international markets, while also increasing the export of energy equipment and technologies [115].

The solutions that are offered by the document are modernization of the equipment and technologies used in the energy sector, increasing energy efficiency, and exploration of new hydrocarbon deposits. Moreover, it is planned to undertake thorough analysis of energy resources (including renewables) available in Russia's regions to ensure their self-sufficiency and lower energy transportation volumes. To this end, it is planned to set up hybrid facilities based on renewables and diesel in Russia's regions located behind the Polar Circle. Today they are entirely dependent on expensive diesel generation. More prospective energy technologies are reflected in the National Science and Technology Foresight until 2030 [116] and the sectoral energy technology foresight [117]. Some priority energy technologies identified in these documents were selected based on energy security considerations.

To sum up, Germany is continuing its energy transition path, where energy efficiency and renewables have long occupied a central place. For Russia and China a more substantial increase in energy efficiency and the advancement of renewables today also seems inevitable, despite little attention in the past. The main rationale for China is its boosting energy demand and major environmental damage, and for Russia—the need to increase international competitiveness, lowering budget costs for energy consumption in energy-poor regions and unstable hydrocarbon exports (tough competition, low prices and depletion of traditional reserves). Germany (like other EU countries) and China striving to diversify suppliers are bad news for fossil fuel exporters like Russia. Clearly, all three countries will require new technologies to address their energy security issues.

Germany has an ubergoal to diversify its energy mix by substantially increasing the share of renewables, and, decreasing the dependence on imported fossil fuels. Its policies are within the boundaries of neoliberalism with some elements of constructivism. China is the largest energy consumer that is aiming to diversify its energy import in terms of contractors/countries, while also increasing domestic production of all types of fuels (including renewables). Its policies are predominantly constructivist with some elements of neorealism [118]. Russia has an old school neorealist approach to energy security [119] with some elements of political economy [120]. It has been predominantly relying on the domestic production of fossil fuels for own consumption and budget revenues from export [121].

Despite the variety of approaches to the definition of energy security, the cases of Germany, China and Russia show that countries are equally trying to improve their energy security by increasing energy efficiency, reducing the vulnerability of the energy system and enhancing power grid stability, aiming at resource self-sufficiency at national and regional level. In some cases, stability is more important for energy security than performance indicators, as well as economic and environmental costs.

## 5 Conclusion and Policy Recommendations

The classical energy security concepts—neorealism, neoliberalism, constructivism and international political economy—are based on the premises of sufficient and reliable supply of fossil fuels at affordable prices. Fossil fuels were considered to be the most reliable and most wanted energy resources, centralized systems—the predominant energy generation schemes, and energy infrastructure to remain unchanged in the long-term. Today with the rapid advancement of renewables and smart grid, decentralization of energy systems, new environmental and climate challenges the basic elements of energy security should be questioned and revisited.

More specifically, all concepts should master technological advancements. The proponents of neorealism that place resource nationalism at the center, should support national champions that produce own energy technologies and equipment, and provide energy services. Neoliberals may prefer to support international cooperation in basic energy research. Constructivists need to overcome diverse interpretations of prospective technologies in multiple-actor energy R&D programs. Policymakers that have international political economy views should set minimal security standards for existing and future energy facilities and technologies that are observed by market actors.

Energy technologies should also be assessed in terms of new energy sources that may become available (i.e. hydrogen, nuclear fission), new faster ways of energy transportation, new energy storage options and other areas that may become evident in the course of foresight studies. The outcomes of these studies are already applied at national and sectoral level in Germany, China and Russia. All of these advancements impact on the reliable supply of energy resources at affordable prices.

Neorealists should invest in the development of the national centers of excellence. Neoliberals plan foresight studies with participation of international experts and consideration of best international experience. In case of a constructivist approach, the decision to use or neglect the available science and technology studies and technologies is made by each actor independently, based on their strategic documents and priorities. The international political economy policies rely on national monitoring systems for energy technology trends and 'weak signals' that are early markers of substantial future changes.

Energy security studies have a direct impact on national and international energy policies. Therefore, it is of utmost importance to see that energy security concepts are constantly scrutinized in order to reflect the fast changes that occur in research and development. Technology foresight provides evidence to decision-makers and researchers who want to foresee future shifts in the energy sector and pay attention to social and economic areas that determine its development. Foresight studies of various energy resource characteristics (economic, technological, policy regulation, etc.) is an inherent element of contemporary energy security policy and planning.

The policymakers and managers will continue to have divergent views on the national energy priorities. While neorealists will primarily focus of hydrocarbons (including their more efficient use and unconventional deposits) and advanced nuclear technologies, neoliberals will support any new energy technologies that are economically and technologically feasible and have good prospects at the world market. In constructivism international organizations, states and companies set their own priorities based on self-identified requirements and limitations. Under international political economy the policy support will focus on easily scalable technologies with short pay-back period, or to technologies with high added value.

International relations and energy researchers' discourse of energy security differs markedly: the papers with highest impact in both disciplines focus on very different topics that are hard to match. While international relations research treats the various energy security issues separately, energy research in natural sciences offers an interdependent set of studies with a vast variety of focus areas. An interdisciplinary approach to energy security, combining the natural and social sciences ideas and tools, would definitely enrich the debate on energy security.

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# The Role of Social Discount Rate in Energy Modelling

**Asma Dhakouani, Essia Znouda, and Chiheb Bouden**

**Abstract** Energy systems modelling aims to introduce a sustainable energy system design with an improved understanding of present and future interactions between demand-supply, environment, and economy. Treating energy systems started in the 1950s and have led to various approaches and models. Amongst common metrics, the discount rate impacts time horizon costs, benefits, demand and supply. This chapter presents an *objective* overview of energy systems approaches based on their historical evolutions. In order to point out social benefits and costs, the use of social discount rate for the Tunisian power system is argued.

**Keywords** Energy systems modelling · Social discount rate · Tunisia power system · Approaches historic evolution · Open source modelling · Demand modelling · Supply optimisation · Economic growth · Sustainable energy · Energy economics

## 1 Introduction

Several international organisations have worked on the concept of sustainable development (SD). Given its wide scope, there is no a fit-all definition. The definitions agree about some points and differ on others. For instance, the [43] has set 17 goals that address the challenges the world is facing. And, the International Institute for Sustainable Development points out intergenerational coherences in sustainable development [11].

In the energy sector, considering sustainable development is not about identifying operational and short term solutions. Sustainable development is emphasised when decision makers rely on the past trends to find solutions for the present and optimise the future. Then, sustainable development is rather based on long term planning and

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is treated as a goal or several goals to achieve. Planning through modelling points out the interactions between different agents of energy systems on a holistic and integrated vision.

The discount rate is a common metric that plays an important role in energy systems modelling (ESM) and is a driver of sustainable development. This factor links supply to demand not only based on discounting cash flows, but also based on economic growth and intergenerational preferences.

This chapter overviews objectively energy systems modelling approaches based on their historic evolution. Following, open source modelling is examined since it has tackled several barriers to take sustainable decisions. Section 3 covers the identification of key factors in modelling. Section 4 relies on Open Source energy MOdelling SYStem (OSeMOSYS) to model Tunisia power system. The role of the discount rate role in sustainable development is analysed on a long term perspective.

## 2 Overview of Energy Systems Modelling

Johansson et al. [30] and Pfenninger et al. [38] defined the energy system as a process chain covering all steps from the extraction of primary energy to the use of final energy for supplying services and goods. Therefore, the various models that have been appearing lastly aim in general to introduce a better energy supply system design with an improved understanding of the present and future interactions between demand-supply, environment, and economy. According to Hoffman and Wood [24, p. 423], "ESM are formulated using theoretical and analytical methods from several disciplines including engineering, economics, operations research and management science". ESM represents functions of data requirements, technology specifications, skills and computations.

Choosing the adequate model that captures the case specifications might be confusing with the increasing number of models. In addition, elaborated reviews are generally targeted. Therefore, they don't cover some categories which could be interesting for others [9, 38]. Taking into consideration the reviewed scientific researches elaborated to nowadays, there is not a rationalised method for identifying the suitable model to treat a specific case.

Consequently, this review brings together "objectively" the main types of approaches used in energy systems modelling, following the historical appearance and evolution. The concept of open source models is pointed out, as a sustainable tool helping decision-makers and researchers to face access, adaptation and affordability barriers.

## 2.1 The Historical Evolution of Energy Systems Modelling

The utilisation of energy systems analysis and modelling returns initially to the 1950s, when energy supply companies and administrations had to decide about the energy's future versus the incremental increase of OECD countries demand. Strategists applied energy supply analysis approaches [24].

The year 1972 was marked by the first large scale global modelling and the development of supply management analyses. Next year during the oil crisis, there was a sharp increase in technical modelling. In 1974, econometric and macroeconomic models were linked to inter-industry energy models to simulate market penetration, creating thus integrated models. Integrated energy systems modelling takes into consideration several aspects, such as the demand, supply and environment. However, at this stage models were explicitly focusing on one of the aspects and considering other aspects as exogenous parameters or under the form of constraints.

Till 1985, investigations and debates covered interactions and interdependences between energy and economics. Meanwhile, analysts carried out on developing forecasting approaches to manage energy demand, reaching thus advanced sophisticated methods.

Since the 1980s, open source tools have integrated several fields including modelling. While models are generally not able to respond exactly to the needs and capture all peculiarities, the flexibility of open source one allowed tackling these problems [9].

Starting from the 1990s, modellers have introduced electricity system planning models and identified their features, apace with the identification of approaches used for the treatment of environmental issues.

The understanding of models evolved last decades and in order to present insights, modellers have combined technological and economical approaches, and created hybrid models.

Starting from 2002, researchers have attempted to make comparative studies and analyses of the myriad of models available. Till nowadays, there isn't an objective comparative study regrouping all types due to [44]:

i. The increasing number of energy models; and
ii. The subjectivity of researchers towards topics, expected decisions and needs.

To tackle the subjectivity issue, historical evolution has been followed. To cover all models, the overview relies on their approaches.

## 2.2 Supply Side Approaches

Energy supply analyses have been primarily marked by the economic and financial approaches. The economic problem of allocating limited resources to various needs often requires decision making about appropriate investments [35]. The basic analytical framework is based on a cost-benefit analysis following two disciplines:

**Table 1** Economic and financial analyses comparison

| Metrics | Economic | Financial |
|---|---|---|
| Costs | Economics, including external costs | Project: money outgo |
| Benefits | National economy | Shareholders |
| Valuation | Willingness to invest or to accept compensation reflecting the socioeconomic opportunity | Market price |
| Coverage | Broad | Narrow |

- Financial analysis: used for private investments; or
- Economic analysis: used for public investments.

The economic analysis identifies if the project is profitable and financially viable; if it should be undertaken by public or private investors. It considers projects fiscal impacts, efficiency, equity of cost recovery and environmental impacts [42].

Both analyses aim at appraising the profitability of an investment. Table 1 differentiates profit concept in the two disciplines.

For basic analytical framework, the indicators of cost benefit comparison follow either calculation methods without time-value (such as pay-back period and rate of return) or methods employing time-value (such as Net Present Value and discount rates). Equation 1 represents the mathematical formulation of cost-benefit analysis:

$$\sum_{t=1}^{n} b_t \left(\frac{1}{1+r}\right)^t > \sum_{t=1}^{n} c_t \left(\frac{1}{1+r}\right)^t \tag{1}$$

where

- $t$: year from 1 to n
- $b_t$: annual benefits
- $c_t$: annual costs
- $r$: discount rate

The energy supply is highly related to uncertainty due to unknown and unquantifiable situation. And it is subject to risks because of unknown situation with quantified outcomes.

Sensitivity analysis is usually applied when uncertainty occurs. It helps to define drivers, to investigate their changes, to present a potential of reversals and to identify mitigation actions [3]. Systematic risk analysis is usually applied when risks occurs. It is based on qualitative methods giving insights of risk at early stages. The risk matrix assigns a probability distribution to parameters and determines the expected outcomes, e.g. Monte Carlo Simulation [8].

## 2.3 Demand Side Approaches

Energy demand is the energy needed in a country or the energy supplied to consumers. Then, consumption is the satisfied demand.

The demand is generally presented as function of price and quantity. There are various factors influencing energy demand, such as the improvement of living conditions, the rise in concerns about global warming, changes in market operations, security of fuel and evolution of computational and communication facilities. These factors induce difficulties in analysing energy demand. Specifically in developing countries, the scene is outlined by a lack of data on traditional energy, lack of consumer's purchasing power, supply shortage, social differentiation in the access and consumption of energy, and difficulty in price changes response [22].

In brief, the main determinants of demand are generally the price of the good, consumers' income, and preferences. For instance, Ceteris Paribus Assumption[1] has been widely adapted to simplify demand modelling.

According to the evolution of energy demand management models, it exists so far four main approaches of analyses, i.e. *descriptive, decomposition, physical and econometric*. These approaches allow calculating values at a needed time based on their time progress. They have evolved and have been used for forecast and projections leading to sophisticated approaches. They are integrated in models to predict the evolution of some patterns.

Thereafter, most applicable energy demand approaches are presented.

### 2.3.1 Fundamental Approaches

Four main approaches are used to analyse historical evolution of energy demand and to interpret its trends. These approaches are applied to identify causal indicators impacting energy demand. This section points out the following analyses descriptive analysis, decomposition analysis, physical indicators analysis, and econometric analysis.

**Descriptive Analysis**

It involves economic parameters like growth rates, demand elasticity and energy intensities to predict demand. It is a general description of overall energy demand trends in the past, applied to a set of the scope and future priorities. In order to describe trends, we identify parameters defined in Eqs. 2 and 3 [25, 37]:

$$\text{Year-on-year growth rate } \boldsymbol{a} = \frac{E_{t+1} - E_t}{E_t} \tag{2}$$

where

[1]Ceteris Paribus Assumption consists in drawing the relation between the price and the quantity of goods consumed while holding other determinants fixed.

- $E_{t+1}$ is the energy consumption in year t + 1
- $E_t$ is the energy demand in year t

$$\text{Demand elasticity rate } \boldsymbol{e_t} = \frac{\frac{\Delta E_t}{E_t}}{\Delta Y_t / Y_t} \tag{3}$$

where

- $E_t$ is energy consumption during year t
- $Y$ is a driving variable of energy consumption such as GDP, value-added, price, income etc.
- $\Delta Y_t$ is the change in the variable Y from year t to year t + 1.

**Decomposition Analysis**

It is as well called factor analysis or index decomposition analysis [10]. It targets structural changes in energy consumption impacts. Several methods are used for decomposition which are primarily divided into Divisia Index Method developed by Ang [5] and represented in Eqs. 4–6. The aim of this analysis is to model the changes in the use of production factors. Laspeyres Index Method developed by Ang and Zhang [6] and is represented in Eqs. 7–11.

$$\text{Divisia Index Method } \boldsymbol{E} = Y.\boldsymbol{I} = \sum_i \boldsymbol{I}_i \boldsymbol{S}_i \tag{4}$$

$$\text{Sectoral energy intensity } \boldsymbol{I}_i = \frac{E_i}{Y_i} \tag{5}$$

$$\text{Impact of the changes in the sectoral share of total production } \quad \boldsymbol{S_i} = \frac{Y_i}{Y} \tag{6}$$

where

- $E$ is energy consumption measured in terms of energy unit
- $Y$ represents the overall economic activity
- $Y_i$ the added-value of a sector or an activity i (measured in the monetary terms)
- $S_i$ is the share of the activity of sector i relative to the overall activity of the economy
- $I_i$ is the energy intensity in sector i reflected through the ratio of energy consumption by added value of the sector

The sectoral energy intensity $I_i$ is a structural factor of the economy. It could be for example the share of the sector production by the total production. It is the main measure of efficiency in the decomposition analysis.

$$\text{Laspeyres Index Method} \quad \Delta \boldsymbol{E} = \boldsymbol{E_t} - E_0 = \boldsymbol{I_{effect}} + \boldsymbol{Y_{effect}} + \boldsymbol{S_{effect}} \tag{7}$$

$$\text{Activity effect} \quad \boldsymbol{Y_{effect}} = (Y_t - Y_0) \sum_i I_{i,0} S_{i,0} \tag{8}$$

$$\text{Intensity effect} \quad \boldsymbol{I_{effect}} = Q_0 \sum_i S_{i,0} \left( I_{i,t} - I_{i,0} \right) \tag{9}$$

$$\text{Structural effect} \quad \boldsymbol{S_{effect}} = Q_0 \sum_i I_{i,0} \left( S_{i,t} - S_{i,0} \right) \tag{10}$$

where

- $E_t$ is the energy consumption at the year t
- $E_0$ is the energy consumption at the base year 0
- $Q_0$ is the overall economic activity at the base year 0
- $Y_{effect}$ is the activity effect that describes the effect of the total economic growth on the sectoral energy use. It does not directly depend on the sector's own production but the total activity level of the whole economy. Activity effect describes the effect of the total production changes without the impacts from structural and technological factors
- $I_{effect}$ is the intensity effect that describes the impacts of the technological change and the change of production systems on sectoral energy consumption
- $S_{effect}$ is the structural effect that describes the impact of the changes in the sectoral share of total production on the energy consumption

$\mathrm{Y_{effect}}$, $\mathrm{I_{effect}}$ and $\mathrm{S_{effect}}$ are all expressed in energy units.

**Physical Indicators Analysis**

The analysis using physical indicators focuses on unit energy consumption, which measures energy requirements per unit of technical-economic driving variables, like energy consumption per household [10].

The unit-energy ratio is given by the expression in Eq. 11.

$$\text{Unit-Energy ratio} \quad UE_t = {}^{E_t}\!/_{Q_t} \tag{11}$$

where

- $E_t$ is the annual energy consumption
- $Q_t$ is the driving technical-economic outputs (for e.g. $m^3$ of natural gas).

**Econometric Approach**

In this approach, the overview distinguishes aggregate and disaggregate levels.

In a disaggregated level, energy demand is calculated by combining effects of inter-fuel substitution, stock adjustment of appliances and the rate of utilisation of devices. This approach is applied using the model in [18] in Eq. 12.

$$\text{Fuel consumption by an appliance } \boldsymbol{E_i} \equiv \sum_{k=1}^{M} R_{ki} A_{ki} \tag{12}$$

where

- $E_i$ is the energy consumption of a fuel type i considering used appliances of type k, varying from 1 to M
- $A_{ki}$ is the stock of products of such an appliance for each appliance k
- $R_{ki}$ is the utilisation rate of the fuel type i for an appliance k

Then, the total consumption of fuel i is the sum of fuel consumption by k types of appliances. The fuel consumption by an appliance type k is obtained as the product of the stock of such appliance (A) and the utilisation rate (R).

Amongst the determinant factors of demand functions, we mention the price of the fuel i, the price of the appliance k, and the economic activity such as the added-value of related sector.

This method is a static form where the capital stock increases with the increase of fuel demand. There is no distinction between short-term and long-term changes. Within dynamic forms, a partial stock adjustment is considered. Nonetheless, it is assumed that appliances stock cannot adjust rapidly due to time lags in the process of retirement and new capacity addition. Analysing demand changes has been found necessary to amend stock changes.

In an aggregated level, with respect to horizons distinction, the most widely used formula is Eq. 13, calling time series lagged variables[2] [19]. The logarithmic form is applied to highlight short run effects and long run effects.

$$log E_t = \log a + b \log Y_t + c \log P_t + d \log E_{t-1} \tag{13}$$

where

- $E_t$ is the per capita real energy consumption for year t
- $P_t$ is the related price of energy for year t
- $Y_t$ is the per capita real income or sector added-value for year t
- $b$ and $c$ coefficients are price and economic activities elasticities of energy demand
- $d$ is a coefficient reflecting long-term elasticity of the energy demand, which measures percentage changes in energy demand from one year to another and appeals auto-regression principle
- $log\ a$ is the disturbance term normally distributed with zero mean and constant variance
- $E_{t-1}$ is one time-lagged $E_t$

Moreover, final energy demand sectors analysis has been developed, dealing apart with industry, transport, residential, commercial, agriculture and non-energy uses.

[2]In statistical analysis of time series data, models are sometimes built on variables predicted based on historical evolution. This is called auto-regression or autoregressive models, and the values of the variables would be predictive variables, called lagged variables.

**Table 2** Classification of energy demand advanced techniques

| Type | Time horizon | Capture | Data requirements |
|---|---|---|---|
| Sophisticated econometric | Short run<br>Long run | Policy analysis<br>Government intervention | High quantity<br>High quality |
| End-use[a] | Medium run<br>Long run | Role of technology, consumers' behaviours, economic environment | High quantity<br>High quality |
| Input/output | Long run | Structural changes<br>Contributions of activities<br>Climate change and energy efficiency<br>Traditional energy and informal activities | Medium quantity<br>Medium quality |
| Artificial neural networks | Medium run<br>Long run | Technological, micro/macro-economic details<br>Induced policies | High quantity<br>High quality |

[a]Integral part is based on a scenario approach

The industry itself is split into sub-sectors, i.e. mining, manufacturing, and construction. Disaggregated energy demand analysis is prepared using sectoral energy accounting which provides information by sub-sector, process type, or end-users through decomposition methods, econometric and technical-economic approaches.

### 2.3.2 Forecasting Approaches

Forecasting approaches are a continuity of fundamental approaches. They aim to predict the demand evolution and draw a concrete long-term strategy [46]. For these reasons, several approaches have been developed varying from simplistic to sophisticated.

On the one hand, simple approaches consist of forecasting using simple indicators or trend analysis. It is composed of three steps [7]: assumption of change in growth pattern, finding the best trend line that fits the data, and utilisation of the trend line to forecast.

On the other hand, advanced techniques could be classified based on the fundamental approaches exposed above, namely econometric, end-use,[3] input/output and artificial neural networks.[4] Table 2 summarises their main characteristics [34].

Sophisticated econometric is based on the econometric approach to analyse energy demand. The relationship determined for calculating demand can then be used for forecasting by assuming a certain evolution of independent variables (for example GDP) and determining their effect on the dependent variables (namely future energy

[3]End-use called as well engineering-economic or accounting.

[4]Artificial neural networks called as well combined or hybrid.

demand). The forecast is set by determining a systematic way based on judgements, simple indicators, trend analysis, or a combination.

End use is based on the decomposition approach. It consists in disaggregating the demand into homogeneous modules and sectors and links the demand of each module to technical and economic indicators. It emphasises the role of the technology, behaviour of consumers, and the economic environment.

Input-output, based on a disaggregation, captures the contribution of related activities through inter-industry linkages in the economy and relies on Leontief model [33].

Inspired by biological nervous systems, artificial neural networks is structured following a large number of highly interconnected processing elements working together to solve specific problems. These units are connected by communication channels (composed of links and nodes). Each unit operates on its local data and the inputs they receive via the connections: “training method” [4].

### *2.4 Open Source Integrated Modelling*

The interest in managing and forecasting both demand and supply sides of energy and the concerns about climate change has induced the development of integrated energy systems models. Several researchers pointed out their typology, i.e. bottom-up, top-down and hybrid. Bottom-up models are technologically oriented. Top-down models are economically based. Furthermore, hybrid models regroup both aspects. Digging deeper, the models are composed of a set of equations assembling energy-related parameters and variables principally based on the approaches introduced above.

Models are numerous and rapidly growing. Even though the efforts for simplifying their classification objectively, the continuity of their evolution created a certain overlapping between the different types. Then, we have some models classified under two or more approaches, leading to confusions. However, the differentiation is essential to choose the adequate model to use.

In general, it has been demonstrated, based on the attempts of models reviews that each has limitation on reflecting some specific features of energy systems [38]. Pfenninger et al. [39] and other researchers argue that there isn’t a fit-all model, and software sources might be difficult to adopt, adapt and combine for re-use in other contexts. This is due principally to the fact that economic, environmental and social problems highly differ from one case to another. Namely, several issues will be faced by the modeler in this context such as the models’ initial costs, needed skills and the access to the core code for improving the model’s adaptation and reliability. To satisfy these conditions, the development of open source models (OSM) and software, and accessible data started spreading.

Open source tools are usually not imposing purchase fees and their codes might be accessible. Proprietary or commercial tools are usually payable and the code is not accessible.

Modern models are characterised by complex interactions and high quality of analytical tools and data. The research, elaborated by Bazilian et al. [9], demonstrated that using models correctly requires that (i) validated models must be available and appropriate for the target environment; (ii) suitable data must be available for input into the model and for verifying model-based results; and (iii) models must be operated by people trained in the use of the tools and in analysing the outcomes and presenting insights.

In fact, open source concept determines the necessary conditions for a license to be considered open by the Open Source Initiative. The codes available for the open public are generally a result of modellers and programmers collaboration. Open source has already advanced in all major areas of the administration information system. Open source solutions are now at the same level as proprietary solutions in the public sector software landscape. This initiative prioritises the quality of software outputs. Indeed, the code source could be reread, verified and improved, which allows notably the correction of adaptation problems. Developing countries are highly interested in these products since they confer a certain technological independence with lower cost.

Thus, modellers have better knowledge of the applied approaches, the methodology of implementation, i.e. during programming, and know precisely the required data.[5] Furthermore, in case the model doesn't treat some case specifications, the access to the code allow integrating the needed modifications and then adapting the model. Apart the code access, efforts on linking modules from different models and improving the flexibility of some modules are valuable.

## 3 Key Factors of Energy Systems Modelling

Since the 1980s, the research works have demonstrated that the identification of the suitable model should be made based on a process. This points out different model parameters, their adequacy with modelling objectives and a consideration of a variety of typologies [17]. The objectives are illustrated through functions and equations composed of parameters, variables or decisions variables in the model. Presenting insights shows the impact of these components "Key Factors" on energy systems. Amongst the methods translating objectives into key factors is the empirical evidence.

[5]Confusion occurs due to the utilisation of different lexical meaning for parameters. Access to equations gives a clearer insight about the meaning of these parameters.

## 3.1 Application of Empirical Evidence

In respect to the empirical evidence, objectives of modelling and expected results are related to the work hypotheses following a static methodology. Notably, empirical evidence is information acquired by observation or experimentation. Scientists record and analyse obtained data.

Usually, needed characteristics in a model represent the work hypotheses. This is processed by answering questions starting from generalities to specifications. The analyst could answer key questions through a situational review, interviews, data collection, and research, etc. Thus, the analyst will have a full picture of the characteristics for needed model.

There are seven (7) main questions to answer. Firstly, answering question 1 "What is the purpose of modelling?" will identify general purposes on how is the future addressed in the model and specific purposes about aspects that are focused on the model. In question 2, "What are the assumptions that should be taken into consideration?" analysts will identify implicit assumptions embedded in the model structure and explicit assumptions left to be determined by the user. Question 3 "What is the coverage scale?" treats the geographical and sectorial scales. In question 4 "Which methodology should be used?" the analytical approach and underlying methodology are found. The most suitable mathematical approach is answered in question 5. Question 6 delights the time horizon and steps (time slices). The rest of specifications to consider which are contextual are clarified in question 7, i.e. portability of the model to other cases, capability to accept a variation of inputs, data intensiveness, needed skills for modelling, and other criteria to be considered.

## 3.2 The Discount Rate in Modelling

Among the various key factors, the discount rate (DR) is an important metric in energy systems modelling since it impacts the time horizon costs and affects decision-making. According to Freeman et al. [20], the appropriate discount rate could be the market rate of interest or the compound rate including taxes, devaluation, and interest rates. Based on [41], in a macroeconomic perspective and for scenario comparison, it is appropriate to use the social discount rate (SDR) in order to point out social benefits and external costs on a long-term horizon. The social discount rate is the rate used in discounting the value of funds spent or governmental expenditures on projects having social dimension. Further works in [12, 21, 31] concluded that social discount rate is widely applied in cost-benefit analysis for a comparison of total costs and benefits induced by different policy instruments. Generally, it is applied when there is a scenario comparison reflecting the occurrence of a project or a strategy. The social discount rate is calculated using the pure time preference to weigh intergenerational welfare, reflecting the desire to acquire a good now or later. A high social discount rate implies a preference to use resources now; and a low social discount rate implies a time indifference. SDR is also directly connected to the economic growth per capita. In [41], authors concluded that on average, a social discount rate of 2.6% results in 1% of per capita GDP growth per year.

Referring to [47], the Ramsey formula, developed in 1928, has been further agreed to estimate the social discount rate in developed and developing countries. Equation 14 represents the calculation of the social discount rate:

$$\boldsymbol{SDR} = \rho + \mu \times g \tag{14}$$

where

- $\rho$ is the pure time preference rate
- $\mu$ is the elasticity of the marginal utility of consumption
- $g$ is the economic growth per capita
- *SDR* is the social discount rate

In regard to electricity demand, an incremental economic growth rate implies a higher social discount rate and less willingness to save for the future investments. In fact, the willingness to save is reflected in Ramsey formula through the pure time preference.

For the identification of the pure time preference rate, two main cases arise. The first case occurs when the Gross National Income (GNI) per capita growth rate decreases within decades; and the second case occurs when the GNI per capita growth rate increases within decades. Any increase in future income growth rate will induce a high rate of time preference, and vice versa for the decrease in income growth rate.

## 4 Case Study: Power System of Tunisia

This section is based on the case study of modelling the power system in Tunisia in order to show the impact of the key factor "Social Discount Rate". An enhanced version of the Open Source energy MOdelling SYStems is used as a tool to model the power system in Tunisia, taking into consideration the challenges of supply and demand sides.

The enhanced version of OSeMOSYS is a hybrid model based on supply optimisation and econometric approaches. The objective function aims to determine the lowest net present cost of an energy system to meet driven demands and constraints. In regard to the supply side, research works about functionality for reserve capability response and costs of flexible operation are considered in order to refine the analysis of short-term implications due to the penetration of intermittent RES [14]. The variation of prices, economic growth and revenues are combined to determine the evolution of the demand. In regard to electricity demand modelling, the advanced version of OSeMOSYS relied on the econometric approach as detailed in [16].

## 4.1 Main Input Data

### 4.1.1 Supply Hypotheses

Main input data of the model are from [13, 14]. These parameters cover technical, economic and environmental characteristics of modelled technologies. Conventional and renewable technologies are considered, for existing generating capacities and future investments. The principal characteristics of considered scenarios are taken from [16] and are related to the energy transition objectives of Tunisia, where the Business As Usual (BAU) scenario and RE scenario target respectively 5% and 30% of RES penetration by 2030 in the electricity mix. The rate of 5% of RES represents the natural technological integration of renewable energy. The 30% of RES represents the national objective of energy transition. The time horizon of modelling is from 2010 to 2030 [2].

### 4.1.2 Demand Hypotheses

The rate of annual growth of electricity demand has been around 5% during the last three decades. In 2018, the national electricity demand has reached 19 TWh. Referring to [15], almost 90% of the electricity demand is transmitted through the distribution grid, which means that it is either medium voltage or low voltage demand. The rest, of about 10%, is transmitted through the transmission grid. The residential electricity demand plays an important role in the national demand and it represents 1/3 of the total demand. In regard to the annual load curve, the electricity peak occurs in summer time due primarily to weather conditions, where the utilisation of cooling technologies and appliances increase. The second peak is occurring in winter time in night time because of heating, lighting and season-based activities. The troughs are in intermediate seasons, autumn and spring, because of moderate weather conditions and the length of day time. The annual increase of the peak represents the major problem for the system operator.

In order to analyse electricity demand projections, assumptions on GDPs per capita and GNI growth rates scenarios are set on a time horizon from 2010 till 2030. Current values and projections of GDP, GNI and population are extracted from [27, 29, 36], Table 3 summarizes the following scenarios of economic parameters per capita in percentage.

**Table 3** Economic growth per capita scenarios

| Period | Parameter % | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|---|
| 2011–2020 | GDP per capita | 1.8 | 2 | 2.5 |
| | GNI per capita | 3.42 | 3.42 | 3.42 |
| 2021–2030 | GDP per capita | 2 | 3 | 4 |
| | GNI per capita | 2 | 3 | 4 |

For the period 2011–2020, real data values for the years 2011–2017 were considered. For 2018–2020, values were based on [1, 26, 28] reports. The difference occurred in scenarios during 2011–2020 is generated from the period 2018–2020 assumptions. Indeed, scenario 1 reflects a trend-based evolution of the economic growth, where the economic growth rate has increased by 0.2% from the period 2011–2020 to 2021–2030. In scenario 1, we suppose that GNI growth rate will decrease by 1.42% from the period 2011–2020 to 2021–2030. In fact, the hypothesis of the first period (2011–2020) was established as follows:

- 2011–2017: real data of GNI growth rate which achieved 5.7%
- 2018–2020: we have supposed that there won't be any increase in incomes

Then, the GNI growth rate obtained for the 1st decade is 3.42%. This value was considered also for the 1st decade in scenarios 2 and 3. Scenario 2 and 3 reflect minor and major economic growth rates respectively. In scenario 2, economic growth rate will increase by 1% from the 1st decade to the 2nd decade. In scenario 3, economic growth rate will increase by 1.5% from the 1st decade to the 2nd decade. In regard to the GNI growth rate, in scenario 2, it will decrease by 0.42% from the 1st decade to the 2nd decade. In scenario 3, GNI growth rate will increase by 0.58%.

A 1% yearly increase in electricity prices over the time horizon 2010–2030 is considered.

## *4.2 Interpretation of Results*

### 4.2.1 Supply Side Insights

This section considers a discount rate reflecting the market rate of interest. Due to its fluctuations and the lack of prospective data, discount rates of 5%, 8% and 10% were considered. The impact of discount rates on future investments and total discounted costs are analysed. These values have been applied by the Tunisian National Utility Company (STEG) and the study elaborated by Wuppertal Institute related to the national objective of renewable energies integration [32, 40].

Figure 1 in (a) and (b) shows that for both scenarios, an increase in the discount rate has lowered future installed capacities, with higher impact on RE scenario. The decrease registered 1% and 3% respectively for BAU and RE scenarios, if we increase the discount rate from 5% to 10%.

When we increase the discount rate, the lower the value we assign to future savings in today's decision. Since we are optimising on a long-term horizon, then the total discounted costs are lower. The model tends to invest in projects to be consumed in a shorter period, i.e. investments with low lifecycle. For example, in our case pumped storage hydro has a long lifecycle, around 100 years. It then disappears when we apply high discount rates. Therefore, it is preferable to apply moderate discount rates to not reject technically desirable projects.

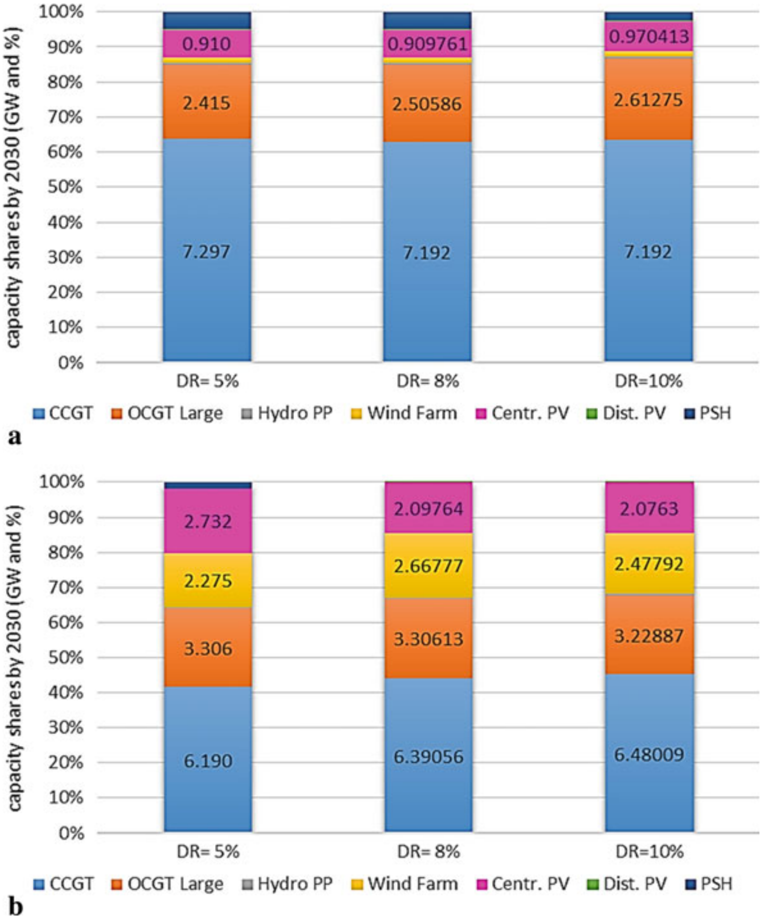


**Fig. 1** Impacts of the discount rate on capacity shares by 2030 (CCGT: Combined Cycle Gas Turbines, OCGT: Open Cycle Gas Turbines, Hydro PP: Hydroelectricity Power Plants, Centr. PV: Centralised Photovoltaic Power Plants, Dist. PV: Distributed Photovoltaic Installations, PSH: Pumping Storage Hydroelectricity) **a** BAU scenario **b** RE scenario

Based on Fig. 2, the impact of varying discount rate in costs is important. We have passed roughly from 18 to 12 billion 2010USD for both scenarios. Indeed, this highlights the significance of this metric in modelling the Tunisian power system. A high discount rate of 10% has discounted long-term future costs to a lower level. An elevated discount rate reflects indeed a *healthy* economic growth rate. If we consider Ramsey Formula, 10% discount rate reflects an economic growth of 5%. This situation represents a capital opportunity favouring short-term investments. Investing in short lifecycle power plants has lowered the total discounted costs.

It is remarkable that increasing the discount rate has minimised the difference between total discounted costs of BAU and RE scenarios. Starting from a discount rate of 8%, the difference in the total discount cost between RE and BAU

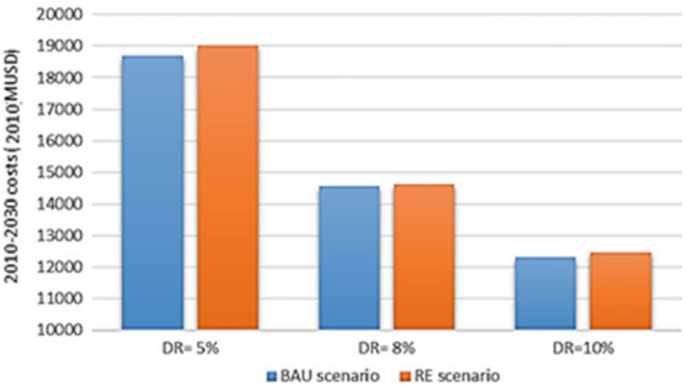


**Fig. 2** Impacts of the discount rate on costs—BAU versus RE scenario

scenarios decreased. RE scenario discounted cost is almost equal to the BAU scenario discounted cost. Growing the DR implies for both scenarios the use of resources in the short term period. In both scenarios, to satisfy the demand in the long-term horizon, the model tends to use RE resources, independently of the objective of reaching 30% of RE by 2030. Indeed, this has led to a minimisation of the difference in costs between the BAU and RE scenarios while applying high discount rates. In conclusion, an increase in the economic growth is favourable for the realisation of the RE scenario in comparison to a BAU scenario.

### 4.2.2 Demand Side Insights

Figure 3 is marked by two principal periods: 2010 till 2020 and 2021 to 2030. During the first period, the electricity demand has evolved similarly with the three scenarios. Supposing an economic growth of 1.8%, 2% and 2.5%, respectively for scenario 1,

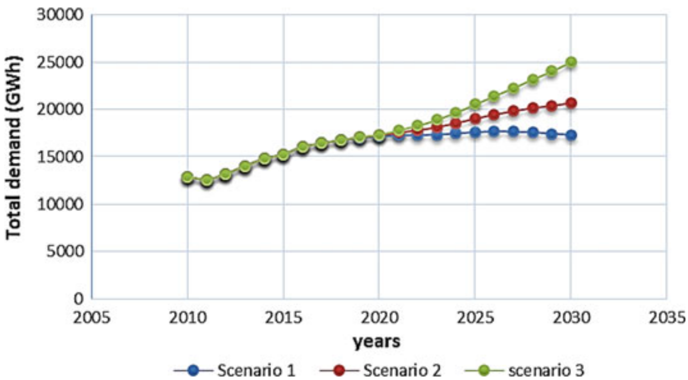


**Fig. 3** Electricity demand evolution as function of economic growth per capita

2 and 3, and the same GNI growth rate have led to a similar profile of electricity demand. This shows that the impact of the residential demand on the whole electricity demand is the most important. As a reminder, the GNI growth rate per capita during the period 2011–2017 has been around 5.4%, which has further impacted residential electricity demand. In the second period 2021–2030, with the increase of economic growth per capita and growth rate of GNI per capita, we have obtained different profiles. Scenario 1 has led to a constant evolution of the demand. Scenario 2 and 3 have led to an increase in the demand with different levels. An increase in the economic growth per capita and the GNI growth rate per capita over the values imposed and achieved during the first period will lead obviously to the increase of standards of living (through GNI), the increase in the purchase power (through GNI) and the increase of local production (through GDP). All these activities will impact the growth of the electricity demand.

### 4.2.3 Demand-Supply Reciprocal Impacts

Based on [45] works, we have estimated a variable pure time preference in Tunisia related to the power system of 3, 7 and 10%. Since then, there were no further research works on this matter elaborated. Following, modelling electricity demand was based on the two cases of 3 and 7% pure time preference ratios. We have integrated into Ramsey formula in Eq. 14, the 3% ratio for scenarios with a decrease in the GNI per capita growth rate from one decade to another. The 7% pure time preference ratio was integrated for scenarios with an increase in the GNI per capita growth rate from one decade to the other. Then, respectively we have obtained a social discount rate (SDR) of 3.35%, 3.53% and 7.72% for scenario 1, scenario 2 and scenario 3 respectively.

At this stage, it is essential to recall the study [41], where the considered SDR for the case of European countries varies between 0.5 and 6.9%. However, these values take into consideration negative externalities of conventional technologies such as environmental and health damages. In [23], analysts distinguish the social discount rate based on a prescriptive approach, using Ramsey Formula, and a descriptive approach, using market rates. The two approaches are complementary.

The first approach considers ethical aspects that could be integrated in the parameters of the Ramsey Formula with a preference rate close by the null value. This allows obtaining a SDR lower than the one used in the market. Then, the values chosen in Sect. 4.2.1 for simulations of the Tunisian context are elevated: 5, 8 and 10%. These values will compromise renewable energies that have high capital costs compared to conventional energies especially in the first period of the time horizon. Nevertheless, analysts argue that the descriptive approach represents a solid starting point for the discount rate and that market rates could be applied since they reflect the opportunity cost of investing in public and private projects and that ethical arguments for a low discount rate are more a reason to increase savings and investment and could lead to misallocation of resources.

As shown in Fig. 4, it is noticeable that the BAU is a conservative scenario (Figures a, c and e). In scenario 1, with a very low increase in electricity demand, total capacity was 8.41 GW by 2030, as displayed in Fig. 4a. This is also impacted by the low discounted rate used. Followed by an increase in scenario 2, in Fig. 4c, and almost a constant profile in scenario 3 in Fig. 4e. Then the model has optimised the capacities shares balancing between the discount rate and the evolution of the demand.

For the RE scenario, in scenario 1 and scenario 2 since close values of discount rates are applied, an increase in total installed capacities by 2030 is stated, respectively 10.68 GW (Fig. 4b) and 11.88 GW (Fig. 4d). This reflects the increase in demand and economic growth rates. For scenario 3 shown in Fig. 4f, installed capacities have achieved 11.22 GW by 2030.

Even though the electricity demand increased due to high applied economic growth rates, the related high SDR 7.72% has led to low installed capacities in the long-term perspective.

Moreover, with a low rate of increase in electricity demand, the results show that PSH will be invested as a storage mean to respond to load curve fluctuations (Fig. 4a–d). Therefore, the model tends to invest in technologies with long life cycles. In regard to low economic growth rate, low social discount rates are registered. SDR will generate higher long-term discounted costs. Since the discount rate is associated to the social discount rate, then projects or strategy set by decision makers has a social dimension (usually analysed using a cost-benefit analysis). Therefore, the obtained discounted costs represent social costs.

However in scenario 3 reflected in Fig. 4f, PSH has disappeared and needed capacities were satisfied by other technologies with lower lifecycle. In fact, when the SDR increases, lower value to future savings in today's decision are assigned. Then, the model follows a trend to invest in projects to be consumed in a shorter period (investments with low lifecycle).

The evolution of the electricity mix in 2010–2030 with a crossing of supply and demand scenarios are illustrated in the second figures matrix as displayed in Fig. 5. As a resultant of the capacities shares, the electricity mix was primarily marked by relatively high utilisation of PSH in BAU for scenarios 1 and 2 (Fig. 5a, c), contrary to the combination of the BAU scenario and scenario 3 (Fig. 5e).

Referring to Table 4, from scenario 1 to scenario 2, the BAU and RE costs have slightly increased. These scenarios have a decremented increase in the social discount rate and a mean evolution of the electricity demand over the time horizon. The increase in costs is due to the slight increase in demand. The increase in total installed capacity has engendered an increase in the total discount cost. The sharp growth of the discount rate has decreased BAU and RE scenarios total discounted costs in scenario 3.

Appealing the concept of discount rates, low SDR and high discounted costs reflect an indifference about using supply resources. This situation might higher social benefits, which has been also deducted when applying Ramsey Formula, where the low discount rate reflects a low pure time preference rate and willingness to assure intergenerational transfer of benefits on a long-term horizon.

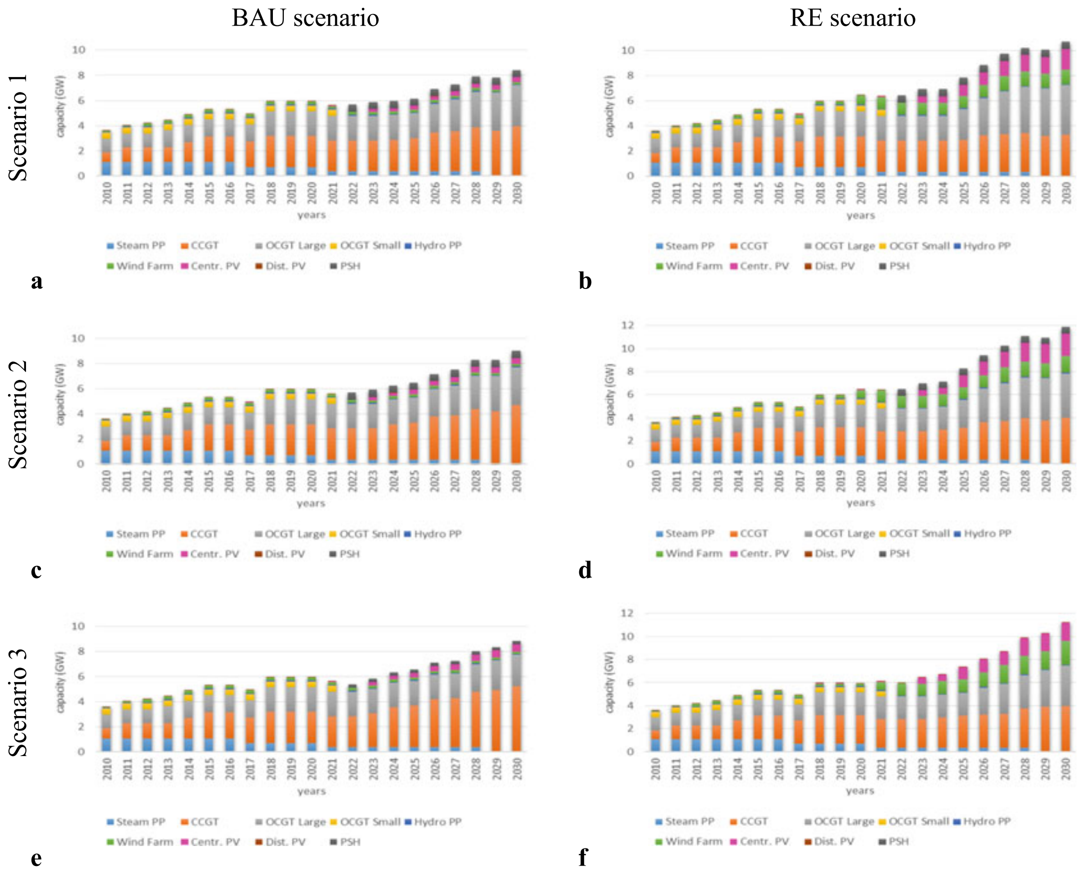


**Fig. 4** Capacity shares evolution—supply scenarios versus demand scenarios

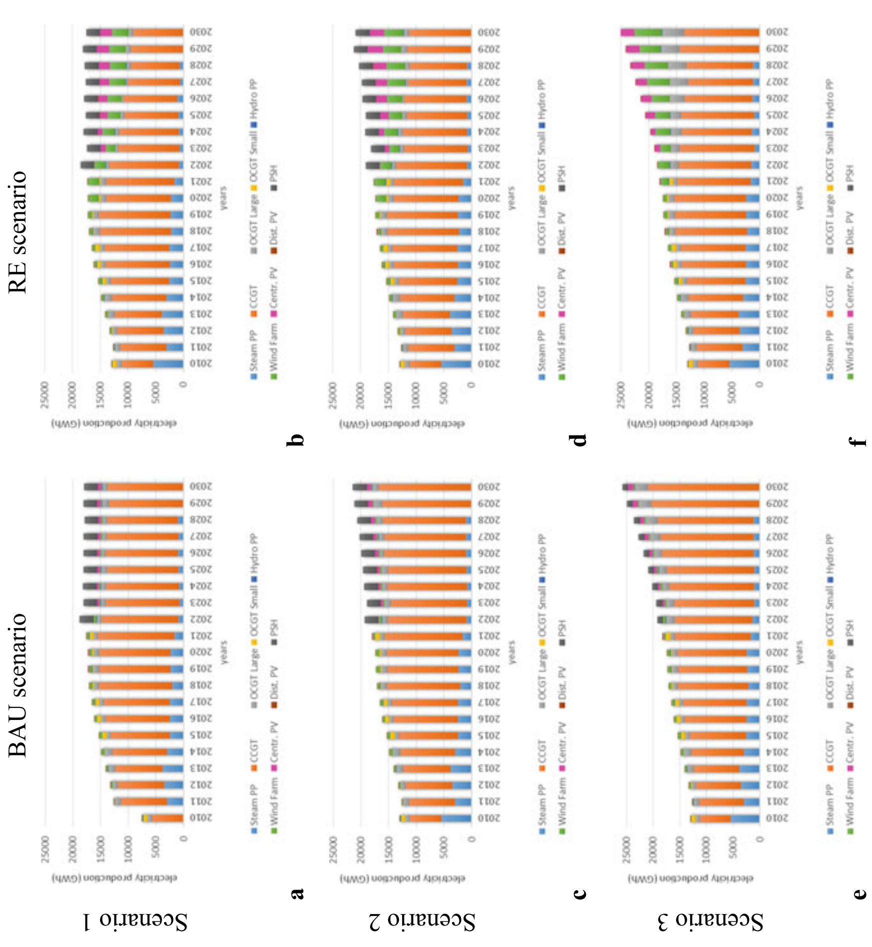


**Fig. 5** Electricity mix evolution—supply scenarios versus demand scenarios

**Table 4** Total discounted costs comparison 2010–2030

| Costs billion USD 2010 | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|
| BAU scenario | 17.78 | 18.10 | 12.97 |
| RE scenario | 18.10 | 18.56 | 13.24 |

Furthermore, a slow economic growth and an ambitious objective of reaching 30% of RE by 2030 have increased the total discounted cost. In fact, the increase in current generation benefits and carrying out meanwhile an objective with long-term benefits (from renewable investments) have generated high benefits for the current and future generations. This has been reflected through increased costs.

Assuring an optimistic economic growth will definitely lower long-term social costs. Carrying out with the BAU scenario, any increase in the economic growth will steeply increase current costs. Yet, assuring a relatively high economic growth will decrease costs.

In this work, a detailed cost-benefit analysis is not accomplished to determine the costs and benefits of each scenario. Considered costs for both scenarios are: capital costs, sunk costs from previous investments, O&M costs, depreciation, and external costs, etc. These costs have been quantified and discounted.

However, benefits are generally associated to the selling prices of electricity. Since prices are distorted with subsidies in Tunisia then quantifying benefits from selling electricity is not possible [16]. Other benefits could be considered such as environmental, economic and social benefits. For instance, an investment in hydro power plants will effectively generate electricity, but also it will provide water for irrigation and for drinking supply. Then, this kind of projects has further benefits.

Similar pricing system for both BAU and RE scenarios are considered. The RE scenario has higher discounted costs during the first decade of the time horizon. During the second decade, RE discounted costs yearly have become more competitive and even lesser than the BAU scenario. Then, by the end of the 2020s, the benefits generated by the RE scenario, from selling electricity, are higher than in the BAU scenario.

Finally, the RE scenario has environmental benefits since it participates in lowering emissions, preserve fossil fuel energies (natural gas and oil) and lowers the dependence on other countries (imports of fossil fuel energies), etc. Then, RE scenario benefits are eventually higher than the BAU scenario. By the end of the modelling period, it is more beneficial to invest in the RE scenario for the Government.

## 5 Conclusions

In order to satisfy needs such as climate policies, energy security or economic development, it has been proven that energy system modelling is a tool to help analysts and decision makers:

- Forecast the environment and present insights;
- Take the right decisions;
- Make the long-term strategic energy planning leading to a sustainable development.

Identifying the most suitable model is becoming very complex given the increasing number of models and the needed peculiarities that should be taken into consideration. However, the different types are at a certain level interconnected and could be classified under different classes. The typology's misperception could also complicate the identification of the suitable model. An overview covering clearly all types arbitrary was not yet examined by the literature.

In this context, this chapter has presented an *objective* overview of approaches based on their historical evolutions, since they represent the foundation of energy system models. A special attention is paid to the appearance of Open Source Modelling (OSM). In fact, OSM could be classified under any of the types acknowledged in the overview. Several characteristics have boosted spreading OSM. For example, free access and open source codes are also considered as a tool promoting transparency, adapting models to reality and better involving developing countries and researchers in modelling. Then, OSM itself is a tool to help achieving sustainable development.

Furthermore, this chapter has demonstrated the important role of key factors in modelling and presenting insights, amongst the discount rate has been argued as a parameter affecting not only the supply side but also the demand side and their interactions in an energy system.

To illustrate the impact of the discount rate, the case study of the power system of Tunisia is analysed. The enhanced version of the Open Source energy MOdelling SYSTem (OSeMOSYS) is used to model the power system taking into consideration the specificities of the supply and the demand. The impact of varying the discount rate parameter is analysed, under assumptions for Business As Usual and Renewable Energy scenarios.

It has been principally concluded that an increase in the discount rate implies an immediate utilisation of resources which favours implementing renewable energies in the long-term horizon. This has led to a decrease in the difference between the BAU and RE scenarios. An increase in the discount rate reflects an increase in the economic growth, favourable for the realisation of RE scenario. The discount rate is a double-edged sword where values should be reflected also while modelling the electricity demand. It is, in fact, related to economic growth rates. Then, simulations have been run to analyse the influence of modelling the demand side on the supply side. It has been concluded that the social discount rate, calculated through Ramsey Formula, is the principal factor impacting supply side investments through changes on economic growth. Indeed, relating economic growth with corresponding social discount rate has shown a differentiation in the shares of supply. A low economic growth leads to investments in technologies of longer lifecycle. Optimistic scenario of economic growth tends to favour renewable energy investments.

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# Effects of Climate Change on Women—Adaptation and Mitigation

**Zaineb Abid and Muhammad Abid**

**Abstract** Earth is undergoing inevitable changes in its climate due to many natural and man-made activities as the temperatures are rising, freshwater resources are drying up, biodiversity is decreasing and natural disasters are increasing. Women, forming a major portion of the world poor and having less education and resources to manage climate risks, are more vulnerable to adverse effects of climate change as compared to men. Due to many social, cultural and religious norms restricting the mobility of women, women are greatly affected by climate-induced agricultural and biodiversity losses, climate-related wars, natural disasters and migrations. Despite of having close relationship with environment and natural resources, women's representation in climate decisions is very less and their role is seldom appreciated. The current study sheds light on different scenarios of climate change including agriculture, biodiversity, water, natural disasters, wars, migration, pollution, health and sanitation, education, disempowerment, security, social and psychological effects and human rights in relation to women's vulnerability to it. It also discusses the mitigation measures to reduce the effects of climate change on women.

## 1 Introduction

In the world of today, climate change is the major threat affecting the survival and livelihood of mankind and other species all around the world. Natural activities such as hurricanes and earthquakes and man-made activities such as rapid population growth, urbanization, agricultural intensification, excessive use of vehicles and fossil-based industries are leading to physical global imbalance and depletion of natural resources. Temperatures are rising, glaciers are melting and sea levels

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are increasing, heat waves and droughts are becoming common and more severe, precipitation patterns are changing and extreme weather events are becoming more frequent. The temperature of Earth has increased by 0.6 °C in the last 100 years and the year 2015 has been recorded as the hottest in the past 39 years that has resulted in rapid rise in sea levels [1]. Consequently, agriculture, biodiversity and ecosystems, food security, freshwater resources, human health and settlement patterns, and energy supply etc. are being adversely affected. The major weight-bearers of the issue have been identified as the developing countries which are home to the majority of the poor people in the world. About 80% of the world's biodiversity is maintained by indigenous people who make up about 15% of the world's poorest [2]. However, these people face the greatest risks of climate change. Emphasizing the discrimination faced by different groups in facing climate effects, the Intergovernmental Panel on Climate Change warned that "**climate change impacts will be differently distributed among different regions, generations, age classes, income groups, occupations and genders**". According to the Swedish bill on climate and energy, 'many developing countries are especially vulnerable to climate effects because of poverty, conflicts of gender and social equality, the environmental degradation and lack of food [3]'.

Women and children, forming the major portion of the world poor, are most vulnerable to climate effects. Women form 70% of the 1.3 billion people living below the poverty line in the developing countries [3] and form 60% of the gravely hungry people in the world. Emphasizing the plight of women, a former UN peacekeeping operation commander, Major General Patrick Cammert said that 'it is now more dangerous to be a woman than to be a soldier in modern conflict [4]'.

Women are more dependent and more closely related to natural resources than men as can be observed by looking at their daily life activities which makes women more vulnerable to effects of climate change [4]. These activities include:

- Finding, collecting, carrying, storing, securing, purifying and distributing water and food for various household purposes such as drinking, cleaning, washing, sanitation and feeding families.
- Production of livestock products and household crops.
- Cutting and carrying fuel such as agricultural waste or wood for heating homes, drying clothes, and cooking.
- Cutting and learning about herbs to treat diseases and taking care of the elderly and the sick [5–8].

It is, thus, clearly understandable that any adverse effect on the environment will adversely affect women. Hence, in 2002, World Summit on Sustainable Development held in Johannesburg declared climate change as an 'ethical' issue [9].

Women's vulnerability to climate change can be attributed to number of factors: less land or assets' ownership, less work opportunities, less awareness about legal rights, high levels of illiteracy, less empowerment activities, low social status, limited mobility, discriminatory laws and customs, socially formed barriers of dependence on males, unequal burden of unpaid domestic responsibilities, unequal access of resources and less involvement in decision-making processes [8]. In a study conducted by the World Bank, it is revealed that in 103 out of 141 countries (25 of 35 economies in sub-Saharan Africa), there are legal distinctions between men and women hampering economic opportunities for women [10].

IPCC Fifth Assessment Report highlighted an important aspect that the women are not inherently vulnerable because of their biological sex and that focusing on this aspect ignores "**the complex, dynamic and intersecting power relations and other structural and placed-based causes of inequality** [11]". However, women are most capable of adapting to the effects of climate change despite being most vulnerable to the climate effects and have proven to be more equitable and responsible towards sustainability needs. It is, therefore, necessary to involve women in climate-related decision-making processes at all levels. This requires an in-depth analysis of gender-based responsibilities and needs and assigning them mitigation roles accordingly.

The book chapter sheds light on climate change and its relation to women in different scenarios of the changing climate including agriculture, biodiversity, water, natural disasters, wars, migration, pollution, health and sanitation, education, disempowerment, security, social and psychological effects and human rights. Lastly, to mitigate the effects of climate change on women, recommendations to involve international funding organizations are also discussed.

## 2 Vulnerability of Women to Climate Change

### *2.1 Women, Climate Change and Agriculture*

Climate change and resulting extreme weather events such as floods and droughts and increased global temperatures are threatening four main aspects of food security as the crops are failing, natural resources such as water and land are depleting and there is an outburst of pests [1, 5]. These major aspects are food availability, food systems stability, food accessibility, and food utilization [8]. Consequently, there is a decrease in food availability and an increase in market prices of the crops making food unaffordable.

Being the major part of the agricultural workforce and carrying out the tasks of collecting, carrying, storing and preparing food, women are largely affected by these disturbances. In the developing countries, on average, women form 43% of the total agricultural labour force and account for 45–80% of all food production [8] while in Asia and Sub-Saharan Africa, 50–60% of the workforce of agriculture is accounted for by women [12]. Women form 73% of the agricultural labor force in Pakistan [7]. Moreover, majority of the time of the African women is spent in low-level agricultural activities contributing about 50% of the labour working on the farms [13]. About 60–90% and about two-third of the female workforce in Africa is involved in agriculture with African women producing about 80% of the food for the continent [7]. The daily life activities of African women and the effects of climate change faced by them have been described as '**In Africa, most farmers are women.**

**Decline in agricultural yields increases women's workload to obtain enough yields to feed their families; it directly affects household nutrition and incomes and a decrease in woody vegetation makes it difficult to feed their animals**'. In addition, women also play part in afforestation activities and activities of crop domestication and soil and water conservation all over the world [1].

Due to the loss of harvests and adverse impacts of climate change on food production, it is women who face the major consequences since they don't own enough land and don't have any other sources of income. Worldwide women own only 10–20% of the agricultural land while Women's Environment and Development organization (WEDO) provides that women have the ownership of less than 2% land all over the world despite producing 50–80% of the world's food [10, 13]. On the other hand, men own majority of the land and dominate the decision-making processes and market affairs even though women mostly work in these irrigated fields. Moreover, even that small percentage of the land that is owned by women is less fertile hence, women are forced to work on less fertile land. Due to culturally constructed myths of social and physical subservience of women to men, women get lesser microfinances i.e. loans for investment in individual projects, and receive lesser agricultural facilities in comparison to men. It has been found that women receive only 5% of agricultural extension services worldwide and even when they do, the loans are controlled by the males. In a study of 210 households conducted in rural Paraguay, about 23% women reported that their credit was constrained and controlled by men, while freedom of access to adequate credit was reported in two-third cases by their husbands [14]. A study conducted about the agricultural productivity gaps on the basis of gender showed that in Nigeria, Uganda and Tanzania, gender productivity gaps are 18.6%, 30.6% and 27.4% respectively [1]. However, resources have been found to be used more sustainably if women are given security of land rights. According to FAO, agricultural yields would increase by 20–30% in the farms owned by women while national agricultural productivity would increase by 4% if women farmers are given access to the same agricultural tools and finances as men. Also, 12–17% decrease in the number of malnourished people would be observed.

In Africa, the climate-related crop changes affect 48% women in Burkina Faso to about 73% in the Congo [10]. Thus, in cases of extreme losses caused by climate change, women bear the brunt of losing their income and sole sources of food and their financial conditions further worsen. They further fall into the pit of poverty and face the pressure of feeding themselves and their families. In these conditions, women need to work harder to secure food which leaves less time for women's empowerment or education activities and many young girls have to drop out of their schools. Moreover, availability of less food leads to many health issues such as malnutrition etc. [5]. There are many cultural, social and political constraints hampering women's mobility in cases of calamity and they are solely left behind to look after the farms, livestock and the families while men, on the other hand, freely migrate to cities or better areas when tough conditions arrive. According to Vore Gana Seck, executive director of Green Senegal and president of the international and nongovernmental coalition Conseil des ONG d'Appui au Développment, "**Climate change affects women because they are usually the main food producers of**

**crops like rice, millet, vegetables. Because of no rain, climate change affects them. And girls have to drop out of school because they need to start working for their families** [15]."

## *2.2 Women, Climate Change and Loss of Biodiversity*

Climate change is likely to cause extinction of more than 25% species worldwide by the year 2050 [16]. Global ecological imbalance being caused by increased temperatures and frequent and severe rainfall, flood and drought patterns is leading to extinction of many plants and animal species as the habitats of these animal and plant species are being damaged and their living requirements are not being fulfilled. These species either have to adapt continuously to these frequently changing conditions or migrate to more favourable areas to survive. However, many of them are not capable of coping with these changes and do not survive. Moreover, climate change has an impact on the environmental conditions that act as limiting factors for different species and interfere with their tolerance ranges such as availability of light, moisture, temperature, disturbances such as storms and fire, tides, water depth, availability of nutrients and salinity leading to loss of biodiversity. Loss of Arctic sea ice, ocean acidification due to high concentration of carbon dioxide in the atmosphere and deforestation which emits about 20% of the carbon dioxide in the air is posing a potential threat to the biodiversity across an entire biome and beyond [8]. Coastal biomes, being one of the most sensitive ecosystems, are being severely affected. Many people depend upon these ecosystems for their livelihood with fishing, seaweed farming, trading and tourism being the major livelihood activities.

Due to these effects on biodiversity, women are majorly affected since women are mostly involved in collecting and carrying natural resources such as firewood for fuel and many herbs and shrubs for use as food and medicine. Moreover, women also play an important role in fishing industries. Half of the global total workforce of the seafood industry is accounted for by women who are involved in inland fisheries, processing of seafood, collection of shellfish and seaweed and repair and weaving of the nets, according to a gender and development expert, Mariette Correa. Also, women manage finances and aquatic resources at household and community level respectively in small-scale fisheries. Hence, women in coastal settings face significant loss of food source and income when the coastal areas are hardly hit.

Similarly, livelihood of millions of people is at stake due to biodiversity losses in forest ecosystems caused by changing climate especially in Asia and Africa. All over the world, women spend number of hours collecting and carrying extremely heavy loads of firewood and other forest resources to be used for heating homes and cooking food. With climate change aggravating further and natural resources becoming scarcer, women have to spend more of their time and walk longer distances to collect the resources [8]. On average, a woman spends 2–20 or more hours per week carrying and collecting fuel and walk fairly long distances which leaves very little or no time for domestic and educational activities, and causes adverse health effects such as arthritis and spinal deformities. Since women work very closely with nature, they have a great deal of knowledge about plant and animal species, food supply, seed development and production patterns and other natural resources. Hence, they can be of great help in mitigating climate effects and protecting biodiversity.

### *2.3 Women, Climate Change and Water Resources*

Freshwater is the biggest blessing that the Mother Nature has blessed the earth with but it is also the one that is being depleted at a very fast pace due to human activities and the one to which about 663 million people all over the world lack access. Water is not only necessary for the survival but for the existence of life itself. However, water shortage and scarcity is already an issue in 80 countries which are home to about 40% of the world population. It had been predicted that by 2020, 75–250 million people will face the issue of water shortage with rain-fed agriculture reduced by 50%. By 2025, about 5.5 billion people (two-thirds of the world population) will face water shortage [1]. Pakistan's water resources have been predicted to dry up by 2025 by the UNDP [17]. Pollution, acidification, floods etc. due to climate change are affecting water supply with freshwater availability and access being the frontline issues.

Being the primary collectors of water in most rural areas, women are responsible for managing water at household level and have to find the places or sources of water, think about appropriate methods for drawing, collecting and transporting water and about the places and techniques to store that water. They further bear the burden of adequately managing and distributing water for various uses depending upon the quality of water. On an average, carrying of water for three hours per day is needed to fulfill the needs of a family containing six people [17]. At household level, water is required for a number of purposes such as:

- Cooking,
- Cleaning,
- Washing and hygiene,
- Sanitation,
- Child care,
- Waste disposal,
- Agriculture,
- Vegetable growing,
- Food processing,
- Electricity production.

These all aspects are a deep part of women's life and are dealt with only by women mostly. Hence, unavailability of water specifically affects women. Women are generally more involved in water collection and distribution as compared to men as shown by the data obtained by eight countries. In Guinea, women spend 30 minutes per day on water collection while men spend only 8 minutes. Globally, about 200 million hours are spent every day by women and girls in collecting and carrying water from water wells or water sources to their houses in water buckets that weigh more than 40 kg in some cases. In Africa, women travel a distance of 3.7 miles and carry 5 gallons per trip in one day to collect water. African women are five times more likely than men to collect and carry water. In rural areas of sub-Saharan Africa, 63% women collect water while only 11% men carry out the task. In urban areas, only 10% men collect water in comparison with 29% women as per the World's Women report (2010) [17, 18]. Because of lack of transportation, women in rural areas of Pakistan spend 4 hours a day in collecting and carrying waters on their heads [7]. As the climate effects worsen and water resources continue drying up, the burden of work for women is increased and women have to walk greater distances collecting and carrying water. In Lalibela district of Ethiopia, fetching time increased from two hours to six hours per day during the period of drought. However, since the water is sometimes contaminated, even this amount of water is not usable and poor sanitation becomes an issue.

There are also risks to the health, education, livelihood, privacy and safety of women. The need to spend greater amount of time in fetching water leads to an increase in girls' dropout ratio from schools and women get less time for their own income-generating activities such as selling hand-made products and crafts and running cottage industries. Moreover, greater time needed to collect water makes it difficult for women to tend to their own agricultural farms. Hence, women are faced with the hard choice of either working on their own farms to grow food for tomorrow or working on their neighbour's farms at lower wages or even in some cases, leave both and collect water. In case of agricultural farms owned by women, water deficit causes failure of harvests and fields since women very rarely have access to agricultural equipment and technology that can be employed to buffer the climate impacts and variation in water levels. Similarly, many agricultural investments, incentives and water management policies do not take gender-based requirements into account.

Having very less opportunities of migrating to urban areas for earning their livelihoods during crisis as compared to men who migrate to lucrative areas for generating profits, women are left responsible for water management Even a single man could not be found in Sonari village in the Thar area of Pakistan and all water-related and domestic tasks were being carried out by women when the area was studied. These women fetched brackish water and food from trees and they lived in pitiful conditions with their lives concerned only with goats, donkeys and malnourished children [6].

### *2.4 Women, Climate Change and Natural Disasters*

Frequent and more severe natural and slowly occurring disasters such as droughts, famines, floods, cyclones, hurricanes, typhoons, mudslides, desertification, salinization of coastal areas and coastal erosion have been observed in the recent years. Sir John Holmes states that the number of recorded natural disasters in the last 20 years has increased from 200 to 400 per year with about nine out of every ten natural disasters being related to climate change. Many consequences are being faced due to these disasters such as loss of shelter, health issues and deaths, poverty, agricultural losses, loss of education and empowerment, with migration, disturbed human settlements and displacement being the primary or major impacts. According to the UN Secretary-General report, about $250 billion-$300 billion is spent per year on climate-related disasters.

The majorly affected section of the society due to natural disasters is poor and the needy as shown by the study of International Federation of Red Cross and Red Crescent Societies according to which people in low-income countries are 4 times more likely to die in natural disasters than people in high-income countries. Bison and Goh [19] provide that location and socio-economic conditions affect the level of preparedness for the disasters which further affects vulnerability and resilience of people in specific area. As has been mentioned earlier, women lack the major resources and form major part of the poor people and hence, are more vulnerable than men. However, a study conducted in Orissa, India shows that it is difficult to determine vulnerability of women to disasters without considering:

- Class,
- Gender,
- Ethnicity notions of the place or the region.

Following are some of the major factors that make women more vulnerable to natural disasters:

- The notion of socially constructed 'dependence of women on men',
- Economic disadvantage,
- Gender discrimination in ownership and in access and control of land and resources,
- Limited decision-making,
- Lower literacy rates which make them susceptible to damage during natural disasters, and
- Cultural and religious restrictions hampering women's timely escape at times of disasters.

Women's vulnerability to natural disasters in comparison to men is also influenced by the extent of the socially constructed vulnerability of women as found by Neumayer and Plumper in their analysis of 141 countries between the years 1981 and 2000. Many cases of gender-based cultural and religious restrictions have been reported in many instances of natural disasters. Since it was against the norms of social propriety, many women could not escape their houses in times of floods and because women did not know how to swim or climb trees, many women who tried to escape could not save themselves. In some regions, the social injustice and gender inequality is so extreme that the women are not even made aware of the disaster warnings and women's coping capacity and chances of survival are severely limited. In 1991 cyclone in Bangladesh, official warnings were communicated to men in public settings and men were fully aware whereas, females were totally unaware as these warnings were never communicated on to the other family members.

Preferential treatment is provided to men in post-disaster relief activities or treatment with no substantial consideration given to the needs of women such as sanitary pads, contraception options etc. Consequently, issues related to reproductive health (miscarriages), food shortage, toilets, bathing facilities and sleeping arrangements for women are prevalent in such situations. There are no laws specifically protecting the rights of women in many countries in the first place. Even if there are some laws, women are not literate enough or do not have enough financial resources to claim them.

In these disasters, women and children have been found to have a death rate 14 times higher than men. Among the people who died in 2004 tsunami in Asia, about 70–80% were women while in 1991 Bangladesh cyclone, women with age above 40 years had 31% higher death rate compared to men. In 2003 European heat-wave and in Indonesian and Sri Lankan tsunami in 2006, more women lost their lives. Increased deaths of women in case of natural disasters can be attributed to the fact that prevalence of water-borne diseases is increased during such events which increases women's nursing responsibilities. Moreover, women, themselves, are given less quality health care facilities due to which women are more susceptible to contracting diseases such as skin diseases, gynaecological problems after natural disasters and their morbidity and mortality rates are higher.

In addition to the loss of lives, women are more likely to suffer loss of livelihood and face poverty in cases of disasters. In 2005 when Hurricane Katrina hit USA, more women than men formed the marginalized part of the community and had to see the loss of livelihoods. In Louisiana, a total of 180,000 people lost their livelihoods. Out of these, about 103,000 were women [20]. In 2008, due to the cyclone Nargis that hit Ayeyarwaddy Delta in Myanmar, loss of income source was faced by about 87% unmarried and 100% married women. One reason for greater loss of women's livelihoods is the ownership of income-generating resources solely by men. For example, being the owners of agricultural lands, men's losses are usually recorded in cases of disasters and they are compensated accordingly. However, women mostly run small-scale household industries which are not considered. Loss of productive assets of women such as sewing machines, animals, kitchen utensils etc. are not considered and women are not compensated for their loss which makes them more dependent on men. Similarly, after the natural disasters, natural resources such as water, wood and food etc. are depleted and women's workload is exponentially increased as the women have to travel greater distances and more of their time is consumed. There is a decline in quantity and quality of food and women have to sacrifice themselves and their lucrative activities for the sake of their families. Moreover, depletion of resources affects sources of income for women and they have to face poverty. Thus, it has been found that even though women and girls make up about half of the affectees of the natural disasters, they disproportionately face greater risks than men. The effects are not only limited to these, natural disasters further aggravate existing gender inequalities and biases leading to increased discrimination and vulnerability of women in the society.

### 2.5 Women, Climate Change and Migration

Climate-related disasters, environmental degradation and consequent decrease in natural resources and land productivity is resulting in internal and cross-border migration all over the world and it is further predicted to increase. In Mexico's dry lands, desertification led to the displacement of about 600,000 to 700,000 people per year [21]. Since 2008, about 21.5 million people per year are estimated to have been displaced due to climate disasters out of the total 68.5 million people displaced forcibly. Cyclone Nargis caused the displacement of 800,000 people. Norwegian Refugee Council reports that about 20 million people were displaced by climate-related natural disasters in 2008. About 18.8 million people were displaced in 2017 alone due to natural disasters such as floods and storms [22]. Increased pressure on already meagre public services and water resources is being exerted. This leads to increase in prices of food and energy and outbreak of disease which results in health, social and psychological issues. Moreover, political conflicts might also arise [23].

Loss of biodiversity and disturbance in ecosystems in the receiving area is commonly observed after migrations since settlement of humans in that area is accompanied by the use of that area's natural resources such as water, food, fuel etc. Moreover, damage to seas and loss of coral reefs usually occurs since water is removed from the rivers, the rivers are modified and there are changes in land use. The trend is most common in coastal areas due to overfishing or poor fishing practices, sedimentation or coastal development, land pollution and marine pollution. These activities cause ocean acidification which dissolves/decays calcifying organisms e.g. mollusks and coral reefs [24].

During migrations, women have been found to have higher mortality rate especially in the least developed countries. This might be attributed to the social, cultural, behavioural and religious restrictions on women in these countries and to the poor socioeconomic status and lack of information to women. Being more vulnerable to the effects of wars and natural disasters, women are also more vulnerable to impacts of migration as compared to men [8]. Pregnant women are specifically more at risk of contracting diseases and becoming sick due to malnutrition. Stillbirths, infant deaths and maternal mortalities are thus commonly observed during migrations. A number of studies are available that prove women's vulnerability to migration and natural disasters. In 2007, floods and rains displaced about 1.5 million people in 18 African countries among whom three-quarters were women and children. Moreover, women and children were significantly displaced during Hurricane Katrina as indicated by a decrease in number of households run by low-income mothers from 18,000 in 2005 to 3000.

## 2.6 *Women, Climate Change and Wars*

Decline in natural resources, species extinction and frequent droughts and famines are increasing wars and conflicts as nations are fighting against each other to get food, water etc. to fulfill the needs of their populations. This is one dark aspect of climate change that has just started coming to the spotlight. In a report written by Marco Sánchez Cantillo at the UN FAO, it is stated that **"There's no doubt that there's a clear interaction between climate change and conflict. They work together to accelerate and deepen the severity of hunger."** It considers droughts to be responsible for conflicts and food crisis in Afghanistan, Sudan, Yemen, Somalia, Syria and Iraq. Furthermore, it provides that from 2003 to 2016, the number of undernourished people in the world increased yearly. The number of malnourished people in 2015 was 777 million which increased to 815 million in 2016. Among these, 489 million undernourished people were in the countries having high conflict rate. Today, there are about 53.5 million people with no reliable food source. Scarcity of water has been highlighted as the major reason for third world war. 'My belief is that we will see renaissance of violent conflict in the twenty-first century, and that many of these conflicts will spring from climate change', says author of the book 'Climate Wars: Why People Will Be Killed in the 21st Century', Harald Welzer. This assumption has been supported by Marcus King, author of the chapter 'weaponizing water' who also predicted that water scarcity might lead to interstate wars in the coming years. One example is the issue of damming of River Nile over which Egypt had issued a threat of air strikes to Ethiopia. As per Pentagon's study of climate change, countries such as Iraq and Afghanistan are already fighting wars for natural resources. However, not only wars are increasing due to climate change but the wars are also deteriorating the environment even further since militaristic acquisition and unjust use of natural resources are resulting in intensive emissions of greenhouse gases. America is reported by Gwyn Kirk of Women for Genuine Security to have been fighting a war for oil against Iraq. Military spending and greenhouse gas emissions of United States have greatly increased over the years [21]. United States military spent under $300 billion in 2000 while the spending increased to $700 billion in 2008. About 40 million gallons of fuel were burnt by army during three-week combat in Iraq which is equivalent to burning 2 million gallons per day. This is equal to total amount of gasoline consumed by all the allies in the First World War.

During wars, when male members of the households are killed, women are left responsible to provide for their families and burden increases. In some instances, these women are forced to leave their houses and migrate to faraway places. As a result, these women fall into pit of poverty. At times of wars, may cases of sexual violence are reported as women are increasingly subjected to sexual abuse at the hands of male soldiers. Moreover, in societies where militarism and violence becomes normal, domestic violence also increases. All these situations suppress women and their rights more than men. Hence, women are the major weight-bearers of climate related wars [4].

## 2.7 Women, Climate Change and Loss of Education/Disempowerment

Women form three quarter of the total 876 million illiterate adults of the world [10]. This condition is being further worsened by the adverse impacts of climate change. Due to the precarious circumstances posed by decreasing water resources, stressed agricultural conditions, natural disasters and subsequent migrations, young girls and women drop out of schools and other jobs to help their families with increased workload of working in the fields, fetching water, firewood, and overcoming the catastrophic effects of natural disasters and migration. The discrimination is specifically intensified in cases of natural disasters, migrations and wars when social constraints do not allow mobility of women to earn a living [6]. Hence, women are left penniless and destitute if male members of the family die in such situations since women themselves are also not literate. Moreover, during natural disasters, only number of households that are destroyed are counted as loss with household equipment used by women to run cottage industries such as kitchen utensils, sewing machines etc. being never considered. Hence, financial losses faced by women are never compensated and women are left disempowered. Students had no choice but to leave schools and support their families in household and agricultural work when their schools were washed away during floods in Jhangin Punjab, Pakistan.

In many poor regions of the world, increased ratio of girls tend to drop out of schools as they reach puberty due to the lack of washrooms, sanitation facilities and sanitary napkin disposals due to water shortage.

In a study conducted by International Labour Organization (ILO), gendered-impacts on employees' absence from the formal work have been observed with the increase in air pollution. The gender gap in working hours doubled when air pollution levels averaged 1000 $\mu$g per meter cube with women's working hours being reduced and men's working hours being increased. Women had to take care of the sick family members due to air pollution while men had to compensate for the working hours lost by women. Even though this condition is strenuous for men as well, women lose their empowerment chances altogether [11].

## 2.8 Women, Climate Change and Loss of Security

Climate change is threatening the safety, security and resilience of women in addition to threats to their health and education. Women are increasingly falling prey to sexual harassments, assaults and animal attacks as they have to walk greater distances to faraway fields for procuring water and fuel etc. as environmental degradation intensifies. This not only addresses the issue of unequal labour between men and women but also the issue of women's security [8]. In many parts of the world such as in some villages of Nepal, women are compelled to wait till night to use washrooms for bathing and washing clothes, since they are not involved in tube well designing procedures and there are no washrooms near their houses with public washrooms located alongside roads with no privacy.

Gender-based violence (GBV) is normally increased at times of climate disasters, wars and migrations which includes increased domestic violence, sexual assaults and exploitation of women and human trafficking Overcrowded and unsafe living conditions in evacuation camps and internally displaced centers and consequent loss of community and poverty increase the chances of violence making women more vulnerable to sexual violence at the hands of male soldiers and also domestic violence. Resultantly, women fear going out. Due to the fear of being attacked, many women did not access safe medical facilities and the mothers and children both died during childbirth in Papua New Guinea.

Not giving women social status that they deserve and not involving them in decision-making processes is itself a harm to women's resilience.

### *2.9 Women, Climate Change, Social and Psychological Issues*

Social life and mental health of women is being greatly affected due to climate issues. However, these aspects are seldom considered. Due to increase in women's workload due to environmental degradation, they are left with very little time for themselves and their social interactions. Hence, women's social relations are crippled and they are confined to themselves. Women suffer from Post-traumatic Stress Disorder (PTSD) more than men during wars and natural disasters as found by the study conducted in Nicaragua after Hurricane Mitch where about 74% emotionally effected people were women.

Many social issues are also arising as increased number of women are suffering from infertility and skin lesions caused by arsenic-related or other water-borne and air-borne diseases due to which women are shunned and excluded from societies and they are left unmarried. Unmarried women are more prone to social exclusion, poverty and depression [21]. In Pakistan, during floods, many houses were destroyed leading to severe financial losses due to which parents had to sell their daughters' dowries and jewellery which delayed their marriages. However, these girls fell victim to feelings of self-pity and worthlessness since delay in marriages is considered a taboo in these societies. Among 1.2 million Iraqi refugees who migrated to Syria during US occupation of Iraq, many women, being sole supporters of their families, had no other option and turned to prostitution.

On the other hand, rise in incidents of forced and early marriages have been observed. Many parents, being unable to support and secure their families after disasters or migration, force their daughters to get married early or sell them to lessen the burden. In Haiti, Pakistan and other countries affected by Indian Ocean tsunami, many cases of forced and early marriages were reported after disaster.

### 2.10 Climate Change and Violation of Human Rights

Climate change has emerged as a social and moral issue as basic human rights of many people around the world are being violated. Increase in loss of livelihoods, exposure to many diseases, hunger and malnutrition with lack of access to clean drinking water, sanitation and adequate housing is impeding the fulfillment of basic rights including food, shelter, health and education. The severity of issue can be realized by the fact that climate crisis is threatening the right to social life and security. Most importantly, it is threatening the existence and survival of life itself. As it has been mentioned that women are majorly affected by all these issues, it is concluded that the women all over the world are not receiving the basic rights that they deserve.

It is important to realize that it's not only the rights of human race that are being crippled but also the rights of those animal and plant species that are being endangered due to human activities.

### 2.11 Women, Climate Change and World Economy

With climate crisis getting worse, there is a continuous increase in the cost spent on mitigation of the effects posed by it. In the year 2014, about 18% increase occurred in global climate change finance and $391 billion was spent on low-carbon and climate-resilient growth. At present, many public and private agencies are working at international levels to provide climate funds. World Bank provides that about 50 international public funding agencies, 6000 private equity funds and 45 carbon markets are providing finance for climate change mitigation and adaptation. Several studies have calculated the cost of mitigating climate change for the coming years. The mitigation and adaptation costs till 2030 are likely to increase between $249 billion to $1,371 billion annually while the costs will rise up to $44 trillion till 2060. A report by the World Bank predicts that the financial cost spent on the climate change adaptation would be between $75 billion to $100 billion from the year 2010 to 2050. Moreover, it has been predicted that the world economy will suffer 23% loss by the year 2100 if the climate change remains unmitigated. In the worst case scenario, it is likely to cause the loss of 1% to global GDP per year [25].

The involvement of women in such financial matters can be very beneficial in dealing with climate crisis due to their direct relation to environment as mentioned above. A study was conducted by McKinsey Global Institute in 95 countries to determine the impact of minimizing gender gap in labour markets on economy of the country. The results showed significant increase of about 9% in the GDP of each country and an increase of 26% or $428 trillion in the global GDP. Moreover, if women are allowed access to credit and land, the number of malnourished people would decrease by 12–17% all over the world as reported by FAO. The ratio of malnourished children is 85% higher in countries where women do not have access to credit [13]. Furthermore, increased ratification of international environmental treaties has been found in parliaments having higher female representation highlighting the fact that women are environmentally more conscious and are major change-makers in fight against climate issues.

Despite of all these benefits, women are seldom involved and they remain under-represented in most of the financial dealings. Moreover, in those committees or organizations where women are involved, gender analysis is very comprehensive or undertaken later in the process due to lack of enough climate expertise [11]. In 2015, women had only 22% representation in bodies governing climate funds with only 14 out of 193 finance ministers being women. Moreover, only 21% seats were held by women in national parliaments, 25% seats in Latin America and Caribbean parliament and less than 14% seats in Arabian parliament. Only 5 out of 3,864 projects highlighted gender in their documents according to the 2012 Climate Development assessment report and only 2% of the total bilateral aid ($469 million) was given to women's economic empowerment initiatives during the period 2011–2012. This shows that globally, women in only 2 countries have representation matching their population.

## *2.12 Women, Climate Change and Pollution/Environmental Awareness*

All over the world, the use of fossil energy sources such as coal, oil and natural gas etc. for cooking and heating homes is very common. In developing world, about 2.9 billion people use these solid fuels in their homes which are the direct source of polluting gases leading to climate change. About 2.8–4 million people die prematurely every year due to the household air pollution with about $123 billion per year being the environmental, health and economic cost of inefficient cooking. Another report provides that about 2 million women and children die every year due to indoor biomass burning [10]. Women, spending more time in the houses, are more susceptible to the adverse impacts of unclean cooking fuels and inefficient lighting.

Furthermore, women contract water-borne and air-borne diseases more frequently than men as managing and disposing off household wastes, water wastes and agricultural wastes are among many of their responsibilities. In addition, women are more exposed to agro-chemicals such as pesticides, organic pollutants and infectious agents found in waste.

The study titled 'The effects of gender on climate change knowledge and concern in the American public' conducted by Aaron M. McCright in 2010 analysed the gender-based knowledge and concerns related to climate change. The results are illustrated in the following Table 1.

Table 1 clearly demonstrates that women are more concerned about global warming than men. In terms of acceptance of phenomenon of global warming, about 59% women believe that global warming is happening as opposed to 54%

**Table 1** Climate change knowledge and concerns by gender (2001–2008 pooled sample)

| Belief or attitude item/index | Men | Women | Gamma[a] |
|---|---|---|---|
| *Assessed climate change knowledge* | | | |
| % who believe the effects of global warming have already begun to happen | 0.54 | 0.59 | 0.107*** |
| % who believe pollution from human activities are primary cause of global warming | 0.56 | 0.64 | 0.168*** |
| % who believe most scientists believe global warming is occurring | 0.60 | 0.66 | 0.141*** |
| Climate change knowledge index mean | 1.73 | 1.91 | 0.107*** |
| *Perceived understanding* | | | |
| Perceived understanding of global warming mean | 3.04 | 2.75 | −0.336*** |
| *Climate change concern* | | | |
| % who worry about climate change a great deal | 0.29 | 0.35 | 0.162*** |
| % who believe global warming will threaten their way of life | 0.28 | 0.37 | 0.198*** |
| % who believe the seriousness of global warming is underestimated in the news | 0.28 | 0.35 | 0.225*** |
| Climate change concern index mean | 1.29 | 1.55 | 0.174*** |

[a]Gamma for the relationship between gender and each item/index
*$P < 0.05$, **$p < 0.01$, ***$p < 0.001$
*Source* [23, 24]

men. Similarly, about 66% women and 60% men consider the scientists' belief that global warming is happening as true. While considering human activities to be the major cause of global warming, more women (64%) than men (56%) agreed that global warming is the result of human activities. However, despite of women showing more assessed knowledge about climate change, more men exhibit perceived understanding of it.

Women have been found to have greater inclination towards renewable resources and the involvement of women in technology sector has shown that women bring innovative green solutions and clean technologies in the market and promote sustainable technologies. Moreover, women involvement further promotes the use of cleaner technologies at household level. At present, women form only 35% of the renewable energy technology sector of the world depending upon the location and the product. Women's involvement in climate change mitigation activities is linked with reduction in GHGs as shown by the Environment and Gender Index Reports 2012. The parties that involved women in their 2015 Intended Nationally Determined Contributions (INDCs) emitted only 18% GHGs while parties that didn't involve women emitted 82% gases [26].

### 2.13 Women, Climate Change, Health and Sanitation Issues

Water-borne diseases are among the most frequently occurring health issues due to poor water quality and lack of water availability. UNICEF/WHO report of the year 2000 reports that a total of 250 million people were diagnosed with water-borne diseases at the beginning of twenty-first century out of whom, 75% were slum-dwellers and majority were women. In the report of year 2002, WHO mentions gender and sex as the determinant of health-status [9]. The condition is being further worsened by the effects of climate change. Increased temperatures increase evaporation from water bodies and rapid melting of glaciers leading to shortage of water or droughts and rise in sea levels. The communities where people depend on glaciers as their freshwater source are the hardest hit. Moreover, weather patterns such as rainfall patterns etc. are drastically changing leading to heavy downpours and floods etc. that increase the runoff and flow of pollutants, sediments, trash and other waste materials and toxic elements into the rivers and lakes making the water unsafe for drinking. Natural disasters and migrations also lead to water-borne diseases.

Due to the lack of freshwater availability, women in many parts of the world travel long distances carrying pots of water on their heads and shoulders that sometimes weigh up to 40 kg. Consequently, they suffer from pectoral, pelvic and spinal deformities along with arthritic injuries. Those women that have poor nutritional intake might be most adversely affected due to intensive energy consumption. The task of collecting and carrying water consumes about 30% of average daily per capita calorie intake as shown by the case study in Zimbabwe [27]. These health issues also affect childbirth processes. In addition, pregnant women form the most sensitive group to water issues since they can easily contract diseases like hepatitis and sepsis. Moreover, availability of clean water for drinking, sanitation and cleaning/washing is necessary during childbirth processes as its absence can risk the life of both mother and the child. Trachoma, a bacterial eye infection is another disease that majorly affects people in areas with lack of safe drinking water. The major proportion of people affected by trachoma is of women and children. Women account for 70% of the trachoma-blinded people.

For school going girls, sanitation is also an issue. It is provided that globally, about one-third schools lack access to sanitation making female education difficult. Similarly, globally, about 266 million hours per day are spent by women in finding a washroom to go to. In many rural areas with poor socio-economic conditions, contamination of groundwater with arsenic is a common issue. This gives rise to many health issues especially skin diseases such as lesions, dark spots on hands and feet, hardening of skin, loss of feeling and swollen limbs. An example is Bangladesh with large number of affected women.

Increased growth and spread of infectious parasites and bacteria are being observed due to climate change and disturbed weather patterns as climate and weather patterns are the determinants of geographic spread of diseases/illnesses and time of onset. All over the world, disturbed weather patterns are leading to frequent heat waves, droughts, fires, floods and storms which are increasing the rate of morbidity and mortality and are increasing the risk of contraction of illnesses. For example, the rate of maturation and mosquito biting is increasing due to increased temperatures. With rise in temperature and dryness outside malarial zones, the growth of parasites responsible for malaria and Tsetse fly is increasing. Africa is most severely affected by malaria with malaria being the major cause of death of African children. Pregnant women are very sensitive to malaria since they easily develop anemia and give birth to infants who have weak immunity and low body-weight. Not only is health of people being affected but the increased medical costs, deaths and lost productivity cost African economy $12 billion per year. Similarly, cholera epidemic is also increasing due to temperature increase since it is temperature dependent disease [28].

Climate change has been found to be directly linked with HIV in the recent years. HIV cases have been found to be more prevalent in the areas with frequent droughts since malnourished people have weak immune systems and are more susceptible to contracting the disease. In South Africa, Lesotho has the highest rate of HIV and it also has the record of worst droughts in the history. In areas where the prevalence of diseases such as HIV is high, the health, education and social life of women is also compromised. It has been reported that about 80% of the HIV infected women reside in Sub-Saharan Africa. Since the women in these areas are responsible for water collection, contraction of HIV poses difficulties in this task. As a result, young girls have to compromise their time, education and health, and have to take hold of water collection activities and other househod responsibilities.

NGOs working in Karakalpakstan, Uzbekistan have found close links between women's poor health and environmental degradation. In areas with greater environmental degradation, women have higher rates of maternal mortality, miscarriages, stillbirths, and anemia. Similarly, skin diseases, respiratory diseases and diarrhea are found to be prevalent among children. Since women are majorly involved with waste disposal activities at homes etc., they are more exposed to effects of pollution. The use of primitive methods of waste disposal such as incineration and landfilling lead to many water-borne and air-borne diseases among women in regions such as Sub-Saharan Africa. Similarly, those women who are involved in agriculture are exposed to the adverse effects of pesticides since these women are in direct contact with organic pollutants, agro-chemicals and different types of pesticides. These pesticides and persistent organic pollutants can enter the women's body tissues and their breast milk causing reproductive disorders in these females and immunological disorders in their babies. Furthermore, the use of pesticides is further increasing due to changes in land use, crop rotations and climate. These changes lead to different type of pests which result in increased use of pesticides which can further cause more problems for these women.

Climate change takes a great number of lives every year and is further expected to claim about 250,000 lives every year between the year 2030 and 2050 due to malnutrition, malaria, diarrhea, and heat stress.

## 3 Ecofeminism for Mitigation and Adaptation of Climate Change Effects on Women

Climate change is a 'gender-sensitive' issue and women can play an equally important part in dealing with the issue as men. To emphasize the close relation of women and ecology, the concept of 'ecofeminism' has emerged. It encourages women's participation in actively protecting the environment [29]. It is important that women are taken into equal consideration in climate-related discussions and their role is emphasized. Following steps should be taken to empower women in their role of combating climate change:

- It is important to conduct thorough gender analysis including daily life roles of both men and women, their interests, age, social structure, socio-economic and technological factors, wealth and ethnicity, distribution of resources and labour, timing and payments, gender-specific hazards, vulnerability and impacts, gender equality audit and setting gender-sensitive benchmarks [5].
- Due to women's close relation with environment, women are stewards of natural resources. They possess a great deal of indigenous knowledge about wildlife and food, medicinal plants and domestic animals, reproduction of plants and animals, ecosystems, geographic ranges of species, and disaster management by mobilization of community for better risk-assessment and management. In Ganga river basin in Bangladesh, Nepal and India, research was conducted on women who provided knowledge about many new adaptation strategies for floods and about drug-resistant crops and varieties of plants capable of sustaining floods by growing higher than normal water level. The shea nut treeis a new crop that has been developed by women in Mali that can survive tough weather conditions. It can be used for firewood and nuts and can also be used for making butter and beauty creams.
- Four actions must be taken for active participation of women. These are
  - Mitigation: involving women in controlling greenhouse gas concentrations.
  - Adaptation: adjust women's behaviour, provide resources and technology for reducing their vulnerability to climate risk.
  - Financial mechanisms: formulating gender-sensitive policies and making special investments for women.
  - Technological developments: women should be provided with knowledge, information and relevant technologies according to their needs.
- Women should be allowed ownership of land, access to agricultural resources and technology. In many countries, women's involvement in agriculture has found to have increased agricultural productivity from 2.4 to 4% [13]. Moreover, in Nigeria, Tanzania and Uganda, agricultural productivity is found to be increased by 2.8%, 8.1% and 10.3% respectively due to women's participation. In Pakistan, waste land owned by women was transformed to water course for bringing water from river to the village. About 10,400 trees for fuel and 8,700 trees for fruits were planted and vegetables were sown [7]. Similarly, if women are allowed

access to clean water and other natural resources, women would spend hours for economically benefitting activities.

- As mentioned above, women's involvement in energy and water related matters result in more effective utilization and management as compared to men. In Tanzania, more sustainable wells were dug when women were involved. Similarly, 62% increase in water project development was observed due to women's participation.
- The major lacking is in women's awareness about climate change adaptation and risk-management. Hence, women and young girls should be provided with modern education and training on modern methods and technology, risk-assessment, leadership and management, self-protection, and health. In areas where women have been provided with modern education, improvement in crop varieties, livestock management and pest control techniques have been observed especially in Uganda, Kenya and Tanzania [13]. Another example is of La Masica, Honduras, where no fatalities were observed after Hurricane Mitch due to quick evacuation and post-disaster reconstruction. This was the result of gender-sensitive training regarding disaster management involving both men and women provided by a disaster agency. Therefore, it is observed that empowering women enables them to support and fulfill their own needs, demands, choices and aspirations. To ensure the safety of women, access to bathrooms should be provided near the houses in rural areas or those areas where bathrooms are far away from houses. This will not only allow women to bathe and wash freely at any time of the day, but also give them time to participate in more tangible and productive causes.
- Stringent laws should be constructed for women's empowerment and they should be strictly implemented. Some of the laws that should be implemented are as follows:

  – Education of girls should be made compulsory,
  – Government should take responsibility of single-mothers and unmarried girls in poor areas,
  – Laws should be made for women facing domestic violence,
  – Government should provide compensations to women running cottage factories in disaster situations,
  – Workload of collecting and carrying fuel and water should be equally shared between males and females.

- There is a need to involve women in policy making processes and other measures or tools that are taken for sustainable development at national, local and international levels. Local governments must address women's issues, ensure their security and involve national government for solving the issue. National government must provide finance for mitigating environmental issues along with solving health-related, educational, legal issues and for ensuring protection of women against climate change. At international level, collaboration of NGOs and different companies can benefit women. Donor governments can play a great role as major contributors to women empowerment through their technical and financial support. All bilateral environmental and developmental initiatives must ensure gender equality. Civil society can also play their part by ensuring that legal laws are properly implemented and that rights of women are being fulfilled.

- Among all the other major factors identified that hamper women's development, socially-constructed constraints are the major barriers. The centuries old cultural, religious and social norms keep women from participating in educational and leadership activities. Thus, there is a dire need to bring a change in centuries old social structure. For this, it is necessary to not only educate women but also educate men about women's rights and importance of female involvement in decision-making affairs at all levels. Special focus should be on men living in backward areas. These men can themselves become gender trainers and support women. The concept of 'gender equality' should be emphasized. In order to remove the misleading religious constraints on women, religious personalities or scholars should come forward and clarify any misunderstandings. Angela Davis puts it very appropriately as **'We have to talk about liberating minds as well as liberating society.'**
- Many international and well-known programs are working at present to encourage women's role in combating climate change. These are United Nations Development Programme (UNDP), United States Agency for International Development (USAID), United Nations Charter and the Universal Declaration of Human Rights, UN Women Watch, Food and Agricultural Organization (FAO), Women's Environment and Development Organization (WEDO), Millennium Development Goals 2000, World Health Organization (WHO), Beijing Platform of Action (1995), Financing for Gender Equality and the Empowerment of Women at 52nd session of the Commission on the Status of Women, Swedish International Development Agency (SIDA), CARE, IPCC (Intergovernmental Panel on Climate Change), UNFCCC (United Nations Framework Convention on Climate Change), The International Union for Conservation of Nature (IUCN), and Aurat Foundation in Pakistan.

## 4 Conclusions

Women are more vulnerable to effects of climate change by the virtue of their dependence on natural resources, daily-life roles, and socio-economic status. Women, all over the world, are closely involved in agriculture; collection of fuel and water; and taking care of the elderly and the sick of the household. As climate change is posing adverse impacts on agriculture, biodiversity, water resources and weather patterns, women's health, education and safety is being greatly affected due to social and religious norms restricting their mobility. Even though women are more concerned about environment, women own less resources and have less education or information to tackle climate effects and have very less representation in climate-related decisions. This is not only making women more vulnerable but also hampering the climate change mitigation process. One big factor is the research gap in analyzing women's roles in environment, their vulnerabilities, adaptive capacities and possible contribution. Hence, there is a need to map women and their relation to environment, educate them about climate risks and increase their resilience. Women should be involved in climate policing and financing mechanisms at local, national and international levels so that their knowledge can be utilized in combating the climate issue. Laws of women's involvement in policy decisions should be enacted and society as a whole should be educated about women's rights to bring down the social constraints. In addition, many national and international organizations can join hands to uplift women as environmental stewards.

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# Carbon Capture for Sustainable Environment in Developing Countries

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**Abstract** The most critical energy and environmental challenge that the developing countries are facing today is to minimize the dependence on fossil fuels. Carbon dioxide may prove to be of utmost significance as a solution of this issue through realization of carbon neutral energy cycle. Potentially, this could be achieved through the $CO_2$ capture as the urgent response to ongoing climate change around the globe. Owing to the more than 39% increase in atmospheric $CO_2$, the average global temperature has risen to 0.8 °C during the past century. According to an estimate, $CO_2$ concentration in the atmosphere would reach to 1600 ppm almost, and the greenhouse gases emissions would also rise from 30 to 90% over the level of 2000 within next 10 years, i.e. by the end of 2030. $CO_2$ is also deemed to intensify the contamination of CO, apart from its importance as GHG while both exist in the same gas. Hence, fears on GHG pollution have given rise to significant interest in developing the area of $CO_2$ capture to tackle environmental and sustainability concerns. Increased $CO_2$ causes stress on the earth's climate system, and carbon capture technology is one of the most viable approaches accepted so far for mitigating this stress. The commercial technologies are also used for carbon capture. Owing to the high production cost and consumption of resources, the regeneration of the different materials used for carbon capture remains a key problem. Used materials is yet to gain widespread use for carbon capture due to the energy penalty associated with regeneration of

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the adsorbents that is typically achieved via temperature swing adsorption (TSA) and/or pressure swing adsorption (PSA) with an estimated 25–40% energy penalty. In this chapter, critical study of these established techniques regarding significant challenges in terms of energy consumption, regeneration and operating costs will be analyzed. In addition, it includes cost-effective solutions in-situ regeneration of spent materials using electric potential swing desorption compared with the conventional methods of PSA and/or TSA for sustainable environment.

# 1 Introduction

Growing concerns about the consequences of climate change may severely restrict future access to fossil fuels. Forced choice between energy and the environment could lead to a major economic crisis, an environmental crisis, or both. Averting such a crisis will be difficult, as fossil energy resources are an essential part of the world's energy supply, and climate change is driven mainly by carbon dioxide build-up in the atmosphere. Owing to an increase of more than 39% in atmospheric $CO_2$, the average global temperature has risen to 0.8 ˚C over the last century. Carbon dioxide ($CO_2$) is the inevitable product of fossil fuel consumption. The use of fossil fuels is therefore directly related to global environmental concerns. Unfortunately, fossil fuels are difficult to replace, but stabilizing the atmospheric concentration of carbon dioxide requires an almost complete transition to a carbon–neutral economy. This involves either the abandonment of fossil fuels or the introduction of carbon capture and storage, with each ton of carbon extracted from the ground being returned to another ton of carbon. This chapter discusses the extent to which carbon dioxide emissions need to be reduced and the options available for achieving such reductions. It puts the continued use of fossil fuels, carbon capture and storage, in the context of other approaches to achieving carbon–neutral energy infrastructure or otherwise avoiding serious climate change impacts.

## *1.1 Effect of Greenhouse Gases in Developing Countries*

Rapid change in climate tends to increase extreme weather conditions in future. Recent studies and analytical data shows the areas of the world where climate changes are frequent. The Developing countries have always been at higher risks under these studies due to low resources and less efficient policies Nationally determined contributions (NDC's) were the pillars of Paris Agreement in which different developed (Annex 1) and developing (non-Annex1) countries proposed contributions to lessen the greenhouse gases emissions. If the countries implement Paris Agreement, the mean global temperature would be reduced from 3.6 to 2.7 °C within the beginning of new era.

A study in Bangladesh shows that global warming would result in risks of extreme rainfall events in near future. It is found that the anthropogenic aerosols amplify global warming due to which temperature has increased from 1.5 and 2° and simultaneously rainfall events have also increased compared with natural levels across most of the parts of Bangladesh. The impacts were observed both during the monsoon and pre-monsoon periods, but were variable depending upon the concentration of aerosols in different parts of the country.

The study about the energy sources in Pakistan and India shows the concentration of dangerous greenhouse gases increase by the use of fuel and electricity. These activities are responsible of increasing temperature in the south Asia. Pakistan's average temperature is usually higher than the global average temperature and due to its location on map about 60% of its total land area gets less than 250 mm rainfall per year. (rivers) in Pakistan are naturally fed by Himalayas and Hindukush glaciers which are rapidly melting and Pakistan is at the highest risk of facing water deficiency. In India, the global surface temperature study shows that the increasing concentrations of methane and carbon dioxide can increase temperature up to 0.7 mK and 0.036 mK in next 20 years.

## 1.2 Carbon Neutral Green Fuel

Energy utilization demand has increased since the last decade due to swift increase in population and economical flourishment [1]. The worldwide global primary energy consumption was about 92 PWh in 1990 and this figure has increased about 2% annually to 153 PWh in 2015, where, these non-renewable sources provide approximately 138 PWh of energy that is almost about 87% of the basic necessary energy requirement [2]. Acid rain, ozone layer depletion and global warming are also non-sustainable results obtained after using natural energy sources like fuel. Consequently, there has been a shift to carbon natural fuel as a major fuel across the globe. The production of carbon neutral green fuel, could therefore gain immense importance and attention regarding the environmental, economic and energy conservation perspectives [3].

For each ton of waste food reprocessed by anaerobic digestion saves our atmosphere from $CO_2$, which is about 0.5–1.0 ton of $CO_2$ that is added in the atmosphere if it was landfilled. Currently, the biogas can be used to carbon capture. However, the main problem is economic removal of the $CO_2$.

Table 1 shows main composition of $CO_2$ formation during use of different sources. Common feedstock includes energy crops, manure, metropolitan consumed, animal feces, farming land waste, wasted and damaged crops, organic waste streams include products from food processing, for example cake and salt manufacture and pasteurization of eatables and from industries, involving tube and tyre, wood, cement plant, fertilizer companies and narcotics. The $CO_2$ is 30–40% typically of all sources.

**Table 1** Main composition of $CO_2$ formation during use of different sources [4, 36, 49]

| Components | Agriculture/animal waste | Waste from agro food industry | Municipal waste | Sewage treatment | Landfill |
|---|---|---|---|---|---|
| $CO_2$ (Vol. %) | 37–38<br>19–33<br>30–50<br>30–40 | 26 | 34–38 | 36–38<br>19–33<br>30–45<br>35–45 | 37–41<br>35–40<br>30–60<br>15–50<br>(Avg. 40)<br>30–40 |

**Table 2** Overview of $CO_2$ composition in different countries: a partial summary of the key gas quality requirements

| Country | Required composition (%) |
|---|---|
| Austria | $CO_2 < 2.0$ |
| France | $CO_2 < 2$ |
| Germany | $CO_2 < 6$ |
| Italy | $CO_2 < 3$ |
| Netherlands | $CO_2 < 2.5$ |

### *1.3 Why $CO_2$ Capture is Required?*

High amount of $CO_2$ is emitted in burning of fuel, natural gas and other industrial processes. This $CO_2$ is directly exhausted in atmosphere. The biggest threat to sustainable environment is global warming which is due to increasing concentration of $CO_2$ in the environment. While it is impossible to substitute traditional activities with unpolluted regeneration technologies, which produce no $CO_2$ hence Carbon Capture Technology is utilized that reduces $CO_2$ concentration in atmosphere.

Table 2 compares the composition of different European countries for the $CO_2$. $CO_2$ standards varies in different countries, it is allowed <2% for Austria, France and Netherlands, whereas, it is <6% higher for Germany and Switzerland.

## 2 Carbon Capture in Developing Countries

### *2.1 Overview of Carbon Capture*

The carbon capture practice begins by collecting extra $CO_2$ produced by the burning of fossil fuels or other industrial processes. This gaseous carbon dioxide is then compressed to form a dense fluid. The liquid phase aids in easy transportation of $CO_2$ in addition to saving it. This dense fluid is transported through pipelines and then inserted into the underground storage facilities.

The current CCUS technologies are usually very costly There is a dire need for devising some new techniques or improving the existing ones to generate a cost effective method in this regard so that the lower scale industries may benefit from it.

## *2.2 Carbon Capture Processes*

$CO_2$ is the product of Carbon and Oxygen atoms and its emission to the environment causes global warming. Typically, $CO_2$ separation study can be classified as.

- Pre-combustion
- Post-combustion
- Oxy fuel combustion.

### 2.2.1 Pre-combustion

In pre combustion process hydrocarbon is burned in the limited supply of oxygen which results in formation of CO and $H_2$. Figure 1 shows this. $CO_2$ is further coming in contact with $O_2$ and produced $CO_2$ and $H_2$. The quantity of $CO_2$can be enhanced by increasing the concentration of $O_{2.}$ On the other hand, the by-product $H_2$ is used as a fuel in cell while $CO_2$ separates from the mixture.

- Gasification of fuel such as coal causes production of CO and $H_2$.

  Coal $CO + H_2$

- Now this mixture is advanced and mixed up by water vapors in the presence of reaction enhancer where due to water gas shifts forming $CO_2$ and $H_2$ is separated.

  $CO + H_2O\ CO_2 + H_2$.

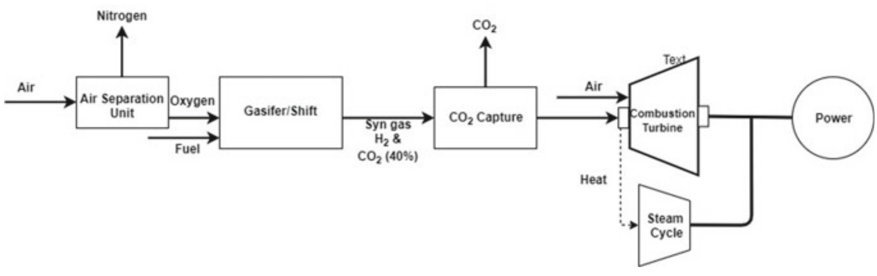



**Fig. 1** Pre-combustion process

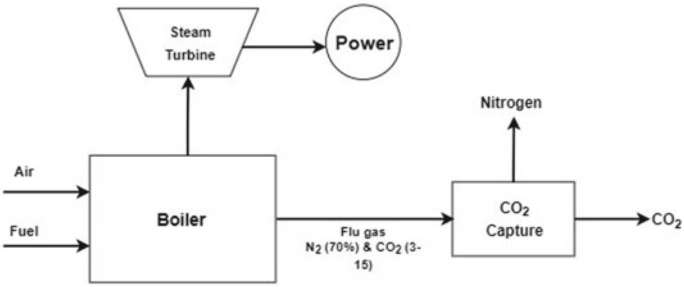
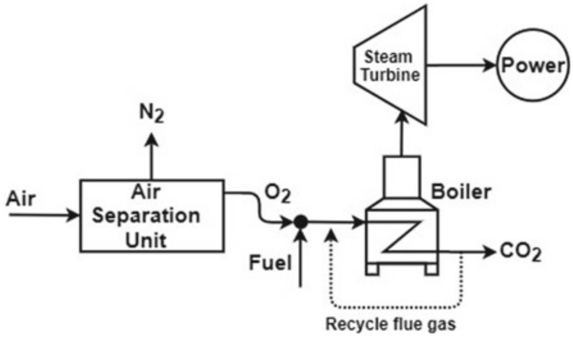



**Fig. 2** Post-combustion process

**Fig. 3** Oxy fuel combustion process




### 2.2.2 Post-combustion

Figure 2 shows the most efficient and industrial way to capture $CO_2$ is the post combustion capture (PCC). Lean condition is set for the combustion chamber where $CO_2$ reacts with pure steam. As a result of this reaction the amount of inert gas $N_2$ is increased the concentration of $CO_2$ is also increased up to 98% by volume. In the excess amount of oxygen the complete burning of fuel not only increased $CO_2$% but also increased inert gas especially $N_2$ Steam is also a by-product of this exothermic reaction, which is used to run turbine and produce power.

### 2.2.3 Oxy Fuel Combustion

Oxy fuel combustion process refers to the burning of the hydrocarbons with pure and rich oxygen supply in order to separate the flu-mixture consisting of $CO_2$ and water vapors by controlling the temperature. In the power plant this process is a leading technology for the separation of $CO_2$. The by-products of this process are $SO_2$, $NO_4$ and water contents. Their concentration is increased with the increase in amount of pure oxygen. But the optimum concentration of $SO_2$ and water contents are required otherwise they cause erosion to the equipment. Figure 3 shows that there are four following units for power generation by oxy fuel combustion:

- Cryogenic process—for rich and pure air
- Combustion Unit—burning of fuel
- Flue gas processing unit—flu mixture processing
- $CO_2$ purification—$CO_2$ separation and storage.

## *2.3 Carbon Capture Technologies*

The commercial technologies used for carbon capture are mainly absorptive or adsorptive processes as well as processes based on membrane filtration or cryogenic separation. Selection criteria for these methods is totally based on economic feasibility and availability of material. Table 3 compares the different parameters of various carbon capture methods, which are physical adsorption, water scrubbing (WS), pressure swing adsorption (PSA), membrane separation (MS) and cryogenic separation (CS). The water scrubbing method is very common technique used for generation of activated carbon (AC). Easy to practice and its efficient record are the major reasons for its frequent use. PSA is an environment friendly and effective method, but its working and net costs are very high [5]. Separation of gases by membrane is a safe and efficient method and its cost are not high, but it has regenerative, scale-up and operational issues Membranes have high economical set-up and it requires high upkeep rate.

Cryogenic system is effective and unpolluted, but it has one disadvantage that it requires higher operational cost due to very difficult apparatus to get the necessary cryogenic environment Owing to its high cost this technique is mostly used in large scale industries [6].

While by using physical adsorption there are so many advantages in terms of apparatus availability with low operational cost.

Different techniques are available for the carbon capture [8]. Figure 4 lists the techniques that are comprised of water scrubbing, chemical absorption, membrane separation, cryogenic separation and physical adsorption systems.

### 2.3.1 Water Scrubbing System

Figure 5 shows the high water pressurised scrubbing process for carbon capture. Spraying water on the high pressurized gas entering into the absorption column removes $CO_2$. The packing material is used to fill the column to increase the contact between the liquid and the gas. The removal of $CO_2$ from the gas can be carried out by water scrubbing system due to their high solubility in water as compared to methane. This process is safe with high loading capacity. However, the elementary sulphur produced by high level of $H_2S$ can cause the operational problems. The air is not recommended to strip the operation. $H_2S$ has a slightly higher solubility than

**Table 3** Comparison of different technologies for carbon capture [7, 8–6]

| Component | Physical adsorption | Water scrubbing | Pressure swing adsorption | Membrane separation | Cryogenic separation |
|---|---|---|---|---|---|
| Efficiency | √ | √ | √ | X | √ |
| Low operational costs | X | X | X | √ | X |
| Low capital costs | √ | √ | X | √ | X |
| Applicable scale | √ | √ | √ | √ | √ |
| Applicable inlet conc.(2000 ppm) | √ | √ | X | X | x |
| Environmentally friendly | √ | X | √ | √ | √ |
| Safe | √ | √ | √ | √ | x |
| Economic regeneration | X | √ | X | N/A | N/A |
| Low energy regeneration | X | X | N/A | N/A | N/A |

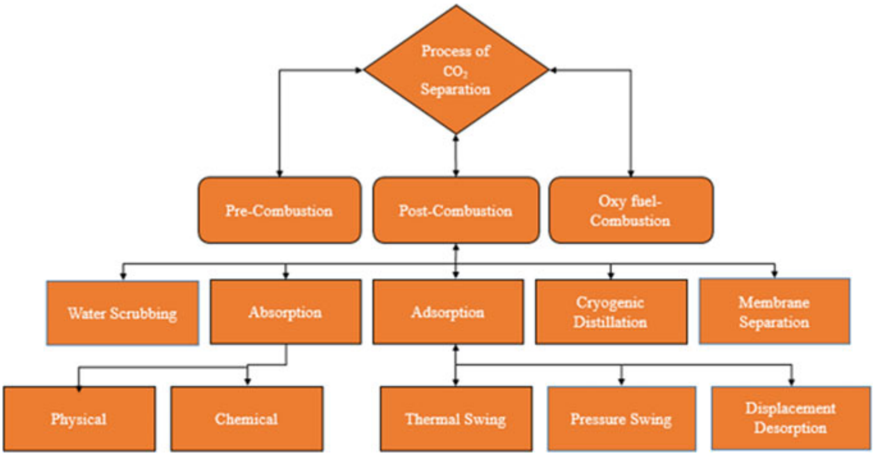



**Fig. 4** Carbon capture technologies

$CO_2$ and cost associated with selective removal of $H_2S$ using water scrubbing are comparatively higher [9].

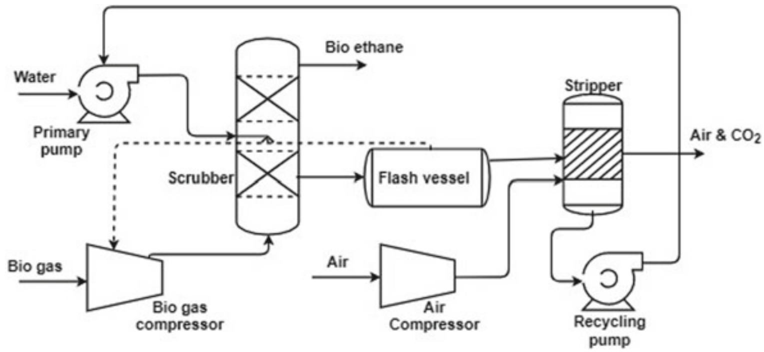



**Fig. 5** Water scrubbing technology for carbon capture

### 2.3.2 Chemical Absorption Method

This reversible process uses chemical bonds that are formed between the solvent and the solute due to chemical absorption [10]. Chemical solvents are either aqueous solution of alkaline salts for example calcium hydroxide, sodium and potassium or the aqueous solutions of amines as di- or tri-ethanolamine. These bonds are broken by applying the heat that is known as solvent regeneration and is very energy intensive. This process requires small volume, but safety of the operation is a concern. Figure 6 explains the chemical absorption technique for the carbon capture.

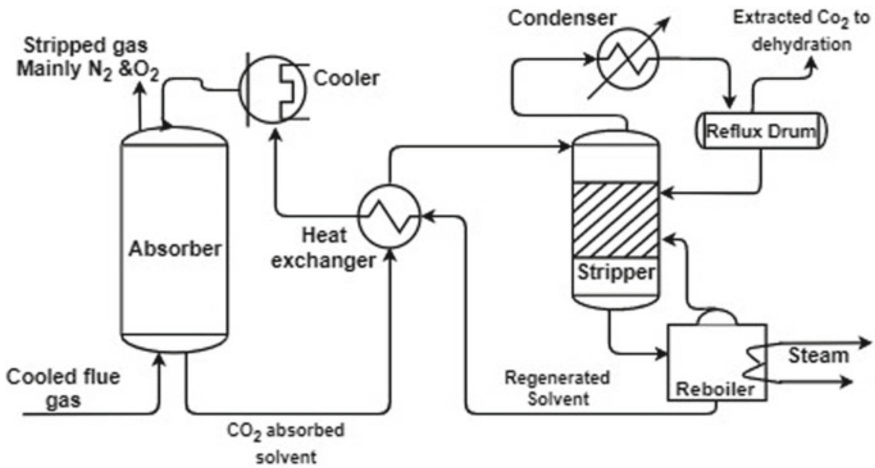



**Fig. 6** Chemical absorption technique

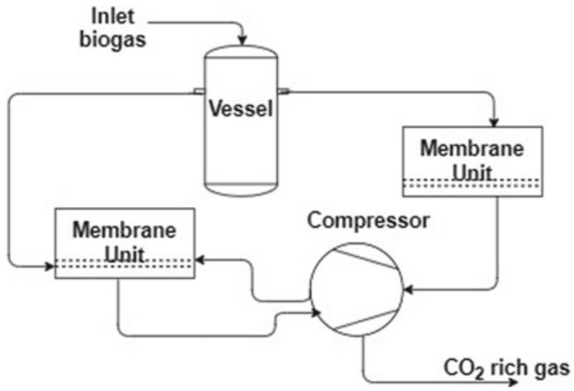



**Fig. 7** Membrane separation technique

### 2.3.3 Membrane Separation Method

The difference in affinity or particle size is the main feature used by membrane separation method where only selected molecules pass through the membrane The pressure difference between the inlet and outlet is the driving force that is used to carry out this process as shown in the Fig. 7, thus selective infusion like polymeric film can provide a base for membrane $CO_2$ separation. The permeation rate is calculated by the diffusion coefficient. Molecules small in size and high in affinity permeate promptly than the larger ones. It means that the raw gas stream is fed to the membrane, where, a faster rate of the $CO_2$ permeation will occur as compared to the natural gas contents. The hollow fibers and/or flat film polymer and copolymer membranes were used for the gas separation systems, where the pressure difference across the film is the factor of transportation. This is environment friendly technique and has low capital costs. However, the membranes are expensive with complex structure, and no regeneration is possible.

### 2.3.4 Cryogenic Separation Method

Cryogenic separation is an efficient and environmental friendly method, however, it is recommended for the large-scale industrial level because of its high operational and capital costs. The boiling point of methane at atmospheric pressure is −160 °C whereas it is −78 °C for carbon dioxide. This helps in carbon dioxide separation from biogas in the form of liquid by carrying out the cooling process of gas mixture at high pressure. Methane can be collected in gas or liquid phase. By condensing methane, nitrogen is separated because of its lower boiling point and this helps when it is dealt with landfill gas. However, contaminants such as hydrogen sulphide and water, are pre-separated to avoid the danger of freezing during the process [11]. Figure 8 explains the basic cryogenic separation method for $CO_2$ capture.

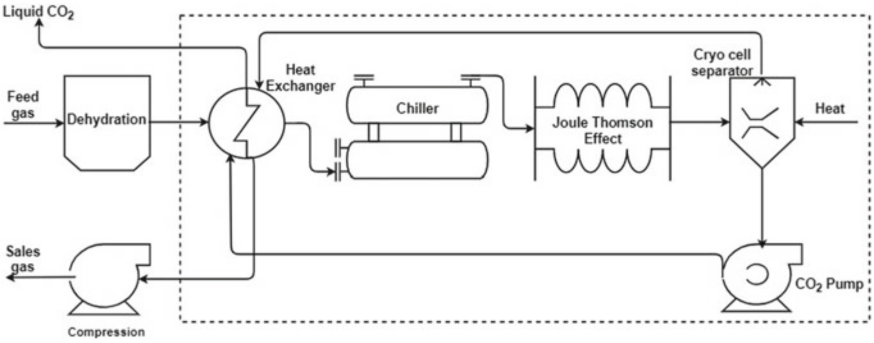



**Fig. 8** Cryogenic separation method

### 2.3.5 Physical Carbon Adsorption System

The activated carbon is commonly used in adsorption processes because of its high surface area, hydrophobicity and high pore volume which are the unique attributes of activated carbons. The presence of minerals and oxygen functional groups on its surface are the important features of activated carbon that may play active roles in the processes such as physical adsorption. The physical adsorption for activated carbon is demonstrated in Fig. 9, where a fixed-bed reactor made up of stainless steel was equipped with porous plate. The breakthrough and adsorption capabilities of the activated carbons were calculated during the process of the gas mixtures The adsorption by physical sorbents is very much efficient as it gives high purification rate with low capital costs as compared to chemical adsorption because there is no new chemical bond originated between physical sorbent and adsorbent, so therefore

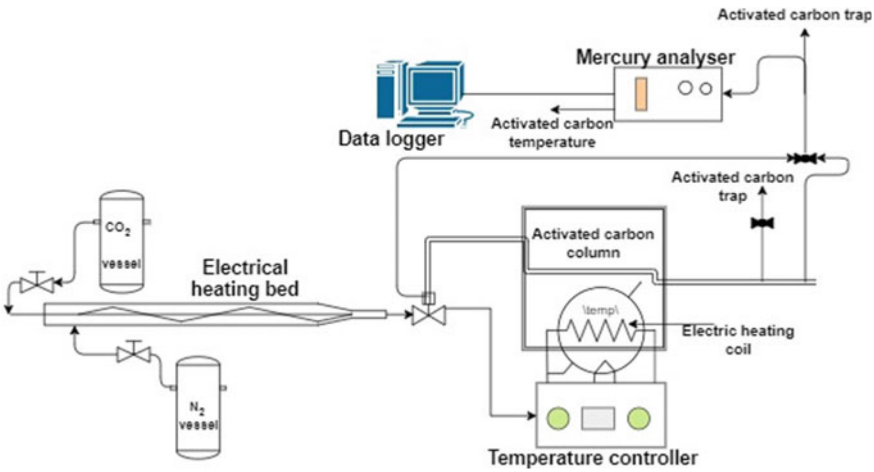



**Fig. 9** Fixed bed adsorption unit

less energy is required for regeneration process. Water scrubbing is an important commonly treated technique for gas isolation system, which is regenerative with low capital costs. However, it requires high energy of regeneration and high pressure which means high operational costs. Compared to other carbon capture technologies, adsorption by physical sorbent is safe, environmentally and has high loading capacities.

## 3 Challenges for Carbon Capture for Clean and Green Environment

Several processes are available in the literature for the carbon capture, including scrubbing of water at high pressure, chemical absorption, physical adsorption, cryogenic separation and membrane separation. Water scrubbing at high pressure is currently common in practice. However, the adsorption carried out by physical activated carbon is the most effective method for carbon capture. Table 4 compares the pros and cons of various carbon collection methods, which are physical adsorption, chemical absorption (CA), water scrubbing (WS), cryogenic separation (CS) pressurized swing adsorption (PSA) and membrane separation (MS). In Table 4, a comparison of the carbon capture has been made. The distinction between physical

**Table 4** Advantages and disadvantages of carbon capture techniques [7, 8–6]

| Method | Advantages | Disadvantages |
|---|---|---|
| Activated carbon (physical adsorption) | High purification rate; Low capital costs; environmental friendly and safe; High loading capacity; Low operation temperature; Compact technique | Operational cost are high; Regeneration is expensive |
| Water scrubbing | Efficient method; Low capital costs; safe; regenerative; Cheap when water is available; | Operational costs are high; high pressure; environmental issue; high energy of regeneration |
| Pressure swing adsorption | Efficient; Environmental friendly and safe | Capital and operational costs are high; |
| Membrane swing adsorption | Low capital costs; Environmental friendly; | Efficiency is not very high; membranes are expensive; No regeneration possible; Complex operation and maintenance |
| Chemical absorption | Low electricity requirement; Small volume required | Expensive investment and operation; safety is concern |
| Cryogenic separation | Efficient, Environmental friendly | High operational and capital costs; suitable for large scale only; non-regenerative |

activated carbon and pressure swing adsorption was also made for this purpose. The water scrubbing method is an important and generally adopted technique for carbon isolation. The major problem with this technique is its high operational budget [5]. PSA is an environment friendly and effective method, but its working and net costs are very high. Separation of gases by membrane is a safe and efficient method and its cost are not high, but it has regenerative, scale-up and operational issues. Membranes have high economical set-up and it required high upkeep rate.

Cryogenic system is effective and unpolluted, but it has one disadvantage that it requires higher operational cost due to very difficult apparatus to get the necessary cryogenic environment. On the base of cost this technique is mostly used in large scale industries [11].

While by using physical adsorption there are so many advantages in terms of apparatus availability with low operational cost. Physical activated carbons due to their higher surface areas pore volume and water opposition of the surface are less costly as compared to zeolites, alumina, silica or other inorganic sorbents. By using this technique the only problem which needs to handles is its operational budget and requires long time for recycling of the absorbent. A better understanding of activated carbon could lead to in-situ regeneration that would lower operational cost and energy loss during regeneration.

## 4 Regeneration Technologies for Carbon Capture Adsorption System

### *4.1 Regeneration Technologies for Carbon Capture*

Over the years a variety of regeneration techniques were developed based on desorption, including induced changing pressure (Pressure Swing Adsorption, PSA), applying vacuum (vacuum pressure swing adsorption, VPSA), or temperature (Temperature Swing Adsorption, TSA; Electric Swing Adsorption, ESA) [13].

### *4.2 Pressure Swing Adsorption (PSA)*

Pressure swing adsorption (PSA) is a technique which can separate the gas species from the gas mixture using adsorbent such as activated carbon, which plays significant part in the adsorption process. This method could be used for the gas separation because several gases tend to get attracted to the different solid surfaces [14]. In this process, raw gas is pressurized and provided to adsorption reactor as shown in Fig. 10. When the column material is saturated with the gas, pressure is released to desorb the gas and feed it into a gas outlet stream. To achieve constant generation of

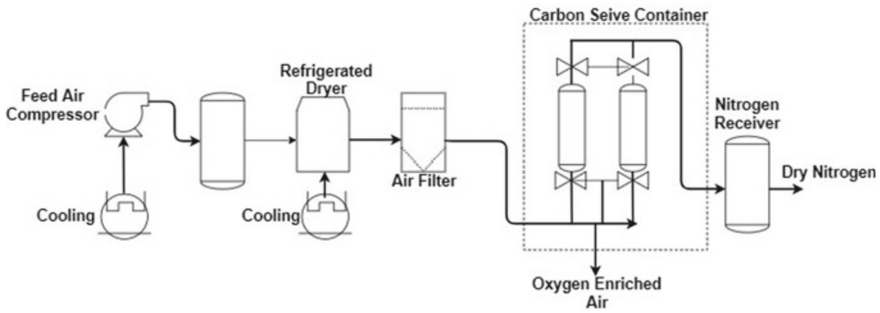



**Fig. 10** Pressure swing adsorption method for regeneration and carbon capturePressure swing adsorption method for regeneration and carbon capture

**Table 5** Pressure swing adsorption (PSA) for regeneration and carbon capture [15, 16]

| # | Type | Ads | Energy Req. (KWh/Tonnes) | Purity $CO_2$% | Rec. $CO_2$% |
|---|---|---|---|---|---|
| 1 | 3 bed, 7 steps | Zeolite | 656 | 81 | 79 |
| 2 | 3 bed, 8 steps | Activated Carbon | 677 | 90.2 | 95.6 |

activated carbon, a number of vertical adsorption reactors are provided and operated sequentially.

Table 5 compares the regeneration system with PSA for different adsorbents. Liu et al. used a three-bed, seven-step pressure swing adsorption (PSA) with vacuum step included in it. The zeolite was used as an adsorbent with enrichment of $CO_2$ to 81% purity with a recovery of 79% of $CO_2$. The process involves high energy consumption of 656kWh/tons [15]. In different experiment, Wang et al. used activated carbon as adsorbent with three-beds and eight-step process. The energy consumption was slightly higher and was about 677.78 kWh/tons.

Raw gas is commonly provided at low pressure, hence we need to pressurize it at pressure between 4 and 10 bars before the PSA apparatus. Although there are many advantages of using regeneration of activated carbon by PSA but, multi columns of the process unit has high capital and maintenance cost The energy utilization is higher because of high-pressure involvement, which needs to be minimized.

## *4.3 Vacuum Swing Adsorption (VSA)*

Vacuum swing adsorption is the modified and enhanced technique of pressure swing adsorption in which materials are operated at very low pressure conditions. This technique is frequently used for the activation of carbon for the isolation purposes. It has capability to give optimal time for recycling of adsorbent, hence prolonging the adsorbent lifespan. More than 50% energy savings are achieved by using this technique rather than PSA. Figure 11 shows simple major stages which are involved during the VSA technique—Pressurization—Adsorption—De-pressurization—Desorption and Purge to declare the operating credibility and to judge optimum method limitations for various adsorbents. For continuous adsorption–desorption production was commonly performed by the help of PSA, TSA, or VSA by using various materials [17].

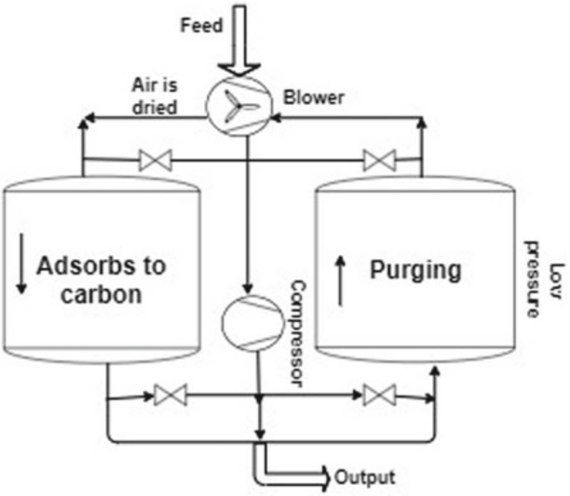



**Fig. 11** Vacuum swing adsorption method for regeneration

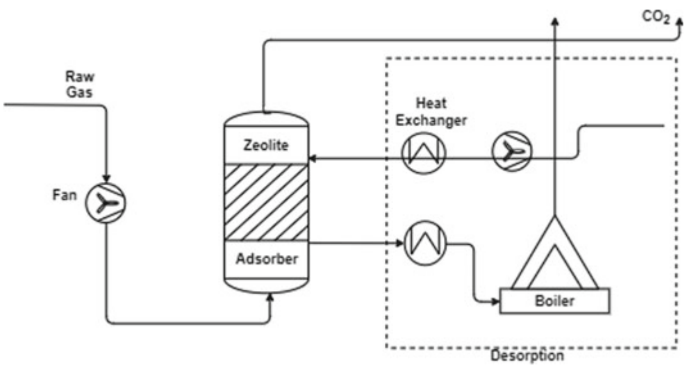



**Fig. 12** Temperature swing adsorption method

### 4.4 Temperature Swing Adsorption (TSA)

TSA process is an indirectly heat driven process generally used for low productivity. In TSA, heat is given to the system in two stages to increase the heat transfer coefficient which reduces the regeneration time. When solid adsorbent is concentrated with $CO_2$ then the temperature of the bed is increased and as a result $CO_2$ desorb at purity. A concentric heat exchanger is used as absorber filled with adsorbent. Typically use adsorbents are 13X zeolites and 5A zeolites. During desorption process steam condenses and more water pipe lines are used to cool down the temperature of pours bed. During desorption stage, water is sprayed at very low pressure and required temperature is obtained in the container. Figure 12 shows the TSA process. Usually TSA is applied for the separation of $H_2O$ and sweetened gas. So, higher heat is required for adsorption process. TSA is good for strongly absorbed species moreover with very small degree change in temperature adsorbate change, so desorption occur at high saturation. It is feasible for both gases and liquids.

Heat is adding to the system which causes inefficiency in energy use due to heat loss. Which enhance the regeneration cost adsorbate [18]. In the temperature swing adsorption, a more effective way of heating, such as microwave, could lead towards a more efficient regeneration method.

### 4.5 Microwave Swing Adsorption (MSA)

During the MSA, microwave heating provides volumetric heating, quick heat flow rates while having no surface interaction between heat source and adsorbent. By treating at high temperature in MSA material's electrons are dislocated and the capability of material is enhanced hence in MSA absorptivity is a function of heating. By these incentives, less power is required in MSA than others heating methods. Additionally, in microwave heating, mass and heat transfer may be fed to system in one-way to enhance desorption adeptness [10] as shown in the Fig. 13.

Optimum restoring methods used for thorough retrieval of adsorption capability by using economical and optimum time in order to save the adsorbent from changing its characteristics which do not harmfully disturb the adsorbate.

It could be helpful to check if microwave restoration can be equally effective and non-harmful when desorbing high molecular weight, and high boiling point impurities. Microwave influences on chemical reactions can be accredited to thermal or non-thermal results. Thermal effects include overheating, hot spots, and selective heating, while non-thermal effects include molecular mobility and field stabilization.

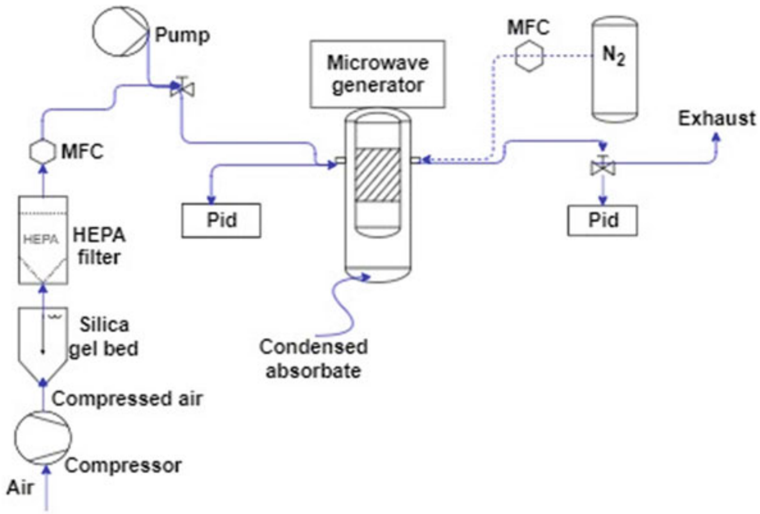



**Fig. 13** Microwave swing adsorption

## *4.6 Electric Swing Adsorption (ESA)*

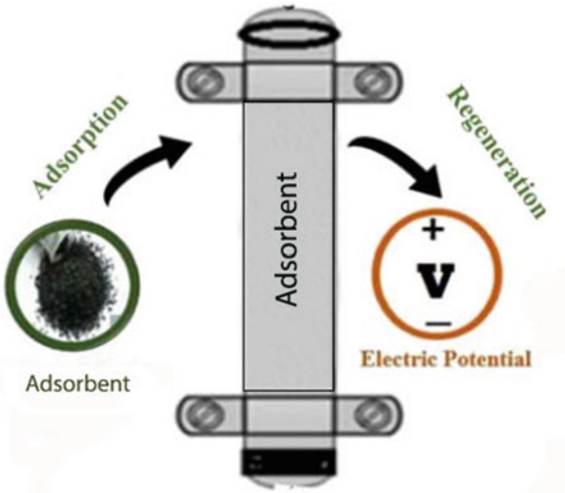
The ESA is a special type of the TSA technique in which adsorbent is heated by direct supply of electric current. The ESA has many pros over other heating techniques. As in other heating methods energy is supplied indirectly so energy consumption is higher but in ESA due to direct transfer of heat via electricity energy consumption is decreased.

Although physical activated carbon adsorbents have the advantage of being easily available and inexpensive yet they normally display inhomogeneous electrical conductivity, and thus, heating may be difficult to control.

## *4.7 Electrical Potential Swing Desorption (EPSD)*

Electrical potential swing desorption (EPSD) is a new method of regeneration as shown in the Fig. 14, whereas potential is applied during desorption as a replacement of the conventional TSA/PSA techniques. It has the benefits of adsorption traits of activated carbon by which it has gained the focus because it has the electro conductive properties. Being power storage devices, these activated carbons are studied as potential polarisable electrodes for super-capacitors They can also work as semi-conductors with number of bands of energy and forbidden gap with the rise of temperature [19]. In electro-sorption, activated carbons were investigated as charged electrodes for the adsorption of ions and promising results have been obtained For

**Fig. 14** Electrical potential swing adsorption process




EPSD to take effect, the resistivity of the carbon should be tailored to allow for a potential to build up but not for thermal heating to take place.

## 5 Summary of Regeneration Challenges

Metropolitan waste and industrial organic waste are eradicated by using activated carbon. In view of the high production cost and consumption of resources, the regeneration of the exhausted activated carbon remains a key problem. The spent activated carbon previously used as adsorbent has to be replaced by a fresh or regenerated material. Adsorbent materials is yet to gain widespread use for carbon capture due to the energy penalty associated with regeneration of the adsorbents that is typically achieved via temperature swing adsorption (TSA) and/or pressure swing adsorption (PSA) with an estimated 25–40% energy penalty [20]. Restoration of activated carbon through PSA requires high-pressure compressors which causes greater energy utilization and setting up expenditures [15]. In TSA de-absorbent is heated directly, in ESA it is heated indirectly by using electric current while in MSA microwaves are used for heating. In typical TSA, heat is supplied through hot gases which have less heat carrying capability as a result large volume of gases is required, which causes desorption of the adsorbate weakened in the heating gas [7]. Advanced modification in the TSA regeneration is the practice of MSA, which gives optimum and confined volumetric heating, high heating rates and no contact between heating source and adsorbent, MSA is much effective as compared to typical TSA, but still it is greater power consuming method the way it cools down the temperature of the bed after desorption. In the ESA process the heat is directly supplied using an electric current through a conductive material, i.e., by the Joule Effect. However, inhomogeneous electrical conduction and heating may be expected when employing particulate adsorbents. A major objective is the temperature slope or change, which cannot be linearly proportional to the feed energy. Any heat curve abnormality will lower desorption performance because the portion of the thermal energy obtained from electrical energy has to be distributed to recompense for the heat loss.

## 6 Conclusion

Over the last decade, demand in energy consumption has increased due to increasingly growing population and economic prosperity. Acid rain, loss of the ozone layer and global pollution are all unacceptable effects that are produced through the usage of renewable energy sources such as fuel. Global change is the greatest challenge to the climate, due to the rising accumulation of $CO_2$ in the atmosphere. While conventional practices can't be replaced with unpolluted regeneration techniques, which do not emit $CO_2$ hence, carbon capture technology is used which reduces atmospheric $CO_2$ concentration. Current carbon capture technologies are typically very costly and far more technical improvement is required to develop stronger and cheaper carbon capture technology so that lower-scale industries can use these. Nevertheless, economically various techniques are used for capturing $CO_2$ and these techniques are based on the environment and resource supply. Carbon capture includes many methods, including high pressure water scrubbing, chemical absorption, physical adsorption, cryogenic separation, and membrane separation. High pressure water scrubbing is common nowadays in use. However, the adsorption by solid activated carbon is the most efficient form of carbon capture. Due to the high manufacturing costs and resource use, a major challenge remains the regeneration of the exhausted activated carbon. Currently, adsorbent materials are yet to be utilized extensively for carbon capture due to the energy penalty associated with adsorbent regeneration usually accomplished by temperature swing adsorption (TSA) and/or pressure swing adsorption (PSA) with an average energy penalty of 25–40%. This can be helpful in future for CO2 capture using the local used resources and can be less expensive.

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# Promoting Solar Energy in India to Meet the Country's Commitment to Climate Change and Energy Security

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**Abstract** India's energy demand is rising continuously. Its availability is critical for the country's development. Most of the current energy requirement is met through conventional fossil fuel-based power generation. India is the third largest emitter of carbon emissions in the world. The energy sector, and within that the power sector, is the major contributor to these emissions. Under the United Nations Framework Convention on Climate Change (UNFCCC), enshrined in the Paris Agreement, 2015, India has committed to reduce its carbon intensity by 33–35%. Juxtaposing the current energy generation and carbon emission scenario with its global commitments, policy makers have been compelled to devise policies to promote and mainstream renewable energy. This chapter reviews India's renewable energy policies, specifically solar energy promoting policies, evaluating their impact on expanding the share of solar energy in the overall energy mix. It highlights fiscal and other benefits of these policies. It includes the institutional framework, key actors and the operational mechanisms for supporting policy implementation. It examines on-the-ground implementation—the challenges in upscaling solar energy and improving its penetration have also been discussed. Now ranked third, India has improved its global position in solar power deployment. More needs to be done to ensure stable and continual growth of the solar power sector to achieve its ambitious targets.

**Keywords** India · $CO_2$ emissions · Solar energy · Policies · Targets · Institutional framework · Operational mechanisms · Challenges

## 1 Introduction

The energy demand in India has been rising rapidly due to economic development, urbanization, increasing population and improvement in the standard of living of the citizens. The country is still heavily dependent on thermal sources for meeting its energy requirements as shown in Fig. 1 (MNRE 2020). Though the installed

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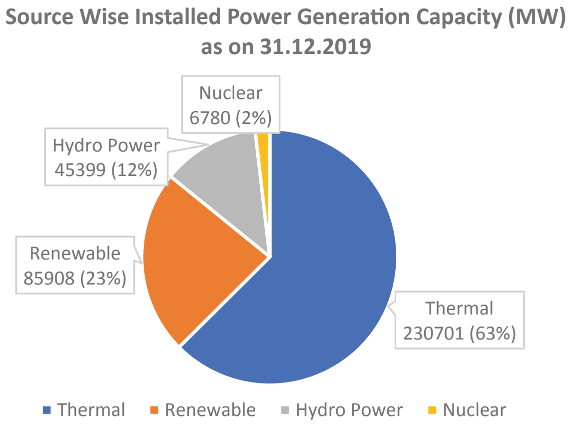
**Fig. 1** Source-wise installed power generation capacity (MW) in India




capacity from thermal sources is 63%, the actual power generation from these is still higher and almost two-thirds of all the electricity produced in the country is from fossil fuels. The high dependence on fossil fuel-based power generation leads to high emission of greenhouse gases (GHGs) into the atmosphere. India is the third largest emitter of $CO_2$ globally, though per capita emissions are very less. It is estimated that two-thirds of the GHG emissions in India are from the energy sector and within the energy sector, 77% is from electricity generation (WRI 2018). India thus needs to shift from conventional energy sources to new and renewable energy sources to decarbonize its energy sector and reduce the carbon footprint of the country.

Under the United Nations Framework Convention on Climate Change (UNFCCC), enshrined in the Paris Agreement—2015, as part of intended nationally determined contributions (INDC), India has committed to reducing carbon intensity of its GDP by 33–35% below its 2005 levels by the year 2030. Further, the country has committed itself to create an additional sink of 2.5 to 3 billion tonnes of $CO_2$ by expanding its tree cover.

At the global level too, India has been active in promoting the adoption of solar energy. International Solar Alliance, which is the brainchild of the Prime Minister of India has been kicked-off formally by 62 member countries joining it. This is an alliance formed by solar resource rich countries to provide a platform for cooperation and for increasing the share of solar energy in their renewable energy basket.

## 2 $CO_2$ Emission Scenario in India

### *2.1 Gross Carbon Emissions*

India is the world's third largest emitter of $CO_2$ emissions after China and the United States. However, its emissions are almost one-fourth of that of China

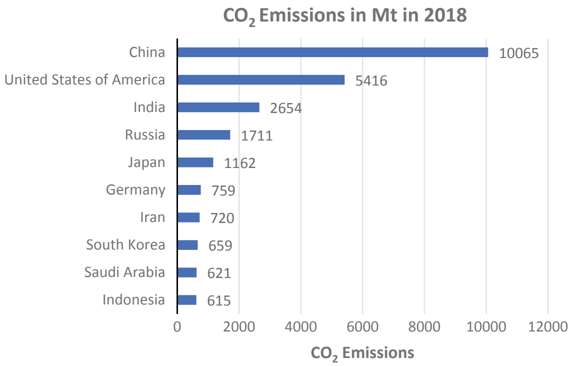



**Fig. 2** Top 10 countries in gross $CO_2$ emissions

(https://www.globalcarbonatlas.org/en/CO2-emissions). Put together, these two countries in Asia contribute 35% of the global $CO_2$ emissions (Fig. 2). This means that any significant improvement in the global scenario is influenced by the actions of these countries.

## 2.2 *Per Capita $CO_2$ Emissions*

The per capita $CO_2$ generation in India stands at a mere 1.84 tonnes per year and the country was ranked at 116 out of 197 countries in 2017 (the year for which data is available) [19]. The highest per capita carbon footprint is of Qatar at 49.18 tonnes per year and others that follow are also from the oil producing countries such as Kuwait, UAE, Brunei, etc. Compared to the top 10 countries having the highest country-wise gross emissions of $CO_2$, India has the lowest per capita $CO_2$ emissions (Table 1).

**Table 1** Per-capita $CO_2$ emissions by countries

| Country | Gross Emissions (Mt $CO_2$) | Emissions (tonnes per capita per year) |
|---|---|---|
| China | 10,065 | 6.98 |
| Unites States of America | 5416 | 16.24 |
| India | 2654 | 1.84 |
| Russia | 1711 | 11.75 |
| Japan | 1162 | 9.45 |
| Germany | 759 | 9.73 |
| Iran | 720 | 8.28 |
| South Korea | 659 | 12.08 |
| Saudi Arabia | 621 | 19.27 |
| Indonesia | 615 | 1.84 |

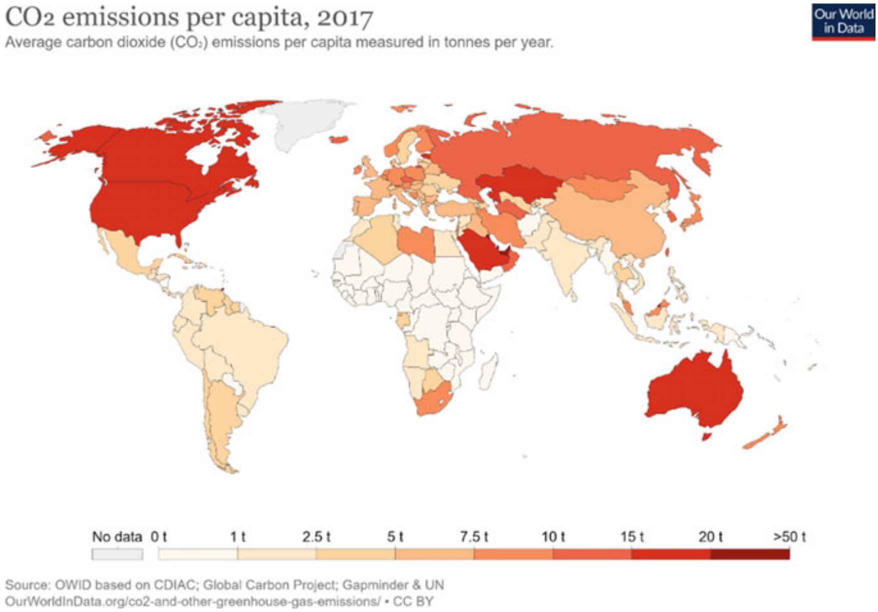



**Fig. 3** Per-capita $CO_2$ emissions [19]

Still the gross emissions by the country cannot be ignored and steps need to be taken to reduce its carbon footprint. The per capita $CO_2$ generation globally is represented in Fig. 3.

## 2.3 *Sector-Wise Emissions*

To have effective policies in place to reduce the carbon emissions, it is important to understand the contribution of different sources to its generation. The energy sector is the largest contributor to the GHG emissions in India, with a share of 68% as shown in Fig. 4 (WRI 2018). This is three times the share of the second largest emitter which is the industrial sector. Within the energy sector, electricity generation has a share of 77%. This means that any effort to reduce carbon emissions in the country must focus on the energy sector, in particular on electricity generation.

**Fig. 4** Sector-wise GHG emissions in India

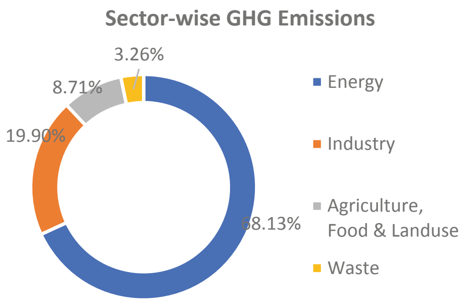



**Table 2** Targets for renewable energy

| Renewable energy sector | Target by 2022 |
|---|---|
| Solar | 100 GW |
| Wind | 60 GW |
| Bioenergy | 10 GW |
| Small hydro | 5 GW |
| Total | 175 GW |

## 3 Targets for Renewable Energy

A major initiative to honour the country's global commitment to reducing carbon intensity of its development is by increasing the share of renewables in power generation. The country is targeting an increase in power generation by renewables to 40% of the installed capacity (MNRE 2020). The Government of India has set an ambitious target of achieving 175 GW power capacity from renewable energy resources by 2022 (Table 2).

Solar and wind are the two most important pillars of the renewable energy sector and are being relied upon by the government to tackle climate change, achieve sustainable development goals (SDGs) and ensure energy access to all. These are essential to meet the increasing energy needs of the country while keeping its energy generation decarbonized.

## 4 Potential for Solar Energy in India

India is a tropical country with abundant sunlight for more than 300 days of the year. The proximity to the equator also provides high solar radiation between 4 and 7 kWh/m$^2$/day [9]. This indicates immense potential for the development of solar power in the country. Solar energy is one of the main sources to accomplish the country's target of generating 40% of electric power from non-fossil fuel-based

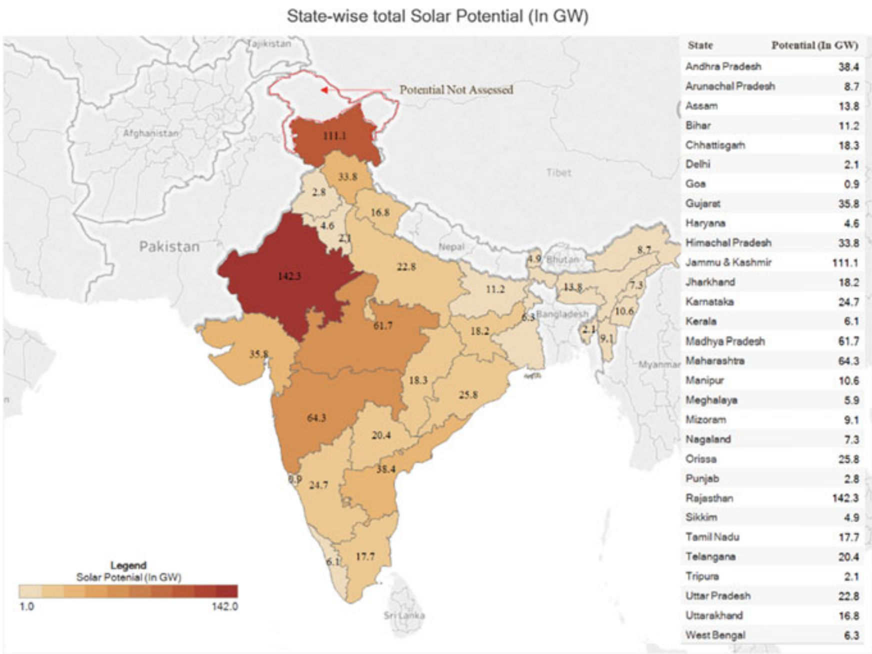



**Fig. 5** State-wise solar power potential in India

sources by the year 2030. Based on the availability of land and solar radiation, the potential solar power in the country has been assessed to be around 750 GW.

The solar irradiance is distributed unevenly across the country. The solar energy potential of the country has been assessed by the National Institute of Solar Energy (NISE). The four states of Rajasthan, Jammu and Kashmir, Maharashtra and Madhya Pradesh account for 51% of the total solar energy potential of the entire country, whereas the seven north-eastern states and West Bengal account for only eight per cent. The distribution of state-wise solar energy potential in the country is shown in Fig. 5 (MNRE 2020). It is very clear that the highest potential of solar resources is in the western part of the country. However, not all the states have been able to capitalize on solar power generation in proportion to their potential. The state-wise solar power generation is discussed further in Sect. 8.

## 5 Policies to Promote Solar Energy

India had launched the Jawaharlal Nehru National Solar Mission (JNNSM) way back in January 2010 under the National Action Plan on Climate Change (NAPCC), much before it made the global commitment to reduce its carbon footprint under the Paris Agreement in 2015. The National Solar Mission is a major initiative of the Government of India (GOI) to promote sustainable growth while addressing India's energy security challenge (GOI 2010). The objective is to establish India as a global leader in solar energy by creating favourable policy conditions for solar energy across the country. The mission has two primary segments for development of solar power—one through utility scale projects and the other through rooftop solar PV projects. The development and commissioning of large-scale projects has been the mainstay of the India's solar energy capacity addition initiatives. At the time of the launch of the mission, the target was to produce 20 GW of solar power by the year 2022 but this target was revised in 2015 and was increased to 100 GW of solar power generation by 2022.

The MNRE has launched a number of policy initiatives to promote solar power generation—grid-connected as well as off-grid, under the JNNSM. There are different models of solar power generation which have been promoted like solar parks, rooftop solar power generation, canal top and canal bank solar power generation etc. The commitment of 100 GW of solar power generation is to be met largely through the grid connected systems. The other schemes are mainly intended to ensure energy access to all. Promoting Research and Design (R&D) and developing solar photovoltaic technology is another area where the MNRE has been allocating budget to promote domestic companies. The policies are discussed in detail in the following paragraphs.

## *5.1 Solar Power—Ground Mounted Grid-Connected*

The first phase of the Solar Mission opted for a reverse bidding mechanism; reverse bids (discounts) on benchmark tariffs set by the Central Electricity Regulatory Commission (CERC) were invited from prospective project developers. Later, it moved to a tariff-based competitive bidding process. There are multiple schemes of the government to promote ground-mounted grid-connected solar power generation and these have been discussed in the following paragraphs.

**Scheme for Solar Parks and Ultra Mega Solar Parks**
Solar parks are defined as those having a capacity of more than 500 MW. The scheme for solar parks was launched in 2014, with a target of 20,000 MW solar power generation from them. The target was later revised in 2017 to 40,000 MW of power generation from solar parks and ultra mega solar parks. Under the scheme, a central financial assistance (CFA) of Rs. 25 lakhs per solar park is provided for the preparation of a detailed project report (DPR). Another financial assistance of Rs. 20 lakhs per solar park is provided for infrastructure, of which Rs. 12 lakhs are for internal infrastructure and Rs. 8 lakhs are for power evacuation infrastructure. Beside this, a CFA of up to Rs. 20 lakhs per MW or 30% of the project cost, including grid-connectivity cost, whichever is lower, is also provided (https://mnre.gov.in/solar/schemes).

**Solar Power by Defence Installations**

A scheme has been approved for viability gap funding (VGF) to produce 300 MW of grid-connected solar PV power generation by defence installations under Phase II of NSM (MNRE 2020).

**Solar PV Power Projects by Government Organizations**

Another scheme was launched on 3 July 2019 to provide VGF for grid-connected solar PV power generation by government agencies for self-use or for consumption by government agencies either directly or through distribution companies (DISCOMs). A total target of 12,000 MW has been set up under this scheme, with an yearly target of 4000 MW from 2019–20 till 2021–22. A maximum of Rs. 0.7 crore/MW has been suggested as the VGF. The user charges of a maximum of Rs. 3.50/unit (other charges like wheeling, transmission, Load Dispatch Centre charges, extra) has been proposed in this scheme. The scheme demands that both the solar cells and the modules be domestically manufactured (MNRE 2020).

**VGF Schemes for Solar PV Power Projects**

The MNRE, from time to time, announces different capacities to be set up for solar power generation under the VGF schemes.

**Scheme for Solar PV Power Plants on Canal Banks and Canal Tops**

The GOI launched a scheme in December 2014 to set up solar PV power projects on canal banks as well as on canal tops. The idea was to utilize the area gainfully. The target set for this mode of power generation was 100 MW in a two-year timeframe. A CFA of Rs. 3 crore per MW or 30% of project cost (whichever is less) was set up for canal top projects and a CFA of Rs. 1.5 crore/MW or 30% of project cost (whichever is less) was set up for canal bank projects (https://mnre.gov.in/solar/schemes). In this scheme, only government agencies were eligible to get the CFA. Under this scheme, the MNRE has sanctioned a net capacity of 50 MW canal bank and 44 MW canal top solar PV power projects. The scheme is now closed for new sanctions.

**Bundling Scheme for National Thermal Power Corporation (NTPC)**

Under this scheme, generation from solar power projects was allowed to be bundled with coal-based power projects in the ratio of 2:1 to bring down the tariff to a lower rate. The scheme has a target capacity of 3000 MW (MNRE 2020).

## *5.2 Solar Power—Rooftop Grid-Connected*

The rooftop solar (RTS) plant is a system installed mainly on the roof of a building having a valid and live electrical connection. The solar power so generated can then be used either for captive consumption in the premises or can be fed into the grid and be adjusted in the electricity bill. Net-metering regulations notified by respective State Electricity Regulatory Commissions (SERCs) provide a legal framework for such adjustment. RTS plants help DISCOMs in reducing transmission and distribution (T&D) losses as power consumption and generation are co-located. These plants are also useful in tackling daytime peak load as solar generation profile matches such peak loads during the day. DISCOMs are the important local nodal points for such a programme as they have direct contact with the end user and have a billing interface with the rooftop owner. The target of 40,000 MW of grid connected rooftop solar power is to be achieved through the institutional (hospitals, educational institutions, etc.), industrial and government buildings as well as the commercial and the housing sector, thus targeting all types of spare rooftop space available.

In Phase I of the programme launched in the year 2010, 100 MW of rooftop solar power generation was targeted. Phase II of the rooftop solar power generation programme was launched with a target of achieving 40,000 MW by the year 2022. In phase II, CFA is provided for residential rooftop solar power systems. CFA has been offered in two slabs—the smaller consumers pay less tariffs and therefore, the MNRE provides CFA up to 40% for RTS systems up to 3 KW. From 3 to 10 KW systems, the CFA of 20% is applicable. For capacity above 10 KW, there is no CFA available (https://mnre.gov.in/solar/schemes).

For Group Housing Societies/Residential Welfare Associations (GHS/RWA), CFA is limited to 20% for installation of RTS plant for the supply of power to common facilities. The capacity eligible for CFA for GHS/RWA is limited to 10 KW per house and total capacity cannot be more than 500 KW. The benchmark costs of RTS systems vary across states and therefore, the CFA is applicable on the benchmark cost of the MNRE or lowest of the costs found in the tenders for that State/Union Territory (UT), whichever is lower.

It has been noted that the rooftop solar power becomes attractive only if the subsidies are present (Bansal et al. 2018). Even in the USA, for residential consumers, the rooftop solar power without subsidies is not attractive in most of the states [12].

CFA is not available for RTS systems for categories other than residential, i.e. institutional, educational, social, government, commercial and industrial, as the beneficiaries in these sectors are high tariff paying consumers and the adoption of solar power would be economically beneficial for them even without CFA. The power generated through an RTS plant would result in significant reduction of the electricity bill paid by them to the DISCOMs, thereby making it an economically viable solution. Although CFA is not admissible for non-residential sectors, the DISCOMs still get incentivized for addition of RTS capacity in these sectors too.

Incentives have also been built-in for the DISCOMs to create an enabling ecosystem for RTS systems and also because these have to incur extra costs in terms of additional manpower, creating infrastructure, capacity building, awareness, etc. DISCOMs are given incentives on incremental RTS capacity installed in their distribution area.

To assess and evaluate various states in India for their preparedness to support rooftop solar deployment, the State Rooftop Solar Attractiveness Index (SARAL) has been developed by the MNRE. This index ranks the states based on parameters that are critical for establishing strong solar rooftop markets.

**Table 3** Systems installed under off-grid decentralized solar PV programme

| Type of solar PV system | Capacity up to 31 December 2019 |
|---|---|
| Streetlights (No.) | 679,772 |
| Home lights (No.) | 1,721,343 |
| Study lamps | 7,426,531 |
| Solar pumps (No.) | 246,074 |
| Solar PV power plants (MW) | 212.5 |

### *5.3 Solar Schemes for Farmers*

The Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM) Scheme, which was launched in March 2019, consists of three components, namely Component-A: setting up of 10,000 MW of decentralized grid-connected solar or other renewable energy power plants on barren/fallow land; Component-B: installation of 17.50 lakh standalone solar agriculture pumps; and Component-C: solarization of 10 lakh grid-connected agriculture pumps. Putting all the three components together, the scheme intends to add 25,750 MW by 2022. This will help to create an avenue for extra income to the farmers, and for the states to meet their renewable purchase obligation (RPO) targets.

For Component-B and Component-C, the MNRE provides a CFA of 30% of the benchmark cost or the tender cost, whichever is lower. The state governments also give a subsidy of 30% and the remaining 40% is to be contributed by the farmer. Bank finance is made available for meeting 30% of the cost borne by the farmer (MNRE 2020).

### *5.4 Off-Grid and Decentralized Solar PV Programme*

Under the off-grid and solar PV programme, the MNRE has been providing CFA for deployment of solar streetlights, solar home lights, solar study lamps, standalone solar pumps, and solar PV power plants to meet the needs of rural areas (MNRE 2020). The details of the cumulative systems installed under this scheme up to 31 December 2019 are shown in Table 1.3. This scheme is very important in providing energy access to the areas not connected to the transmission grid.

### *5.5 National Wind-Solar Hybrid Policy*

The MNRE has launched a hybrid policy for wind-solar PV power generation in 2018, with an objective of achieving optimum and efficient utilization of resources such as land, evacuation infrastructure, to address variability in renewable power generation and to have better grid stability. A wind-solar plant is recognized as a hybrid plant if the rated power capacity of one resource is at least 25% of the rated power capacity of the other resource. All fiscal and financial incentives available to wind and solar power projects are made available to hybrid projects (MNRE 2020).

### 5.6 Other Schemes

In addition to the above schemes which are mainly focused on power generation from solar PV systems, there are certain other systems which are made available at subsidized rates using solar thermal technologies—for example, solar cookers, solar water heating systems, solar drying systems, etc.

### 5.7 Comparison of Fiscal Incentives Under Various Schemes

This section (Table 4) presents a gist of comparison of various incentives made available by the Indian government under policies discussed in Sects. 5.1–5.4.

## 6 Institutional Framework

The Ministry of New and Renewable Energy (MNRE) is the nodal ministry of the Government of India for all matters relating to new and renewable energy including solar energy (Fig. 6). The primary mission of the Ministry is to ensure energy security by reducing oil imports and increasing the share of clean power at affordable prices. Apart from solar energy, the MNRE is responsible for the development of alternate fuels such as hydrogen, bio fuels, synthetic fuels and renewable energy development such as biomass, wind, hydro, geothermal and tidal electricity (MNRE 2017).

The National Institute of Solar Energy (NISE), which comes under the MNRE, is located at Gurugram. The institute is the focal point of all technical support and R&D in the solar energy sector. The Indian Renewable Energy Development Agency (IREDA), a non-banking financial institution, is under the administrative control of this Ministry and provides term loans for renewable energy and energy efficiency projects. It is responsible for providing financial support to projects and schemes for generating electricity through new and renewable energy sources. Several solar power plants and rooftop PV projects under the JNNSM have been financed through the IREDA. The Solar Energy Corporation of India (SECI) functions as the implementing and executing arm of the Ministry for implementation of the National Solar Mission (NSM). A corresponding arrangement at the state level is made by the state governments.

**Table 4** Comparison of fiscal incentives under various schemes

| Type of solar system | Scheme | Target | Incentives |
|---|---|---|---|
| Ground-mounted grid-connected solar power generation | Solar parks and ultra mega solar parks | 40,000 MW | CFA of Rs. 25 lakhs/solar park for preparation of DPR<br>CFA of Rs. 20 lakhs/solar park for development of internal infrastructure and power evacuation infrastructure<br>CFA of up to Rs. 20 lakhs per MW or 30% of the project cost |
| | Solar PV power projects by defence installations | 300 MW | VGA |
| | Solar PV power project on canal bank and canal top | 100 MW | Canal top: CFA of Rs. 3 crores/MW or 30% of project cost (whichever is less) |
| | | | Canal bank: CFA of Rs. 1.5 crores/MW or 30% of project cost (whichever is less) |
| | Solar PV power projects by government organizations | 12,000 MW | VGA of Rs. 0.7 crores/MW |
| | Utility scale solar power projects | 7750 MW | VGA funds allocated from time to time |
| Rooftop grid-connected solar power generation | Residential rooftop solar power generation systems | 40,000 MW | CFA of 40% up to 3 KW systems<br>CFA of 20% above 3 KW up to 10 KW systems<br>No CFA above 10 KW systems |
| | Group Housing Societies/Residential Welfare Associations (GHS/RWA) etc. for common facilities up to 500 kW (@ 10 kW per house) | | CFA of 20% |
| | Other than residential category | | No CFA |
| Scheme for farmers | Component A: Grid connected decentralize solar power plants | | Feed-in-tariff |

(continued)

**Table 4** (continued)

| Type of solar system | Scheme | Target | Incentives |
|---|---|---|---|
| | Component B: Standalone solar agricultural pumps | | CFA (MNRE)—30%<br>State subsidy—30%<br>Bank loans—30% |
| | Component C: Solarization of existing agricultural pumps and connecting to grid | | CFA (MNRE)—30%<br>State subsidy—30%<br>Bank loans—30% |
| Off-grid and decentralized solar PV programme | Solar streetlights, solar study lamps, solar pumps, solar home lights and solar PV power systems | | CFA of 30% |

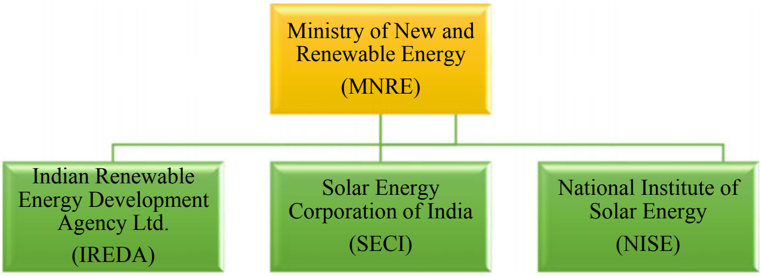



**Fig. 6** Institutional framework for the solar power sector

The other important institution which plays a role in promoting solar energy is the Central Electricity Authority (CEA), set up under the Electricity Act, 2003. The CEA decides on the power generation from different sources in the country. The CERC and the corresponding agencies at the state level are the ones responsible for deciding the tariffs for power including for solar power.

## 7 Operational Mechanisms

In order to achieve the targets, set for solar energy, a number of operational mechanisms have been put in place. At certain junctures, we observe variations amongst the states in India in adopting these mechanisms. The important mechanisms influencing the adoption of solar energy are discussed in the following paragraphs.

**Table 5** Renewable purchase obligations set by GERC—for DISCOM and captive consumers

| Year | Minimum quantum of purchase (in %) from renewable energy sources | | | |
|---|---|---|---|---|
| | Wind % | Solar % | Others % | Total % |
| 2010–11 | 4.5 | 0.25 | 0.25 | 5.0 |
| 2011–12 | 5.0 | 0.5 | 0.5 | 6.0 |
| 2012–13 | 5.5 | 1.0 | 0.5 | 7.0 |
| 2013–14 | 5.5 | 1.0 | 0.5 | 7.0 |
| 2014–15 | 6.25 | 1.25 | 0.5 | 8.0 |
| 2015–16 | 7.0 | 1.5 | 0.5 | 9.0 |
| 2016–17 | 7.75 | 1.75 | 0.5 | 10.0 |
| 2017–18 | 7.85 | 3 | 0.5 | 11.35 |
| 2018–19 | 7.95 | 4.25 | 0.5 | 12.7 |
| 2019–20 | 8.05 | 5.5 | 0.75 | 14.3 |
| 2020–21 | 8.15 | 6.75 | 0.75 | 15.65 |
| 2021–22 | 8.25 | 8.0 | 0.75 | 17.0 |

### *7.1 Renewable Purchase Obligation (RPO)*

The RPO mandates that DISCOMs in India ensure that a certain percentage of their power is generated from renewable energy sources. The RPO mechanism was introduced as part of the Electricity Act, 2003 to create demand for renewable power. The targets are set by the various state electricity regulatory commissions (SERC). The RPOs for DISCOMs and captive power producers in Gujarat for the financial year 2019–20 states that 14.3% of total power must be from renewable energy sources which includes 5.5% from solar ones (Table 5). The share of overall renewables, and solar ones in the RPOs has been proposed to be gradually increased and is going to be 17 and 8% respectively by 2021–22 (GERC 2017). The options available to meet RPO targets are either to set up own renewable power plants or to buy renewable energy certificates (RECs). All units of renewable energy purchased by the DISCOMs qualify towards meeting its renewable purchase obligation (RPO).

### *7.2 Net-Metering for Rooftop Solar*

Net-metering is a concept where the consumers are connected to the DISCOM's grid and are provide with a bi-directional meter which tracks the net power consumption of the consumer. The electricity generated from the rooftop solar PV system is first consumed within the same premises, and any unused surplus electricity is fed into the DISCOM's grid [22, 25]. When the consumer's load is higher than the power produced by the rooftop solar system, power is consumed from the DISCOM. The consumer only pays for the net power consumed, which is the difference between power imported from the grid and the power exported to the grid. There are variations in the state policies on this aspect. The Gujarat Solar Policy relies heavily on net-metering for small consumers with installed capacities less than 1 MW. The state of Maharashtra earlier allowed net-metring but has later shifted to gross-metering in 2019 (MERC 2019). In gross-metering, the power exported to the grid is purchased at a much lower base rate than the retail rate at which power is supplied. The gross-metering makes the financial viability of the systems less attractive.

Some states put a cap on the capacity of rooftop solar system to be installed as a percentage of the sanctioned load. Gujarat and Maharashtra allow setting up of rooftop solar systems to be equal to the sanctioned load. Other states put a cap on the power which can be exported to the grid as a percentage of the power which is imported from the grid—for e.g., Tamil Nadu allows only 90% of power to be exported to the grid. Excess power generated in certain months are carried forward and settled annually. There are a few states where excess power generated beyond the prescribed limit of 90%, turns void at the end of the settlement period. Gujarat has not put any cap on the power which can be exported to the grid under net-metering arrangements. The settlement period in Gujarat for the net-metering, i.e. power imported versus power exported, is the billing cycle, whereas in Maharashtra and Tamil Nadu, this is done annually. All these considerations impact the financial viability and attractiveness of the rooftop solar power systems and the decision of the consumer to set up a rooftop solar power generation system and this, in turn, impacts the installed capacity of the states. The proactive consumer-friendly policies in Gujarat has led the state to be a leader in rooftop solar power generation in the country.

## *7.3 Feed-In-Tariff*

Another important instrument which makes the rooftop solar power generation attractive is the feed-in-tariff (FIT). This is an added incentive for the consumers who now have the option of getting paid for any surplus power which they export to the grid at the end of bi-monthly billing cycle or the settlement period. The feed-in-tariff is normally the base price of electricity and is much lesser than the retail price at which electricity is supplied. The current rate for surplus power fed into the grid is Rs. 2.25/KWh in Gujarat. Every year, the SERCs announce the rates for the FIT.

| 2017–18 | 2018–19 | 2019–20 |
|---|---|---|
| Rs. 3.24/unit | Rs. 3.22/unit | Rs. 2.25/unit |

### 7.4 *Benchmark Cost Including Cost of All Components and Maintenance*

The MNRE as well as the state governments announces the benchmark cost of rooftop solar systems from time to time. In the last few years, this cost has been gradually coming down (Fig. 8). The benchmark cost includes the cost of all components i.e. solar panels, inverter, wiring and cabling, cost of bi-directional meter, mounting structure, etc. (Fig. 7). The cost is also inclusive of government taxes and the profit margin of the channel partners which install the system. This has ensured that all the costs associated with installation of rooftop solar PV systems remain transparent and easy to understand. The only additional cost to be borne by the consumer is the connectivity charges payable to their respective DISCOMs. This charge is variable, based on the consumer type and the DISCOM, and hence it is not included in the overall cost of the system.

The benchmark cost also includes free operation and maintenance (O&M) of the installed rooftop solar PV system for a period of five years. The maintenance includes

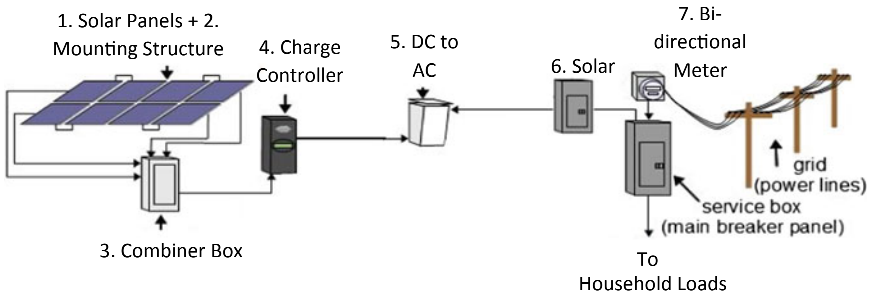



**Fig. 7** Components included in the total cost of RTS

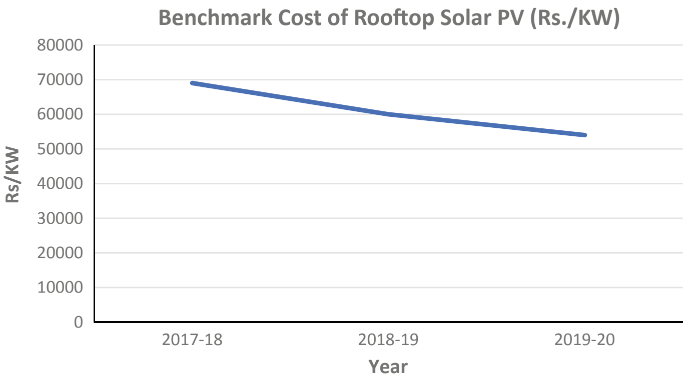



**Fig. 8** Declining benchmark cost of rooftop solar PV

the replacement of PV and BOS[1] components due to any manufacturing defects. The concerns of the consumers with respect to maintenance issues of the rooftop solar system before it achieves its payback period, which is between four to five years, has been smartly negated by this. The benchmark cost for the rooftop solar PV has been gradually declining over the years (https://mercomindia.com/mnre-residential-solar-rooftop-subsidy/).

By ensuring that all costs for the system are included, the government has ensured that there are no price negotiations. Any unscrupulous activity on the part of the channel partners, like demanding additional costs for components, can be easily avoided. By providing a transparent system of capital costs breakup, the confusion and doubts arising in the minds of the consumers, which generally leads to avoidance and reluctance to adopt to new technologies, has been converted into an opportunity as the policy has ensured smooth and simple transactions.

Another important facilitating mechanism is that the subsidy on capital costs offered to residential consumers for installation of rooftop solar PV systems is transferred directly into the account of the channel partner, post the commissioning of the system. The residential rooftop owners thus have to pay only the balance amount to the channel partners.

### *7.5 Mandate Under Model Building By-Laws, 2016*

The model building by-laws released by the Ministry of Urban Development (MOUD) in 2016 mandated the rooftop solar power generation. Many state governments and UTs in India also make it compulsory as per the provisions of these by-laws (Bansal et al. 2018). The provisions in the by-laws for solar power generation on rooftops of the buildings is shown in Table 6. The guidelines for the installation of rooftop solar power generation systems are applicable to the buildings based on their size and their power consumption. There are certain states which have adopted the model by-laws as it is and there are others which have made certain modifications. Although monitoring and implementation of rooftop solar power generation systems on existing buildings may not be very practical, for the new buildings, however, these norms can be implemented via the process of building plan approval. The strict monitoring and enforcement of norms can lead to higher penetration of rooftop solar PV in urban areas.

The above norms provided in the building by-laws translate to a very minimal requirement of rooftop solar power generation systems to be installed on the building premises. However, these norms are likely to create a conducive environment for improving awareness for the requirement of rooftop solar power generation.

[1]BOS: All components of a solar PV system apart from the Photovoltaic Modules are known as Balance of Systems. Detailed description of the same is provided in Chap. 3.

**Table 6** Provisions for rooftop solar under Model Building By-laws, 2016 by MOUD

| S. no | Category of building | Area Standards | Generation Requirement* |
|---|---|---|---|
| Residential | | | |
| 1 | Plotted housing | For HIG plots and above | Minimum 5% of connected load or 20 W/ft$^2$ for available roof space**, whichever is lesser |
| 2 | Group Housing | All proposals, as per Group Housing Norms | Minimum 5% of connected load or 20 W/ft$^2$ for available roof space**, whichever is lesser |
| All other buildings having shadow free rooftop area >50 m$^2$ | | | |
| 3<br>4<br>5<br>6<br>7<br>8 | Educational<br>Institutional<br>Commercial<br>Industrial<br>Mercantile<br>Recreational | Plot size 500 m$^2$ and above | Minimum 5% of connected load or 20 W/ft$^2$ for available roof space**, whichever is lesser |

*Area provisions on rooftop shall be 12 m$^2$ per 1 KW, as suggested by the MNRE
** "available roof area" = 70% of total roof size, considering 30% area reserved for residential amenities

## 8 Grid Parity for Solar Energy

Grid parity is a point in time when the cost of producing power from renewable sources is the same or lower than the cost of producing power from fossil fuels. When the JNNSM was launched in the year 2010–11, solar energy was very expensive as compared to the power generated from conventional fossil fuels. The higher cost of solar power was the main hurdle in promoting this renewable source of energy. However, recently, the tariffs for solar energy have become at par with, and even lower than the conventional coal-based power plants. The lowest tariff for solar power in the country has been Rs. 2.44 per unit through auctions in May 2017 for the Badhla Solar Park in Rajasthan (Dutta 2020). In fact, the lower tariffs for solar and wind power as compared to coal-based power generation (NTPC 2017; Solar [5] are lately giving a tough competition to the coal-based power generation in the country as the tariffs for coal-based power generation are higher now (Fig. 9).

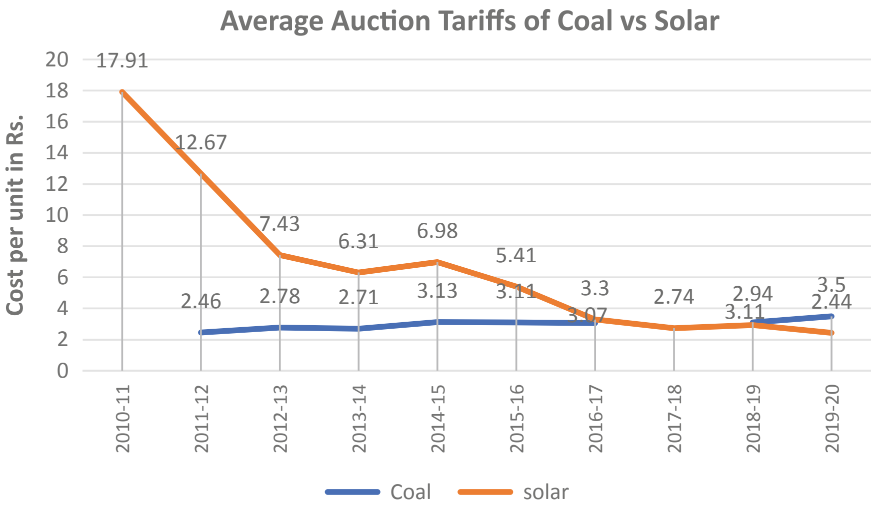



**Fig. 9** Comparison of coal and solar power tariffs

## 9 Targets Achieved

Prior to the JNNSM, the installed solar power in India in 2009 was a mere 0.02% (0.03 GW). However, under the JNSSM, in 2010, an initial target of 20 GW of solar power was set which was later revised upwards in 2015 to 100 GW. Against this, a capacity of 37.5 GW of solar energy has been realized by December 2019 whereas the total renewable energy generation is 85.9 GW. There are many projects which are in the pipeline—for some, a letter of intent (LOI) has been issued and for others, tenders have been issued. At the end of 2019, the country holds the third position globally, after China and the US, in terms of solar power deployment. Solar power generation has been the focus of attention in the last few years and the capacity added has increased ten-fold—from 3.7 GW commissioned till 2014–15 GW to 37.5 GW in December 2019. A target of 30 GW for solar power generation has been set for the financial year 2020–21. The sector-wise renewable energy installed in the country till 31 December 2019 is represented in Fig. 10 (MNRE 2020).

The states in India have varied solar power potential but not all of them have been active in exploiting this potential. The initiatives taken by the state governments greatly influence the deployment of solar power in the respective states. The top 10 states in India in terms of their installed solar capacity are listed in Table 7 (MNRE 2020).

So far, in solar power generation, the major contribution of 93% has been from ground-mounted systems while the rooftops have contributed only seven per cent. The contribution of rooftops is quite less as compared to the targeted share of 40% (Fig. 11) and most of this contribution has come from industrial and government buildings. In fact, in 2019, there was a decline in the growth of rooftop solar power

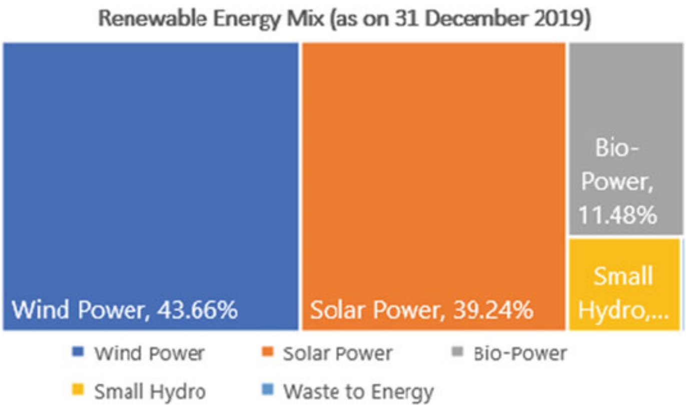



**Fig. 10** Sector-wise renewable energy achievement (MW as on 31 December 2019)

**Table 7** Top 10 states in India in solar installed capacity (MW as on 31 December 2019)

| Rank | State | Capacity installed (MW) |
|---|---|---|
| 1 | Karnataka | 7274.92 |
| 2 | Rajasthan | 4844.21 |
| 3 | Tamil Nadu | 3788.36 |
| 4 | Telangana | 3620.75 |
| 5 | Andhra Pradesh | 3559.02 |
| 6 | Gujarat | 2763.55 |
| 7 | Madhya Pradesh | 2237.48 |
| 8 | Maharashtra | 1663.42 |
| 9 | Uttar Pradesh | 1045.1 |
| 10 | Punjab | 947.1 |

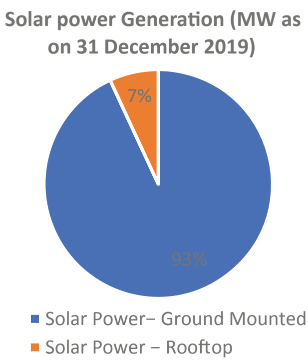



**Fig. 11** A break-up of grid-connected solar power generation

**Table 8** Top 10 states in installed solar rooftop capacity

| Rank | State | Installed solar rooftop capacity (MW as on 31 December 2019) |
|---|---|---|
| 1 | Gujarat | 301.71 |
| 2 | Maharashtra | 216.11 |
| 3 | Tamil Nadu | 155.78 |
| 4 | Uttar Pradesh | 140.87 |
| 5 | Karnataka | 131.83 |
| 6 | Rajasthan | 119.50 |
| 7 | Haryana | 118.47 |
| 8 | NCT of Delhi | 109.80 |
| 9 | Andhra Pradesh | 88.03 |
| 10 | Uttarakhand | 75.71 |

deployment [19]. The top 10 states in the country in rooftop solar power generation have been enumerated in Table 8 (MNRE 2020).

## 10 Co-benefits of Solar Power Generation

### *10.1 Reduced Transmission and Distribution (T&D) Losses*

The transmission and distribution losses are energy losses incurred by DISCOMs between the point of generation and the point of consumption. These may be due to technical and commercial reasons. Transmission losses are technical losses on account of overloading of existing lines, transformer, sub-stations and poor maintenance of equipment. Distribution losses are commercial losses which occur mainly due to power theft, errors in meter readings and poor billing and collection efficiency. Table 9 presents the T&D losses in India (CEA, 2017). There is no assessment available for categorical split of losses due to transmission and distribution. Transmission losses can be minimized by reducing the extent between point of generation and point of consumption. Implementation of rooftop solar power generating systems in cities

**Table 9** Transmission and distribution losses in India

| Year | T&D losses |
|---|---|
| 2010–11 | 23.97 |
| 2011–12 | 23.65 |
| 2012–13 | 23.04 |
| 2013–14 | 21.46 |
| 2014–15 | 22.84 |
| 2015–16 | 22.77 |

can be considered as an opportunity in the power sector for reducing transmission losses since the point of consumption is the same as the point of generation.

The national average of T&D losses in the country is very high [18] in comparison to countries like China and the USA, which have T&D losses ranging between 5 and 6%. This is one of the reasons why the generation of power at the point of consumption in urban areas has been given importance in the JNNSM policy, through the implementation of Solar PV rooftops.

A case in particular that can be cited is of the Union Territory of Diu, located off the coast of Gujarat, with a population of around 50,000 people. It has completely transitioned to solar power to meet its energy demands. The island generates 13 MW of power in which 3 MW is obtained from solar rooftops and 10 MW from solar power plants. The peak energy demand for Diu is only 7 MW and the excess energy produced is exchanged with neighbouring Gujarat. Although the island of Diu generates surplus power, it still imports 73.4% of its power from Gujarat, as solar energy is not available at night. After this reduction of 26.6% in power purchase from Gujarat, the island has managed to reduce its total T&D losses, including interstate transmission losses from 12% to a mere 7% [11]. This is much below the national average. As a result of this reduction in losses, even the power demand for the UT has not increased substantially since 2017. In addition, the cost of power to the end-user has also been reduced.

### *10.2 Reduced Dependence on Imported Coal*

Fossil fuel-based power generation contributes to more than 60% of the power generated in India and a major share of it is from coal. The coal mined in India contains very high ash content, ranging from 20 to 40% (Chandra & [3]). This affects the combustion and efficiency of power plants. Further, there is inadequate infrastructure for evacuation of coal from mines in India. To overcome these constraints of low-grade coal and erratic supply of Indian coal, thermal power plants have resorted to import of foreign coal which makes the power generation costly. On the flip side, the levelized cost of solar power has been constantly falling since 2011, resulting in lower per unit costs. Solar energy now provides an attractive alternative to the conventional power sector in India. The country needs to capitalize on this emerging sector and realize the economic benefits linked to solar energy at the national level.

### *10.3 Energy Security*

The International Energy Agency (IEA) defines energy security as the uninterrupted availability of energy sources at an affordable price. India is a vast country and there are certain regions which are not energy secure. Since the country has good solar irradiance, these regions do have the possibility of generating solar power. The falling cost of solar power production has opened up the possibility of making these regions energy-secure.

For example, Ladakh is a region in the north of India with a very harsh climate. It remains cut off from the rest of the country during winters for almost six months. The region is also not connected by the national transmission grid for supply of electric power. Within the region, there are areas and defence posts which continue to remain disadvantaged from the point of view of access to electric power. The setting up of off-grid solar power units has made these areas energy-secure. The scheme for off-grid solar PV programme offers similar opportunities at the decentralized level for energy access in the remote areas which are not connected to the grid.

Similarly, the special incentive schemes for farmers have made them energy-secure and have opened up new economic opportunities for them. There are farmers who have earned money from DISCOMs by feeding solar power to the electricity grid. The power has been generated from their solar agriculture pumps (TOI 2019). To exploit the opportunity in a collective way, they have started forming cooperatives. The schemes for farmers also have the provision of generating solar power for captive consumption and earning money by injecting extra power into the grid.

Another initiative at the grassroot-level is the setting up of a solar park by salt pan workers in Little Rann of Kutch, Gujarat. Salt manufacturing season typically lasts from October to March. The salt pans use solar pumps to extract saline water for salt manufacturing. For the remaining six months, the solar pumps used to lie idle. The state government in Gujarat has come up with an initiative to use these solar panels in non-salt manufacturing season for generating solar power and feeding it to the grid and in return earn money for the salt pan owners.

## *10.4 Challenges in Scaling-Up Solar Power Generation*

The solar power sector is growing in the country as a result of the policy initiatives, availability of good solar resources and the operational mechanisms put in place. But there are still a few challenges faced by the sector in optimising the growth. These are discussed in the following paragraphs.

**Land Availability for Solar Power Plants**

Land is a critical component for a solar power project. Approximately four to five acres (1 acre = 4046.8 $m^2$) per MW of land is required for setting up a solar park. To facilitate land availability, the SECI has been entrusted with the responsibility of making both government and private land available for renewable power projects. For this, the SECI will be paid at a rate of Rs. 0.02/unit of power being generated. No funds from the CFA can be used for procurement of land. For the solar projects promoted by the states, the governments have started taking initiatives to identify potential lands for setting up the solar power plants.

**Evacuation Infrastructure**

The power evacuation infrastructure for the transmission and distribution of power from large power plant projects is a concern. The fiscal incentive of Rs. 20 lakhs per MW for developing internal and external infrastructure under the policy may not be enough for creating infrastructure for external power evacuation. To address this, the government has proposed that 40% of the cost of external power evacuation should be borne by the renewable energy project developer and the balance 60% will be provided from the CFA to the External Transmission Development Agency (ETDA).

The challenge of land availability and power evacuation infrastructure becomes more complex as many times, the land which can be used for setting up of solar power plants does not have the power evacuation infrastructure in place.

**Policy Uncertainty**

There have been occasions when the central and the state agencies have cancelled auctions when the winning tariffs seemed too high for them. Another concern is the delay in payments of the subsidies by the government to the project developers. The policy revisions happen from time to time in terms of eligible projects and the available subsidies. The in-between periods of policy revision are sometimes blank, with no development taking place during that time.

**New Challenges in View of COVID-19**

Due to the impact of the COVID-19 pandemic, the small players (channel partners) in India engaged in the rooftop solar business are going to be badly hit. It is likely that many of them will close their business. In the rooftop solar business, only 25% of the business is accounted for by the big players and the rest is with small players. Smaller rooftop players don't have the financial capacity to bear losses or meet extra working capital requirements. They are also unlikely to get any financial assistance from the government or banks. Another major aspect in case of rooftop solar is that the consumers may delay the decision to set up the system as it is not a necessity [4]. The larger scale solar projects are also going to face delays as they are dependent upon import of solar PV panels from China. The growth in India's solar capacity has been built on an overwhelming share of imported PV modules because their costs are up to 30% lower. The labour migration is another factor which is going to have a short-term impact on the project schedules.

## *10.5 Conclusions*

This chapter has discussed in detail about the numerous opportunities and tremendous scope of solar energy in India. Solar energy has a great potential in India due to its geographic location. To exploit the potential, a positive policy environment has been created at the central level as well as by many state governments. The policies have tried to cover the length and breadth of all possible options to generate solar power. The market response is favourable, leading to large scale solar installations.

Gradually, the country has gained its position globally and now stands at the third position in solar power deployment. The main challenges in terms of setting up solar parks are land availability and power evacuation. In terms of rooftop solar power generating systems, the main challenge is to attract rooftop owners to set up the system. A lot needs still needs to be done in order to ensure stable and continual growth of solar power to achieve the ambitious targets set by the country. This is more so for the targets set for solar rooftop power generation where against a target of 40 GW by 2022, only 2.33 GW has been realized by December 2019. The country is taking initiatives to meet these challenges and hopefully will emerge successful in meeting the set targets.

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# Bioenergy Production from Halophytes Crops for Sustainable Development

**Mehmood Ali, Atif Mustafa, Zainul Abideen, and Bilquees Gul**

**Abstract** The global demand for food, freshwater and fuel is continuously increasing. The cultivation of salt resistant energy plants including halophytes can be an appropriate choice to exploit saline land and water resources which are often regarded as unsuitable for crop cultivation. Utilization of halophytes, conservation of freshwater and agricultural lands can help in improving food and fodder production in the developing countries. These countries can adopt saline agriculture on marginal lands to produce bioenergy for electricity generation. The salt affected soil reclamation by using halophytes can be a good strategy to develop a sustainable soil reclamation strategy. The global availability of one billion hectares of saline soils with vast areas located in the developing countries can be utilized for energy crop cultivation to meet renewable energy demands. This practice could have direct or indirect potential impacts such as mitigating GHG emissions through carbon sequestration, as well as wider positive impact on ecosystem protection and biodiversity enhancement. In order to improve the lignocellulose composition in biomass, introduction of genetic manipulation techniques can be used in stress tolerant energy feedstocks. Similarly, plant metabolism could be optimized by using agronomy and genetic manipulations to develop new crops for saline land. Constructed wetlands can be used to cultivate halophytes thus providing multiple benefits of wastewater treatment and bioenergy production. Currently the major aim is to evaluate the potential of halophytes for wide economic use in arid and semi-arid regions in the light of progressive shortage of freshwater resources and soil salinization. This book chapter covers topics pertinent to water conservation, food security, biofuels/bioenergy production to mitigate climate change impacts for sustainable development and benefits of cultivating halophytes on marginal land.

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**Keywords** Biofuels · Halophytes · Bioenergy · Water conservation · Food security

## 1 Introduction

Energy generation and environmental security is basically a major challenge in the developing countries. The generation of electricity using fossil fuels produces around 60% emissions of toxic gases globally, that are harmful for the health of humans and as well as have detrimental implications on the ecosystem functions damaging the natural environment through climate change issues. Tackling emissions from energy production is crucial for climate change mitigation and therefore to meet this challenge, the energy poverty can be remediated by utilizing the renewable and sustainable technologies such as biofuels and bioenergy from locally available biomass feedstocks. In this context, bioenergy can be produced from the biomass utilizing agricultural wastes and non-edible crops [35]. However, due to increasing population with the passage of time, the freshwater demand is increasing at an alarming rate and it is becoming difficult to meet demands for drinking purpose and agricultural practices. The freshwater conservation can be achieved by using saline water with high dissolved solids and the salinity added degraded soil to cultivate halophytes as energy crops for power generation and biofuels production. Halophytes have remarkable ability to grow under high saline conditions and can be irrigated with seawater without compromising their biomass and seed yields making them good alternate candidates as bioenergy and biofuel producing crops [30].

This chapter includes the overall review on energy and environmental security in the developing countries that can be met by utilizing the halophytes crops to produce biofuels and bioenergy. Limited resources for energy can be developed by new biomass commodities such as halophytes, which seem environmentally sustainable and adequate to the low quality soil. Therefore, importance of producing non-edible energy crops has been realized to reduce climate change, global warming problems and food competition. Development of halophyte based agriculture would be useful for adopting United Nations Sustainable Development Goals (SDGs). Therefore, the importance of water conservation and food security in the developing world with respect to the UN sustainable development goals such as; (No. 2 Zero Hunger), (No. 7 Affordable and Clean Energy) and (No. 13 Climate Action) has been discussed. The cultivation of halophytes on marginal and barren lands available with water logging and salinity can be a best choice, reducing impact on freshwater consumption and food crises in the world. The chapter covers information about different types of halophytic energy crops, its classifications and mechanisms of growth. Moreover, improvement in the cultivation of halophytes with higher yield using genetically modified halophytic crops for bioenergy generation. Basically, the usage of halophytes for biofuels and bioenergy generation helps in reduction of carbon emissions, thus reducing the risk disaster caused by climate change and global warming issues. The physical, chemical and thermal properties of halophytes are discussed and its conversion into useful solid, liquid and gaseous biofuels and other value added products. Utilization of halophytes with thermochemical treatment such as slow pyrolysis is discussed. The application of constructed wetlands for cultivation of halophytes is also discussed. The end of chapter discusses the challenges and opportunities associated with halophytes farming for biofuels and bioenergy generation.

## 2 Water Conservation and Food Security

The world population is continuously growing and the global demand for food is also increasing subsequently. Most of this population growth is expected in developing countries [10]. Water quantity and quality both are one of the greatest challenges of the 21st century. Moreover, the effects of climate change resulting in disrupted weather patterns are making the situation much more intricate. According to FAO, agriculture sector is considered to be the biggest user of water, accounting for almost 70% of all withdrawals and by 2025, it is estimated the water demand for agriculture globally will increase by 60% [6]. The exponential rise in population coupled with increased food demand in the last century was met by a combination of various strategies. These strategies included government policy, scientific and technological advances, institutional involvement and trade investment, innovation and delivery. However increased farm productivity to meet the global food demand was achieved at the cost of negative impacts on the environment [18].

According to FAO, food security exists when "all people, at all times have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life". Food security is linked to all of the United Nations Sustainable Development Goals (SDGs) [26]. The management of water resources plays an important role in fulfillment of food security goals. But the existing situation where water scarcity problems are magnified by dwindling water supplies coupled with ecosystems degradation and climate change impacts are major challenges to future food security. The variability in temperature and precipitation patterns may also lead to a considerable variation in crop production. Based on FAO projections the global agricultural area will expand from the current 5.1 billion hectares to 5.4 billion hectares in 2030 [40]. So the future challenges include both increased land and freshwater availability for fulfilling the growing global food demand.

## 3 Cultivation of Halophytes to Conserve Freshwater

Approximately 97% of the water on earth is saline and present in the oceans while 41.3% of the earth's total land surface comprise of arid, semi-arid and dry sub-humid areas. Most of the arid and semi-arid regions are located in developing countries where freshwater availability is continuously decreasing. It is here that makes the

**Table 1** Multifunctional applications of halophytes

| S. no. | Application | Halophyte name |
|---|---|---|
| 1 | Biofuel | *Salicornia/Sarcocornia spp* |
| 2 | Bioremediation | *Salicornia/Sarcocornia spp* |
| 3 | Fodder | *Inula crithmoides, Pennisetum clandestinum, Sporobolus virginicus* |
| 4 | Food | *Salicornia/Sarcocornia spp* |
| 5 | Ground cover | *Pennisetum clandestinum, Sporobolus virginicus* |
| 6 | Ornamental | *Atriplex hortensis, Aster tripolium, Crithmum maritimum, Inula crithmoides, Mesembryanthemum crystallinum, Salicornia/Sarcocornia spp* |
| 7 | Vegetable | *Atriplex hortensis, Aster tripolium, Crithmum maritimum, Mesembryanthemum crystallinum, Salicornia/Sarcocornia spp* |
| 8 | Wastewater treatment | *Bassia indica, Phragmites, Salicornia/Sarcocornia spp* |

use of the plentifully available saline water for agriculture inevitable. Moreover, desert land is also abundant and approximately 15% land area equivalent to 130 million hectares that is adjacent to the sea is also available [20]. This area can be utilized to grow crops using seawater for saline agriculture without diverting limited freshwater resources.

Halophytes represent 1% of the global flora and are those plants that can grow and complete their lifecycles in environments with high concentrations (greater than 200 mM) of electrolytes (mostly $Na^+$ and $Cl^-$, but also $SO_4{}^{2-}$, $Mg^{2+}$, $Ca^{2+}$, $K^+$ and $CO_3^{2-)}$ in the root medium [14]. Halophytes have a multitude of benefits and can be used as food, animal feed, biofuels, edible oil and medicine. Over the years researchers have investigated the application of saline water for growing salt tolerant plants including halophytes in arid and semi-arid areas. Table 1 represents the multifunctional applications of halophytes that have been successfully cultivated in various parts of the world.

## 4 Utilization of Uncultivated Land with High Salinity

The US Department of Agriculture estimates that approximately 10 million hectares of arable soils are lost across the globe annually. This is mainly due to unsustainable irrigation practices including excessive use of fertilizers, soil contamination, urban pressure and climate change [21]. One of the major problems that developing countries are facing is the high rates of soil degradation due to salinity. Therefore, salt-tolerant plants including halophytes provide a substitute for many developing countries. These plants can be grown on already degraded soils with high salinity that are inappropriate for conventional crops producing food, biofuel, fodder, fiber and other products. Moreover, these plants can be used concurrently for soil rehabilitation. A research study conducted by [16] to grow three halophytes (an oilseed, forage and grain crop) using saline water demonstrated that halophytes can maintain high productivity of useful agricultural products up to a root-zone salinity of as high as 70 g $L^{-1}$ TDS (double the salinity of seawater). Soliz et al. [34] successfully grew *Atriplex lentiformis* using reverse osmosis brine at a test facility. *Panicum antidotale* a fodder halophyte can produce 60,000 kg of biomass per hectare per year, when irrigated with brackish water. Interestingly in field conditions when *Panicum* is grown with *Suaeda fruticosa* (salt accumulator) in adjacent rows and with saline irrigation, soil salt balance can be achieved. This intercropping system can be a sustainable approach to cultivate fodder crop in saline areas. A study conducted in Pakistan on the above pattern demonstrated that *Panicum antidotale* can be used as a complete replacement for maize in a cattle feeding trial and resulted in equivalent growth and meat production [19]. This study indicated that saline land and brackish water can be used for producing an economically beneficial feed crop.

## 5 Constructed Wetlands for Cultivation of Halophytes

The availability of freshwater is a key controlling factor in sustainable agriculture [21] and saline water agriculture can be practiced to balance the deficit. Saline water sources are both natural and anthropogenic. Major anthropogenic sources include marine/coastal aquaculture and reverse osmosis brine. The conventional wastewater treatment for this kind of wastewater is application of gravitational and mechanical techniques. The disadvantage of these systems is that they have high capital and operating costs. Constructed wetlands (CW) are a green, sustainable, low-energy and low-cost technology that has been successfully used to treat a wide array of wastewaters including municipal, industrial and agricultural wastewaters. A constructed wetland is a system engineered to restructure the plants, substrate, and microbial assemblages found within its naturally occurring counterparts, while exploiting the biogeochemical processes that are occurring within the system [37]. CW usually consists of a bed filled with substrate and having an impermeable liner. The bed is planted with emergent plants and water may pass through it horizontally or vertically. The polluted water enters the CW at the inlet and passes over the bed, passing through the filtration substrate until it reaches the outlet point. A combination of physical, chemical and biological processes including, sedimentation, precipitation, volatilization, adsorption, plant uptake and microbial conversion are responsible for water quality amelioration.

A study was conducted to test the effectiveness of a constructed wetland planted with a halophyte *Salicornia europaea* for treating effluent from marine fish and shrimp farm [38]. This study demonstrated the potential of constructed wetlands for wastewater treatment combined with production of valuable secondary plant crops. Researchers investigated the use of *Bassia indica* for salt phytoremediation in constructed wetlands in desert regions and other ecosystems. This study demonstrated that the halophyte planted in constructed wetlands successfully reduced salinity in the effluent by 20–60%. It was observed that CW have a potential to not only treat wastewaters but also offer multiple benefits of valuable plant crops that can be harvested and used for ancillary benefits including bioenergy production [31].

## 6 Types of Energy Crops

Food and energy consumption are increasing very rapidly and their rising demands creates new challenges. Energy security has emerged as a global problem which has greatly increased the renewable energy resources especially from plants grown on suboptimal lands. Crops can be processed for biofuel production but they must be non-food and require low-maintenance for mass scale plant cultivation. Crops can be divided into many categories on the basis of raw material used for biomass processing for energy. First generation bioenergy crops include sunflower, wheat, corn, maize and barley and edible species which need freshwater and good agricultural lands. Agricultural crop byproducts, non-food crops, plant litter and organic wastes are termed as second generation biofuel. However, experience shows that energy crop production for existing food feedstock may contribute to worsen food security. Biofuels obtained from microbes and microalgae are termed as third generation biofuels. The biomass produced from third generation feedstocks such as microalgae can be cultivated in suboptimal saline degraded land which seems unsuitable for crop cultivation. Moreover, the fourth generation biofuels feedstocks are genetically modified crops can also be cultivated in saline lands with limited water requirements [4].

## 7 Ecology, Distribution and Classification of Halophytes

Plant that can tolerate relatively low concentrations of salt is known as glycophytes. The plants which can survive and complete his life cycle under saline condition (up to 200 mM NaCl) are known as halophytes. Salt resistant plants can change growth, water relations, photosynthesis and balance of oxidative burst under saline conditions compared to glycophytes. The unique ability to resist salt under suboptimal conditions established them as a sustainable candidate to reclaim saline lands and use these plants for industrial purposes [14, 23, 28]. It was suggested that, halophytes consist of 6000 species which can be classified into two main types on the basis of habitats and geographical distribution such as xero-halophytes and hydro-halophytes [41]. High number of halophytes are found in the family Amaranthaceae while they occur in thirty seven of the 65 orders of plants [14].

Halophytes are classified in many different divisions but on the basis of morphology excretive and succulent halophytes are discussed here. Excretive species secretes excess salt from the plant body in the form of salt crystal which may be visible on leaf surface e.g. *Aeluropus lagopoides*, *Halopyrum mucronatum* and *Sporobolus tremulus.* Salt secretes halophytes have glandular cells that assist to exclude excess salt from plant [22]. Succulent halophytes contain fleshy leaves that help them to store large amount of moisture in the plant body to maintain salt at sub-toxic levels [39]. These halophytes mostly found in desert area where storage of water can be critical for enduring dry period e.g. *Salicornia bigelovii*, *Haloxylon recurvum* and *Suaeda fruticosa.* Halophytes are also classified into hydro-halophytes and xero-halophytes on the basis of their geographical distribution or habitat [41]. The halophytes which can grow in aquatic soil or in elevated moist conditions are known as hydro-halophytes. Most of the mangroves species such as *Avicennia marina* grow near coastal areas under marsh are haydro-halophytes. Some halophytes can grow in inland salt marshes such as *Phragmites karka* and *Typha domingensis.* Xerophytes may grow in environment arid saline areas where the soil water is less due to evaporation and many of them are succulents [41]. Figure 1 shows the some halophytes that can be a potential candidate for industrial applications [23].

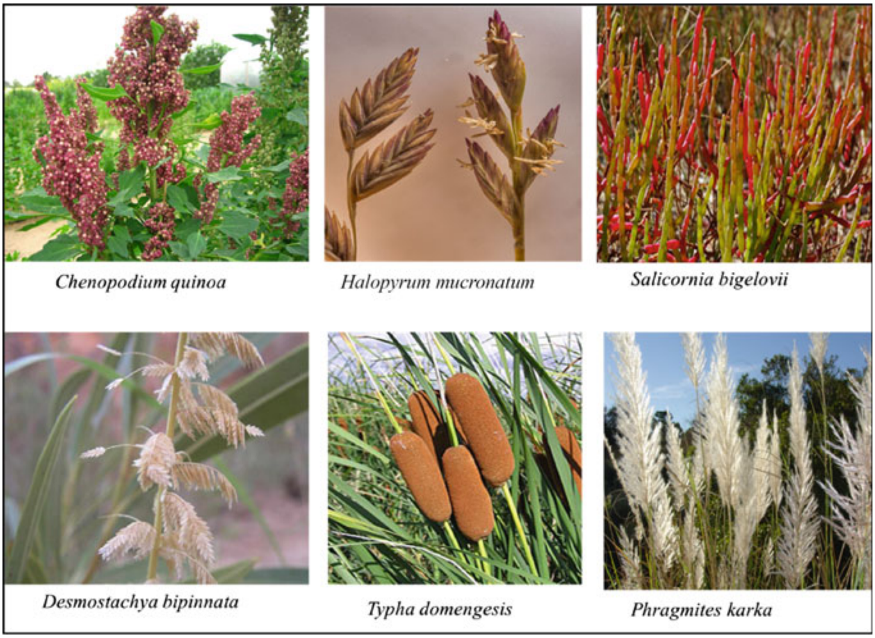


**Fig. 1** Potential halophytes candidate for industrial applications to produce biofuels and bioenergy in developing countries

## 8 Salt Tolerance Mechanisms of Halophytes

Salt tolerance is complex process in plants which is linked with multigenic traits at plant levels. To achieve salinity resistant five aspects of plant activity can be important for biomass production in stress areas such as: (a) growth rate and plant morphology, (b) water relation dynamics, (c) leaf $CO_2/H_2O$ exchange, (d) ion-hemostasis and (e) defense against oxidative stress. The growth responses are directly linked with the productivity and salinity resistant of plants. Salinity caused reduction in plant fresh and dry weight, leaf area expansion, shoot/root, plant height, leaf number, shoot length and relative growth rate. Many halophytes such as *Aeluropus lagopoides, Sporobolus ioclados, Urochondra setulosa and Halopyrum mucronatum*) indicate optimum growth under non-saline conditions. However, moderate salinity stimulates growth parameters in *Phragmites karka*, *Phragmites australis*, *Phragmites communis*, *Spartina maritima* and *Pennisetum clandestinum* but decline substantially in higher salinities [4, 32]. Improvement of biomass is linked with biomass allocation strategy between root/shoot and higher metabolic performance of leaf physiological activity. For instance the higher root development is linked with storage of $Na^+$ and $Cl^-$ ions in the below ground tissue that can prevent $Na^+$ loading in the above ground foliage part [24]. Under high salinity lower root growth is also observed in halophytes that prevent net $Na^+$ influx and preventing $Na^+$ translocation to the shoot.

Halophytes can lower their leaf water and osmotic potential growing in harsh saline conditions. Some halophytes vary their leaf succulence and water content for water uptake and osmotic adjustment to maintain leaf turgidity and water loss. Osmotic balance in halophytes can be achieved by accumulation of inorganic ($Na^+$, $Cl^-$ and $K^+$) and organic substances (sugars proline, glycine betaine and sugar alcohol) for water uptake [32]. Organic osmotic content could be involved in support of other metabolic functions including osmo-protection and radicle scavenging. Accumulation of inorganic substances in plants of saline soil could be cheaper for osmotic adjustment, as compared to relying on organic compounds. Stomata closure is an immediate response to maintain tissue water balance while reducing ion uptake under salinity stress. However, it comes at the cost of intercellular $CO_2$ [24]. The subsequent deficiency of $CO_2$ leads to an over-reduction in the photosynthetic electron transport chain, as well as photo-damage [15]. Plants can protect their photosystems from damage by using enzymatic and non-enzymatic antioxidant substances for optimum metabolic activity and defense against oxidative stress [24].

## 9 Utilization of Halophytes

The world population is increasing with time and demanding more food products in future. Depending upon the current scenario we seriously need a safer solution by finding an alternate crop for cultivation in salt effected soils. The utilization of salt resistant plants could be most suitable option for food, fiber production and to restore salt-affected areas. For example *Chenopodium quinoa*, wild species is used for its nutritional benefits that contribute in food security in various regions especially in native South America. Furthermore, *Portuleca oleracea*, *Sesuvium. portulacastrum, Chenopodium album, Atriplex triangularis, Amaranthus* species and other used as vegetable in many countries. In recent times *Salicornia bigelovii* is emerged as possible source of edible oil and its de-oiled cake can be used as animal feed. Fruits of *Capparis decidua* are used for pickles that possess medicinal importance. Seeds from *Eragrostis ciliaris, Aeluropus lagopoides, Panicum antidotale*, *Eragrostis pilosa* and *Sporobolus ioclados* showed potential for edible oil, phytochemicals medicinal purpose [36].

Halophytes are also known for its alternative fodder/forage value in saline degraded lands. The coastal area is mainly covered by mangrove (*Avicennia, Ceriops, Rhizophora*) and during forage scarcity foliage of these plant exploited as fodder for cattle, camel and goats. Halophytic tress are also a good source for fodder like *Acacia, Salvadora, Prosopis, Ailanthus and Ziziphus* are traditional fodder plants of arid dry regions. Salt resistant grass like *Panicum antidotale, Leptochloa fusca, desmostachya bipinnata, Cynodon dactylon, Sporobolus airoides, Eragrostis tanella, Dichanthium annulatum, D. caricosum, Brachiaria mutica, Bothriochloa pertusa.* The plantation of halophytic fodder can be quite beneficial to achieve cheap meat demands and to reclaim saline lands for industrial purposes. Halophyte fodder may be less costly to produce and used as fodder but needs careful scrutiny during consumption by animals. These undomesticated plants have serious scarcity of relevant information to market them for financial gains. The successful use of halophytes as forage for livestock production also depends on their biomass production; nutritive value and voluntary feed intake [25].

Salt resistant plant can be cheaper source of energy production in the form of biodiesel, bioethanol and biogas feedstock. Halophytes are different feedstock for biofuels than glycopgytes because most of the plants are not involve in food production. Biofuel production from halophytes will be an environment friendly and positive approach to address the fuel versus fuel issue [2]. *Acacia, Capparis, Salsola, Casuarina, Kochia, Prosopis* and *Tamarix* are good source of fuel wood in the world since ancient times. Abideen et al. [5] reported seven promising biodiesel candidate *Salicornia fruticosa*, *Cressa cretica*, *Arthrocnemum macrostachyum*, *Alhagi maurorum*, *Halogeton glomeratus*, *Kosteletzkya virginica* and *Atriplex rosea* on the basis of fatty acid composition, saponification number, cetane number and iodine value. In addition another study highlighted the biofuel potential of halophytes and selected five promising grass species for bioethanol productions. *Typha domingensis, Desmostachya bipinnata, Phragmites karka, Halopyrum mucronatum and Panicum turgidum* are fast growing plant that can produce optimal lignocellulosic biomass for conversion of feedstock into bioethanol fuels.

## 10 Genetic Modifications of Halophytes to Enhance Its Bioenergy Potential

Bioenergy production from halophytic plants can be enhanced by different technological interventions which is necessary to achieve the creeping demand of energy. Complex polysaccharides can be converted into fermentable sugars by using cell wall hydrolyzing enzymes. The induction of cell wall degrading enzymes can directly be induced in the cell through crop bioengineering technologies to reduce dependence on microbial enzyme reactors and total cost of enzyme for biomass Saccharification [9]. Higher lignin content of cell wall is difficult to degrade starch and other carbohydrates to degrade completely to simple sugars such as maltose, glucose and fructose. Cost reduction can be achieved by engineering biosynthesis pathway of lignin and the metrix of lignin with cellulose and hemicellulose. Operative protocol for halophytic species by tissue culture can enhance the biomass yield in rapid and cheaper procedures. Plant tissue culture can be optimized by the procedures accessible for growing a large number of cells in controlled and axenic environment. In addition transgenic changes can be most effective and rapid method to accelerate breeding process of potential halophytic bioenergy plants. Role of genes to enhance total oil yield is reported in *Glycine max and Brassica napus.* Genetic modification can be applied to enhance lipid profile and total lipid content of halophytic seed for bioenergy purposes. Recently plant grown under salinity enhanced the increase membrane lipids unsaturated fatty acid in halophytes which might be the most effective approaches to change oil quality for biodiesel production process.

Halophytic plants grows in coastal saline areas have economic importance because of their plant extracts contains natural antioxidant which can be used as therapeutic medicine. Halophytes grow in salt marshes and inland desert with potential to release phenols, flavonoids, terpenes and anti-carcinogenic compound which can be used as traditional medicine [28]. Plant grown under saline condition substantially enhances the secondary metabolites production as reported in many halophytic plants [12, 13]. These bioactive compounds can be potentially used as medicine with importance to restore marshy saline areas for industrial purposes.

## 11 Clean and Carbon Free Environment

Clean and carbon free environment is a necessity of the current world and can be made through lower emissions of carbon dioxide produced by power generation sources using renewable sources of energy such as biofuels and bioenergy. Greenhouse gases such as nitrous oxide, methane and carbon dioxide have been recognized as the prime cause of global climate change, which have received significant global attention. Among these gases, carbon dioxide is considered as the prominent gas which motivated researchers to explore carbon reduction and mitigation strategies by carbon capturing, predicting future carbon emissions through trend analysis, evaluating carbon performance, identifying carbon mitigation opportunities and ultimately achieving zero carbon emissions [1]. The increasing prices and environmental impacts of fossil fuels have made the production of biofuels and bioenergy feedstocks to reach unprecedented volumes over the last few decades. There are growing opportunities and demands for the use of biomass to provide additional renewables, energy for heat, power and fuel, pharmaceuticals and green chemical feedstocks. Biomass from cellulosic bioenergy crops is expected to play a substantial role in future energy systems. However, the worldwide potential of bioenergy is limited, because all land is multi-functional and land is also needed for food, feed, timber, fiber production and for nature conservation and climate protection [27].

## 12 Properties of Halophytes as a Source of Producing Biofuels and Bioenergy

Halophytes can be used as a source of biofuels production and for bioenergy generation. These plants can be grown on marginal/saline lands, beside other industrial applications they present immense utilization potential as a sustainable source of energy feedstock that can be converted into biofuels [5]. A research study was conducted using anaerobic digestion of seven halophytes collected from Kyzylkum desert (Uzbekistan) in batch scale reactors in mesophilic (35 °C) and thermophilic (55 °C) conditions with F/M (food/microorganism) ratio of 0.2. The results showed that halophytic biomass is considered as a valuable renewable source of biogas production. Though high mineral content was detected in the biomass (i.e., $Na^+$, $K^+$, $Cl^-$ and $SO_4^{2-}$), total biogas yield of anaerobic digestion was 60% and were approximately 200–400 mL (at 35 °C) and 300–500 mL (at 55 °C) from 1 g dry mass . Results indicated that 40–60% of total organic matter in halophyte biomass can be decomposed into biogas. The highest yield of approximately 300–500 $m^3$ of biogas from 1 ton of dry mass could be produced from Atriplex *nitens*, Karelinia *caspia*, Suaeda *paradoxa* and Cynodon *dactylon* [7].

## 13 Thermochemical Conversion of Halophytes Biomass

Biomass is among the most promising renewable resources to provide a sustainable solution to meet the world's increasing energy demand by utilization in biochemical and thermochemical conversion technologies. Thermochemical conversion processes such as gasification, pyrolysis, and combustion thermally convert biomass into intermediates that can be used to produce heat energy, liquid fuels and chemicals through biochemical techniques (enzymatic hydrolysis, sugar fermentation). The biochemical route seeks to convert carbohydrates into lignocellulosic biomass to energy carriers for power generation to bioethanol, biobutanol as liquid fuels and into other useful chemicals. The conversion routes for production of heat, power and transportation fuels are achieved via combustion, gasification, pyrolysis, digestion, fermentation (anaerobic digestion to produce bio-gas) and chemical extraction processes of transesterification to produce biodiesel [8].

A research study was conducted on giant reed as a biomass feedstock that has been recognised as a potential biofuel to substitute for coal. Thermochemical treatment of torrefaction (slow pyrolysis) was applied to process the biomass at a slow heating rate under atmospheric pressure, at a temperature ranging from 200–300 °C, under low presence or complete absence of oxygen. The primary objective of torrefaction is to increase the carbon content and diminish the oxygen and hydrogen content per unit mass of a biomass, consequently raising its energy density. Therefore, torrefaction of giant reed was investigated through diverse operating conditions to assist in the displacement of fossil fuel for bioenergy production. The study proposed an analysis on the thermal behaviour and fuel properties of giant reed which has been thermally treated at 200, 225, 250, 275 and 300 °C for 15, 30, 45 and 60 min respectively during a fixed heating rate of 15 °C/min. It was observed that torrefaction upgraded the calorific value (CV) of the biomass but also exhibited a relative mass loss, due to the evaporation of low molecular weight hydrocarbons and moisture content during the treatment. The raw biomass calorific value was 17.31 MJ/kg but the CV obtained after torrefaction carried out at 200 °C increased to 18.80 MJ/kg, while the highest calorific values were obtained in the longest residence time of 60 min for each temperature that is between 18.80 and 24.58 MJ/kg. It was found that increasing residence time and operating temperature, resulting in an increase of the respective gross calorific values of the biomass as well [29].

Another research investigation on pyrolysis of *Achnatherum splendens* L. was performed under three different pyrolysis temperature (300, 500 and 700 °C) to measure the characteristics of biochar, bio-oil, and syngas. Biochar yield decreased from 48 to 24%, whereas syngas yield increased from 34 to 54% when pyrolysis temperature was increased from 300 to 700 °C. Maximum bio-oil yield (27%) was obtained at 500 °C. The biochar were characterized for elemental composition, surface and adsorption properties. The results showed that obtained biochar could be used as a potential soil amendment. The bio-oil and syngas co-products will be evaluated in the future as bioenergy sources. The experimental results suggest that *A. Splendens L.* could be utilized as a potential feedstock for biochar and bioenergy production through pyrolytic route [17].

The non-food plants which can grow using saline resources and have an oil composition suitable for engine efficiency are more salt resistant than *Jatropha curcas* or other glycophytic feedstock to serve in a bioenergy farming system. Cultivation of such plants for biodiesel production has the additional advantage of reclaiming degraded lands with the environmental benefit of carbon sequestration. Data available on salt tolerance range, seed oil content, composition of fatty acid methyl esters (FAME) and engine performance parameters such as Iodine Value (IV), Cetane Number (CN) and Saponification Number (SN) of 20 salt-resistant plants were examined to assess their suitability for use as diesel engine fuel. Most of the test species were perennial from family *Amaranthaceae*, exhibiting high salt tolerance. The quantity of their seed oil yields ranged from 10–30% while nine species contained >25%

oil content by weight. The SN, IV and CN values varied from 130–206, 29–156 and 38–81, respectively. Based on the above mentioned parameters, seven halophytic plant species; *Salicornia fruticosa*, *Cressa cretica*, *Arthrocnemum macrostachyum*, *Alhagi maurorum*, *Halogeton glomeratus, Kosteletzkya virginica* and *Atriplex rosea* appears to be promising biodiesel production candidates [5].

Global crude oil reserves are being consumed rapidly and expected to exhaust by the middle of this century. This realization has led to the introduction of various grades of ethanol supplemented fuel. This necessitates exploiting saline lands to produce non-food ligno-cellulosic biomass (halophytes) which, may be converted into bioethanol without compromising human food production. Halophytes which produce plenty of biomass using saline resources (water and soil) may be an important alternative. Research investigations showed that species like *Halopyrum mucronatum*, *Desmostachya bipinnata*, *Phragmites karka*, *Typha domingensis* and *Panicum turgidum* found in the coastal region of Pakistan, have huge potential as bioethanol crops. These perennial grasses are salt tolerant with high growth rates to produce ligno-cellulosic biomass of good quality (26–37% cellulose, 24–38% hemi-cellulose and <10% lignin) for bioethanol production [3].

Halophytes species such as *Juncus maritimus* contains (41.5 ± 0.3)% cellulose and (31.34 ± 0.2)% hemicellulose on dry solid basis and has the potential to serve as a low cost feedstock for bioethanol production. The maximum concentration of released glucose from *J. maritimus* (53.78 ± 3.24) g/L) by freezing/thawing pre-treatment and enzymatic saccharification (55 °C, pH 5.0 and 48 h) using CellicCTec2 from Novozymes and (49.14 ± 5.24) g/L obtained by dilute acid pre-treatment. The maximum yield of bioethanol from acid pretreated enzyme saccharified *J. maritimus* hydrolyzate by Saccharomyces cerevisiae strain was (84.28 ± 5.11)% of the theoretical yield with a productivity of (0.88 ± 0.16) g/L/hr. The theoretical yield of (90.87 ± 1.94)% with a productivity of (1.04 ± 0.10) g/L/hr for freezing/thawing pre-treated plant and enzymatic hydrolysis by CellicCTec2 was obtained [33].

## 14 Challenges and Opportunities Associated with Halophytes to Produce Bioenergy

The halophyte-based agriculture, where inputs are marginalized land and saline water from sea, has tremendous potential as biofuel and bioenergy feedstock in developing countries. With their remarkable ability to tolerate salinity and limited energy costs associated with their production, halophytes have opened avenues for utilizing barren land for agriculture. Adapting and improving the yield potential of these plants on desert lands provide huge opportunities for the reclamation of the dry/saline lands like Sahara desert, Southern Africa, Thar Desert and dry lands around the coastal regions. However, inspite of successful experimental results and the ongoing efforts to screen and identify most suitable halophytic species, there are several challenges down the road for large scale adoption of halophytes as crop based/bioenergy feedstock. Firstly, identification of region-specific genotypes and adapting them in existing agricultural infrastructure without compromising their yield potential is required. Since, large scale plantation of halophytes has not been attempted, only time will unveil the practical challenges associated with halophyte farming and guide future research directions [30].

Renewable sources of energy from plant biomass are needed to meet the demands for sustainable energy in those countries which face the problems of growing population and economic transitions. Using halophytes for biofuel production may provide an economically feasible and environmentally sustainable solution for producing bioenergy. Halophytes are considered as potential sources of energy, but there are few technical challenges associated with availability of biomass for producing bioenergy on large scales especially from lignocellulose . Advancement in enzymatic valorisation, converging on salt-tolerant enzymes from halophilic microbial species has greater advantage compared to their conventional mesophilic counterparts for faster degradation of lignocellulose present in halophyte biomass. Some halophytes accumulate high levels of salt in their shoots and have undesirable consequences such as slowing down the biomass degradation of feedstock for bioenergy production or inhibiting the enzymatic decomposition of lignocellulose and accelerating the corrosion of reactor components. Measures to overcome these effects include adjusting the organic loading rate in the reactor or co-digestion with conventional plant materials that serve as energy sources. Another option to increase bioethanol yield is to apply salt-tolerant enzymes from halophilic microorganisms to degrade lignocellulose under saline conditions [11].

## 15 Conclusions

Halophytes are salt tolerant plants that can be cultivated on marginal and saline lands to produce bioenergy in the developing world. The halophytes cultivation can also help to reduce dependence on freshwater and does not compete with edible crops causing food crises. There are different types of halophytes that can be cultivated in the developing countries depending on their climatic conditions and mechanism of growth. Genetic modifications can also help to improve the potential of halophytes as bioenergy and biofuel feedstocks . It also shows that using halophytes can establish productive ecosystems and re-greening of natural saline soils which could be a useful approach to valorize and reclaim salt-affected areas and overcome water shortage issue. Constructed wetlands cultivated with halophytes offer the prospective for wastewater treatment combined with production of plants that can be used for bioenergy production. The contribution of halophytes in bioenergy production provides interesting aspects and should be placed in the context of global climate changeand the increasing salinization of lands and water scarcity, which are major challenges for developing countries. Moreover, the production of bioenergy from indigenous halophytes will substantially reduce the import of petroleum crude oil products in the developing countries required for transportation fuels and power generation.

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# Sustainable Energy: Case Study of Cameroon

**Julius Tangka**

**Abstract** The chapter discusses the present day energy situation in Cameroon. It focuses the current energy practices, potentials and official government policies. It also dwells at large on the other potentials that are yet to be exploited. About 95% of conventional energy supply in Cameroon is from hydro sources while about 2.7% is obtained from the burning of fossil fuels. The hydro potential (estimated 20 GW) and 115 Terawatt-hours per year is the second largest in sub-Saharan Africa after the Democratic Republic of Congo. Of this potential, only 3% is currently being exploited. Cameroon forest area occupies about 25 million Ha covering almost 50% of the country. The electricity potential from biomass has been estimated at about 1 GWh. The majority of Cameroonians use biomass for cooking and the estimate for national access to clean cooking solutions is at 23%. Biomass constitutes 66.7% of national energy consumption. Wind energy has not been commercially exploited in Cameroon. A few isolated studies of wind potential have been studied and published. Trends indicate favorable wind speeds for commercial exploitation in the northern and coastal areas with an average wind speed of 5–7 m/s at some sites. In most regions, however, the average wind speed is only about 2–4 m/s at a height of 100 m. The solar radiation in the southern part of the country is about 4.5 kWh/day/m$^2$ while the northern region has values around (5.8 kWh/day/m$^2$). Only about 50 decentralized PV systems with backup battery banks have been installed in Cameroon. One of the most untapped potential is that of vegetable oils either as SVO or biodiesel. The country if blessed with so many oleaginous grains that can act as substrates in an elaborate biodiesel production program.

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## 1 The Overall Energy Situation in Cameroon

Cameroon's location between lat 1° and 13° North as well as longitudes 8° and 17° E makes it a potential renewable energy rich country [9]. This geographical location falls in the humid tropical region with rain forests and many perennial rivers. The most prominent natural feature in this region is the abundant water resource and biomass. Hydroelectricity accounts for over 95% of Cameroon commercial electricity production while 2.7% is produced from the burning of fossil fuels [13]. Cameroon has a hydro power potential of 115 Terawatt-hours per year, but as late as at end of 2019 only 3% of this potential is being exploited. Modeste et al. (2015), reports that only 5% of the hydro potential is being exploited. The electricity is supplied from two main hydroelectric stations, Edea (384 MW) and Song-Loulou (264 MW), located on the Sananga River, and a the Lagdo in the northern parts of the Country. Cameroon's installed electrical capacity was 3.90 billion kWh by the end of 2010 [10, 13]. About 95% of Cameroonians do not have access to electricity. Electricity consumption is 3.3 billion kWhr and only 22% of the country is electrified with the rural areas having only 3.5 electrification coverage [13]. Electricity supply is characterised by unplanned blackouts and constant voltage fluctuation which often lead to destruction of domestic and industrial electrical appliances. The annual electricity growth rate is only about 100 MW of new installations [12]. The national electricity supplier provides only to about 53,000 people out of a population of more than twenty three million. Energy shortage is further compounded by the fact that about 60% of produced electricity goes to the aluminium smelter at Edéa- at subsidised rates. However the overall hydroelectric power potential (about 55 GW) indicates that Cameroon could easily become an energy exporter if all the resources were developed [4]. The present installations are unable to satisfy the needs of the population due to seasonal fluctuation in the volume of the rivers, climate change, the aging nature of installed plants, and the rapidly growing population. The country has three main independent grids in three regions. In 2014, the southern grid transmitted 5,698 GWh, while the northern transmitted 329 GWh and the eastern grid only 56 GWh. Distribution losses have been estimated at more than 31% [12], while transmission losses stand at 6% [13].

The ADB 2017, states that the Cameroonian energy sector is faced with a number of challenges. These include; inadequate production capacity due to delays in investment, an ageing transmission/distribution network, low electrification rates due to insufficient resources allocated to rural electrification, high electricity distribution losses, restricted technical and financial capacities of institutional actors, absence of appropriate instruments to attract private investors, and the lack of planning and feed-in tariff regimes for renewable-based energy production. This means that the energy law in Cameroon needs to be restructured to remove all the bottlenecks. Electrical energy supply is seriously affected by aging plants, some with outdated infrastructure that are no longer in the market. This makes repair and maintenance very difficult. The energy landscape is characterized by poorly developed infrastructure and underdeveloped markets. The lack of feed in tariffs has been identified as the major cause of slow development of renewable Energies in Cameroon.

In trying to solve the acute energy shortage situation, a few decentralised solar power plants have been installed but these serve only a few villages especially in the southern parts of the country. Back up facilities are provided mainly by 30 aging diesel power stations, the largest of which are located in Garoua (20 MW), Douala (15 MW), and Yaounde (11 MW). Most other areas are served by diesel-generated electricity or have no electricity at all. In general, there is a considerable dearth of published work on the potential of other renewable energy sources in Cameroon. This makes development through stakeholder participation very difficult [1]. In spite of this, the energy **consumption** mix studies carried out in 2018 (Fig. 1a), showed that 71.8% is crude **biomass**, 21.1% oil and gas products and 7.2% electricity totaling around 6000 ktoe (Kilo tons of oil equivalent) for the whole country. This shows that energy efficiency is still very low in Cameroon. The country is endowed with abundant renewable energy potentials [9, 14]. The current breakdown by sector is shown in Fig. 1b with the residential sector consuming over 70% while the industrial sector consumes only about 6%.

In 2014, the total energy production was 4.5 hydro, 5.7% natural gas, 50.2% biofuels and waste and 39.6% oil [14]. Good governance and political will are necessary to free the sector if the renewable energy sector will develop in Cameroon [2, 17, 19]. The high corruption rate in Cameroon hampers investments in the energy sector [6]. In 2010, the Cameroon government came out with the strategic growth and development document to guide the country towards emergence by 2035. In this document it was envisaged that by 2020, the energy consumption rate per unit of GDP would reach 37% and energy production capacities would increase to 3,000 megawatts [13]. The situation has not changed and there is serious shortage of energy especially for

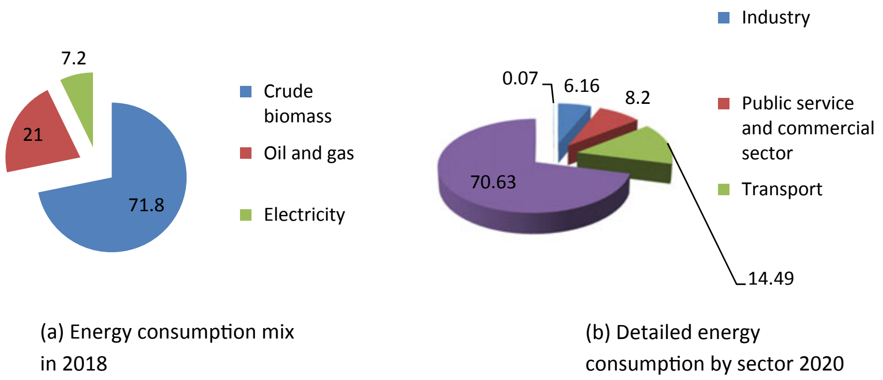


**Fig. 1** Some statistics on energy in Cameroon

industrial activities. The lack of energy is a major bottleneck in economic development of Cameroon since there is a strong statistical relationship between energy and growth.

The development of independent mini grids is authorized in the legal framework in Cameroon, although priority has been given to grid extension. While the regulatory framework permits independent generation and distribution, the opportunity for green mini-grids is limited by a policy focus on grid extension and regulatory limitations [7].

The energy economic and social landscape in Cameroon is managed by some government owned companies with well-defined responsibilities in the sector. These are placed under the Ministry of Water Resources and Energy (MINEE) which is responsible for the development and implementation of government policies in terms of production, transportation, distribution of Water and Energy. MINEE, 2014, describes seven main bodies responsible for controlling the energy sector in Cameroon:

i. The National Refinery Company (SONARA), responsible for refining crude oil and supplying finished products to the local market.
ii. The Hydrocarbons Price Stabilization Fund (CSPH, responsible for price stabilization and equitable distribution of finished petroleum products;
iii. The National Hydrocarbons Corporation (SNH), responsible for oil prospection and exploration as well as management of the State's interests in this sector;
iv. The Electricity Sector Regulatory Agency (ARSEL), to regulate, control and monitor the activities of electricity sector operators;
v. The Rural Electrification Agency (AER), responsible for promoting of rural electrification all over the national territory;
vi. ENEO-CAMEROUN S.A., It is a limited liability company responsible for the transportation and distribution of electricity in Cameroon; (ENEO owns a concession for distribution to over 70% of the communes utilizing the existing grid, ADB [7] and
vii. The Electricity Development Corporation (EDC), which plays a strategic role in the development of the electricity sector by preserving State assets, MINEE 2014.

In order to reduce Cameroon's energy deficit, the Ministry of Water Resources and Energy developed the energy sector strategy. The purpose of the strategy is to improve the energy sectors legal and regulatory framework as well as coordinate activities amongst the various energy stakeholders. MINEE 2014 spells out the responsibilities of the terms of reference of the energy sector strategy i.e. to;

i. develop and guarantee the population's individual and collective access to modern energy services over the long term;
ii. reduce the energy sector's negative impacts and the working burden of women and men;
iii. ensure adequate, efficient, reliable and clean energy supply, everywhere and at all levels of consumption;

iv. improve the country's external energy balance;
v. optimize Cameroon's energy sector efficiency in the use of human capital and inter-sector synergies;
vi. make energy an asset of Cameroonian industry in global industrial competition;
vii. involve financial markets and major industries in the development of Cameroon's energy sector;
viii. make energy a factor of Cameroon's integration; and
ix. reduce the impact of energy on Cameroon's natural, socio-economic and cultural environment. MINEE 2014.

The regulatory framework allows for independent power producers to supply power to the grid, but limits distribution to 100 kW in urban areas and 1 MW in rural areas within ENEO's concession. ENEO is mandated by law to purchase excess energy from independent power producers (IPPs), however this is conditioned on the IPP successfully obtaining authorization from the regulator and negotiating purchase agreements with ENEO [7].

## 2 Hydro Energy Potential

### *2.1 Hydro Energy Production and Distribution in Cameroon*

As earlier mentioned Cameroun has the second highest hydro potential in Africa second only to the Democratic Republic of Congo. The potential has been estimated at 115,000 GWh/year out of which only about 4% is currently being exploited [3]. The theoretical generation potential is estimated at 297 TWh a year [14, 15]. Some geographical features give Cameroon this hydropower potential. Cameroon has eight major drainage basins with many streams that form a dendritic pattern. Each drainage basin has a large river into which small tributaries empty their contents. e.g. the Sanaga is the main stream for the Sanaga Basin, Fig. 2. The plateau located in the northern parts of the country has two hydrographic areas on both sides. The main water catchment for the northern parts of the country is supplied by the Niger and the Chad basins. Likewise the Atlantic and the Congo water sheds provide for the southern parts of the country. The country is drained by some major rivers like the Sanaga, Nyong, Ntem, Mungo and Wouri which all flow into, the Atlantic basin. The River Benue emanates from the Niger Basin and has a length of 1,400 km, 350 km of which flow through Cameroonian territory) conveying about 5.5 billion $m^3$ of water per year [13]. The total area occupied by flood plains is 55,000 ha while lakes and rivers occupy 300,000 and 150,000 ha respectively. Coastal mangroves also occupy a considerable area. There is abundant rainfall with an average of about 2000 mm in the equatorial zone stretching from Lat 2° and 6° North. The equatorial zone is characterized by abundant rainfall with an annual average of 2,000 mm of rainfall. Debunscha town, village located in this region is the second wettest town in the world

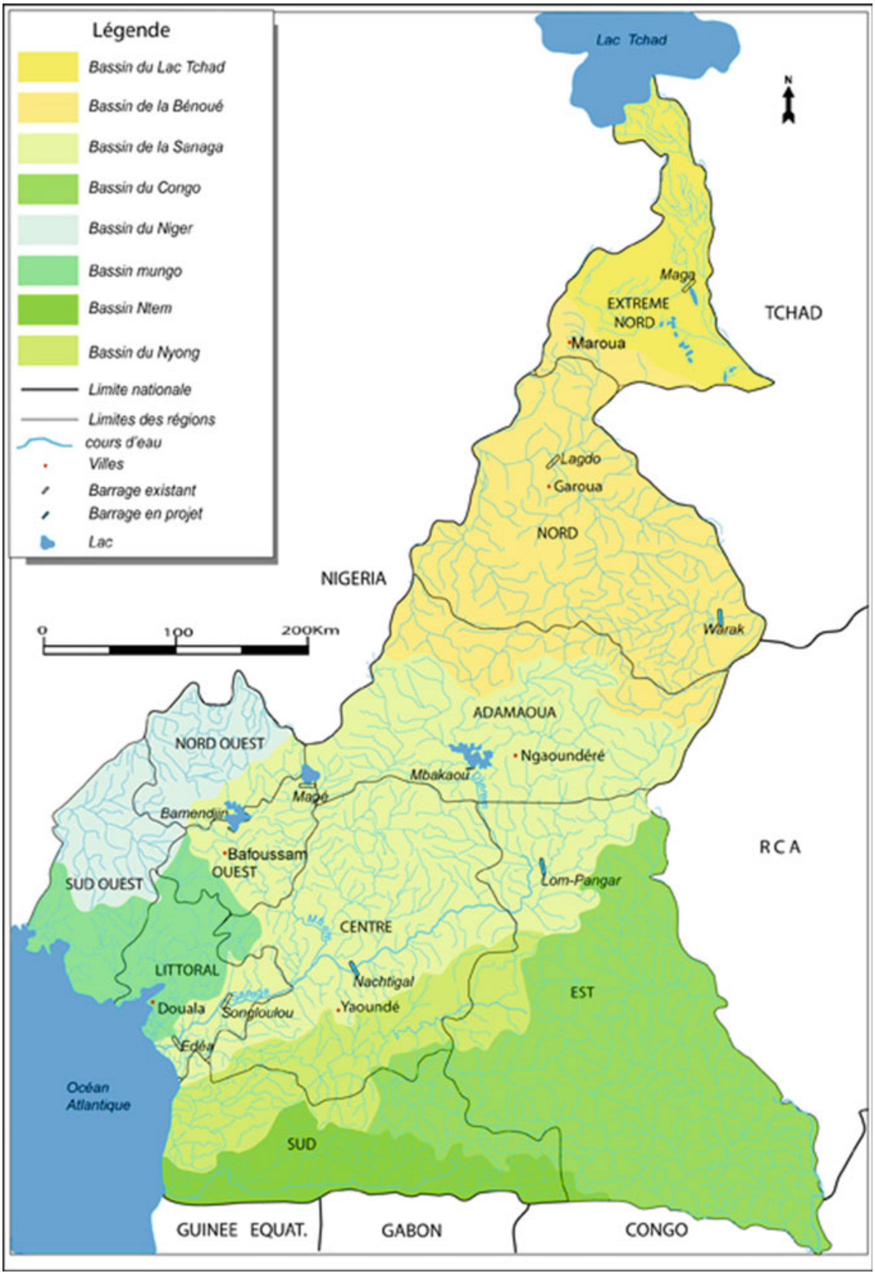


**Fig. 2** Map of Cameroon showing the huge hydro potential and the major drainage basins. *Source* https://cameroon-tour.com/geography/drainage.html [14]

with over 10,000 mm of rainfall. All these abundant water resources have contributed to give the country a considerable hydro energy potential.

The three main existing hydroelectric infrastructures (Lagdo, Edéa, Songloulou) all contribute to an installed capacity of 732 MW. The infrastructure under construction (Lom Pangar, Memve'ele, Mekin and Menchum) will inject nearly 340 MW into the electricity network. The planned infrastructure (identified: Nachtigal 300 MW, Mbakaou 250 MW [3], Bini at Warak 75 MW, Song Mbengue, Grand Ngodi) will provide an installed capacity of 7590.54 MW. Other potentials as listed Ackom et al. [3] include, Grand Ewang 1100 MW, Vogzom 80 MW, and the Ngasoona rural Electrification project with 2 MW potential.

## 2.2 *Micro Hydro Installations*

Approximately 260 small hydro (representing approximately 360 MW) have been identified by several studies [7]. Sixty-seven out of 270 small hydro sites identified in the PDER—with a total generation potential of 317 MW. So many mini grid micro hydro schemes have been successfully installed especially in the North West and West regions of the country [15, 20]. The bulk of them are installed by the NGO ADEID and they range from 25 kW to about 100 kW. The main features of these are a dam, a forebay tank, a penstock, a turbine, a synchronous generator and a mini grid. Table 1 shows some of the mini grids, their capacities and the installation body.

**Table 1** Some functional micro hydro installations in Cameroon

| Location | Power KW | Installation Body |
|---|---|---|
| Dschang—Chuadeng | 25 | ADEID Bafoussam[1] |
| Baleng—Nefelem | 10 k | |
| Mararem | 20 | |
| Wabane | 20 | |
| Batibo-kuruku | 20 | |
| Ngewir Shiy Jakiri | 30 | |
| Ngondzen Kumbo | 25 | KUDOC NGO[2] |
| Bangang | 100 | ACREST |
| Dschang; Fonjumetaw | | Expatriates (French; German) |
| Bapi Bamoungoun | | Expatriates (English) + local craftsmen |

[1]Action pour un Développement Intégré et Durable) is a Bafoussam based NGO
[2]Kumbo Development Organisation

### 2.3 Pico Hydro Exploitation

Nearly 407 watercourse sites have been identified as potential sources for the production of small hydroelectricity throughout the territory of Cameroon. With the exception of the Far North Region, these sites are scattered in the nine other regions of Cameroon. The installed powers vary from 0.005 to 10.28 kW. One other hydro application being carried out in Cameroon is the pico hydro energy installation. This is done in small streams where a height of 1.5 m can be guaranteed. A few trials were installed in the West region of Cameroon by the Renewable Energy laboratory of the University of Dschang. The power output is very small but can run a single household. They are available from 300 to 1000 W capacity.

### 2.4 Problems Affecting the Use of Hydro Energy in Cameroon

Just like in all other renewable energy options, the use of hydro energy in Cameroon is facing a lot of problems. There are environmental concerns with the construction of large as well as small reservoir dams. In the Lom Pangar project, the Cameroon government foresaw an extra generation of power during the dry periods by an estimated 105–216 MW. In the event of any over flow, the Lom Pangar dam might flood one of the Africa's largest biodiversity reserve forest the Deng Deng. During the construction of the Chad Cameroon pipeline project, protection of this forest reserve which is the only hard wood reserve in Africa, was a very expensive task in the project budget.

Displacement and resettlement of villagers during the construction of dams is always a difficult and expensive task. This is always one of the conditions for the acquisition of financing for every hydro energy project. Small dams for micro hydro systems produce stagnant water favouring the growth of mosquitos and consequently a high prevalence of malaria. Malaria is the number one killer diseases in tropical Africa. In some areas in the West Region of Cameroon rivers for micro hydro projects pass through secret forests that have very significant socio cultural values in the lives of the villagers. There is often no public access to these forests. This renders the installation of energy infrastructure difficult if not impossible. Waterfalls are also regarded in this region as secret places and the abodes of some gods that must not be trespassed for what every reason. Villagers are therefore often faced with the dilemma of destroying traditional values in the quest for energy.

The construction of dams disturb the ecosystem sometimes displacing separating some aquatic organisms and distancing them from their feeding grounds. For example some fish that migrate up stream for feeding purposes are blocked by the dams.

There is no well-developed comprehensive regulatory framework to accompany private sector investments in hydro as well as other forms of renewable energies.

There are no feed in tariffs established for energy sales so the idea of encouraging people to invest in hydro is unrealistic.

There is serious lack of data for feasibility studies. State sponsored surveys are not available to the general public. Many possible sites are found in enclave areas without road networks that could facilitate investments.

## 3 Biomass Potential

### *3.1 Biomass Distribution in Cameroon Per Region*

Cameroon's biomass capacity derived from its forest foliage, palm oil, rice, and sugar waste has the potential to generate an additional 700 GWh for the national grid. The Rural Electrification Master Plan estimates a potential of 1000 GWh, 700 GWh of which could be injected into the power network [7]. The country is endowed with great biomass potential [3]. It has the third largest biomass potential in Sub Saharan Africa indicated by the over 25 million Ha of forest [14, 17]. The biomass potential is estimated at 6.3 billion tons. Over 80% of Cameroonians use biomass for heating and cooking. Much of the biomass in Cameroon is exploited for heating and cooking with very little for electricity generation [9]. The forest is threatened by massive deforestation for agriculture and urban expansion. The annual deforestation rate has been estimated at 200,000 Haper year [14, 17], with only 3000 ha being regenerated every year. So much waste is generated from agro industries and only a few of these industries use the waste for electricity generation. The major residues include palm kernel waste, maize, cassava, banana, sorghum, rice millet wheat sugarcane, beans, cocoa coconut coffee and rubber. Approximately 30 biomass (representing approximately 35 MW) sites have been identified across a number of studies [5].

### *3.2 Case Studies of Some Isolated Decentralized Biomass Plants*

A total of 12.8 kW is currently being produced by 5 agro industries using steam turbines. These are mainly from palm oil, cotton and sugar factories. Modern bioenergy remains untapped in Cameroon because of lack of availability of biomass data and gaps in existing policies [3]. Environmentally benign residues amount to 1.11 million bone dry tons per year with a potential of providing 0.12–0.32 billion, litres of ethanol able to displace 17.6–48% national gasoline consumption in the transport sector. These residues equally have a potential of producing 0.8–0.22 billion litres of biomass offsetting 16.8–44.7% of diesel fuel consumption. Table 2 shows some of the biomass potentials in Cameroon. However the lack of credible statistics makes it difficult to have the exact values.

**Table 2** Energy potential from some biomass sources in Cameroon

| Biomass source | Region where applicable | Quantity | Potential energy value GWh |
|---|---|---|---|
| Forest residue | East and South | 500,000 $m^3$ | 720 |
| Sugar cane | Center and East | | 200 |
| Palm oil | Litoral and South West | 270,000 tonnes | 121 |
| Rice | North West, West, South West, and Far North | 22,000 tonnes | 12 |
| Cotton | North and far North | 250,000 | |

### 3.3 Some Traditional Technology Applied to Biomass Exploitation and Use in Cameroon

Crude biomass consumption in Cameroon accounts for over 73% of the energy consumption mix. Crude biomass is consumed using various energy inefficient stoves and fireplaces. The majority of the cases are the traditional three stone fireplaces. The government and some non-governmental organizations have however been promoting the use of energy efficient stoves especially in the Sahel Region where biomass is scarce. Viyoi and Tchouamou 2018, describe the various traditional energy efficient stoves in use in the Far North Region of Cameroon. As crude as these technologies look, they are the main infrastructures that consume over 80% of Cameroonian biomass. These include the traditional three stone fireplace, the improved C shaped mud stove, the simple metallic stove, the *foyer Centraficaine*, and the improved cone shaped stove. These stoves are shown in Fig. 3.

### 3.4 Environmental Problems Associated with the Use of Biomass

The indiscriminate consumption of biomass is threatening the environment. As earlier stated, the annual deforestation for energy, agricultural expansion and urbanization has been estimated at 200,000 Ha per year with an artificial regeneration rate of only 3000 Ha per year. This gradually reduces the country's carbon foot print. This makes the use of biomass as an energy source very unsustainable in the long run. Emphasis should therefore be placed on the consumption of agricultural residues and the improvement of biomass technologies like briquetting of saw dust and the introduction of modern biomass stoves.


**Fig. 3** Some of the biomass stoves used in Cameroon. **a, b** Metallic stoves, **c** wire grate charcoal stove, **d, f** improved three stone stove (All pictures by Viyoi Catherine TANGKA reproduced with permission from Viyoi [21])

## 4 Wind Energy Potential in Cameroon

### *4.1 Wind Distribution Per Region*

The wind energy sector is not well known in Cameroon and the country has no previous wind power generation [12]. Based on available literature, very few studies have been accomplished on performance evaluation of wind turbine for electricity generation. Wind energy is possible in the North and Adamawa regions as well as coastal regions [9]. Wind energy at mountain ridges can be utilised to improve access to clean energy in Cameroon around the far North Region [12]. Preliminary studies show that wind energy can be utilised in the Northern as well as the Littoral regions of the country where average wind speeds of 5–7 m/s at 100 m above the ground

[14]. The wind speeds greatly reduce as one moves from the North to the South. Offshore wind farms have been suggested for Kribi. It has generally been concluded that Cameroon is not a windy country for commercial wind energy exploitation. Analysis [12] of a 28 year wind speed data measured at 100 m above ground level using the Weibull probability density function concluded that exposed hilltops and ridge-tops ranging from 100 to 300 m above ground level around Kouseri and Maroua are suitable for wind turbine applications. Arreyndip and Joseph [6], compared wind energy potentials of three cities in in different coastal regions of Cameroon and found that Kribi in the south region is the best. They proposed the use of Savonius wind turbines for standalone energy needs as well as the installation of up to 100 kW wind turbines ion some sites. Benyoh et al. [8] proposes the multi criteria analysis with PDCA cycle for sustainable Energy planning in hybrid mini systems in Cameroon. However, the and the project is reportedly under development.

### 4.2 Use of Micro Wind Turbines in Cameroon

The only practical example of non-commercial wind turbines operating in Cameroon are the many off grid micro wind turbines developed at the Renewable Energy Laboratory of the University of Dschang. The permanent magnet wind turbines are 1–2 kW capacities while the successful induction motor type are 2–10 kW. These have been installed in various regions. These micro wind turbines operate in off grid standalone systems with a battery bank. Some 25 and 100 kW wind turbines (induction motor type) are currently being experimented at the University of Dschang in the West Region. Some of these machines can be seen in Fig. 4.

## 5 Solar Energy Potential of Cameroon

### 5.1 The General Solar Energy Potential

Little research has been carried out to measure solar radiation in Cameroon [7]. However Cameroon has great solar energy potential estimated at 3491 h of sunshine a year and a solar radiation of 1934 kWhm$^{-2}$ in the Far North Region of the country [9]. It has been estimated that Cameroon is capable of producing up to 2327.5 TWh of electricity per year from solar energy alone and this is about 200 times the possible energy from Hydro sources [9]. The irradiance of 5.8 kW/day/m$^2$ is reported for the northern parts of the country while the southern parts have an average of 4.98 kW/day/m$^2$ and a national average of 4.2 kW/day/m$^2$. Figure 5 shows the PV potential power of Cameroon with solar potential increasing gradually from the south to the northern parts of the country. Njoh et al. [17] reports that the mean radiation in this region is 4 kW/m$^2$/day in the forested area and 8 kW/m$^2$/day in the

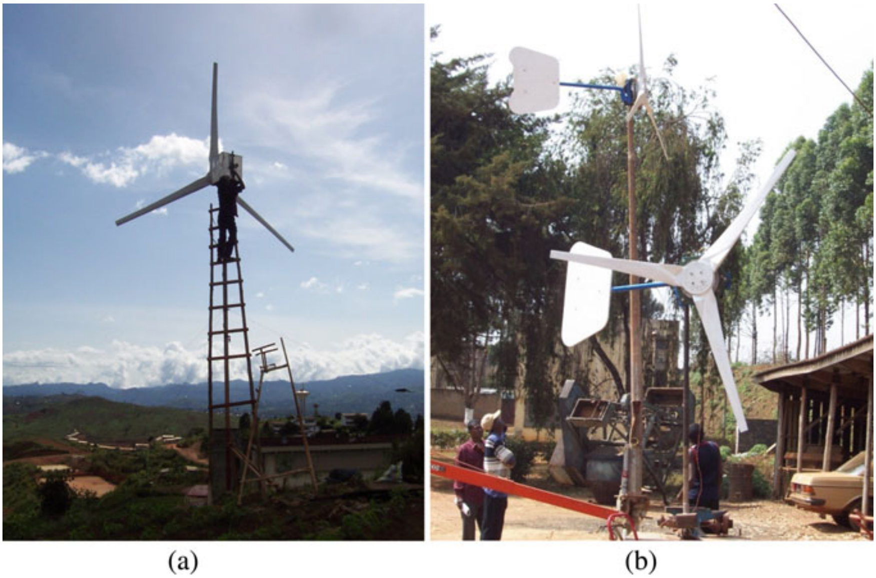


**Fig. 4** Wind turbine testing at the University of Dschang Wind Farm. **a** 50 kW induction motor type. **b** Permanent magnet (1.5 kW). *Source* Arthur

in the lake Chad area. Ayompe and Duffy [7], estimate that 900 trillion kWh of solar energy reaches the country per annum.

## 5.2 Current Installed Capacity

About 50 mini grid commercial PV installations exist in Cameroon today supplying electricity to some villages [17]. An ambitious government-led solar mini-grid program in partnership with the Chinese company, Huawei, aims to electrify 1000 rural population centres. A first phase aimed to electrify 350 centres by the end of 2017 [5]. A 72 MW solar plant in Mbalmayo is being developed by JCM Greenquest and there are equally thousands of domestic small scale off grid stand alone installations for domestic and industrial applications. At the same time, there are negotiations to install two 500 MW, and one 100 MW minigrid systems in the country. To promote solar energy use, the government eliminated the value add tax, VAT, from solar equipment in 2012 [14, 16]. An Israeli NGO "Innovation Africa", using funding for the UNICEF and support from the Embassy of Israel in Cameroon is installing solar systems in villages and hospitals. The project has impacted the lives of over fifty thousand people in the East Region [26]. In 2017, the Bank of China agreed to invest $123 million for the country's solar rural electrification program, and at the same time ENEO the national electricity supplier planned to construct

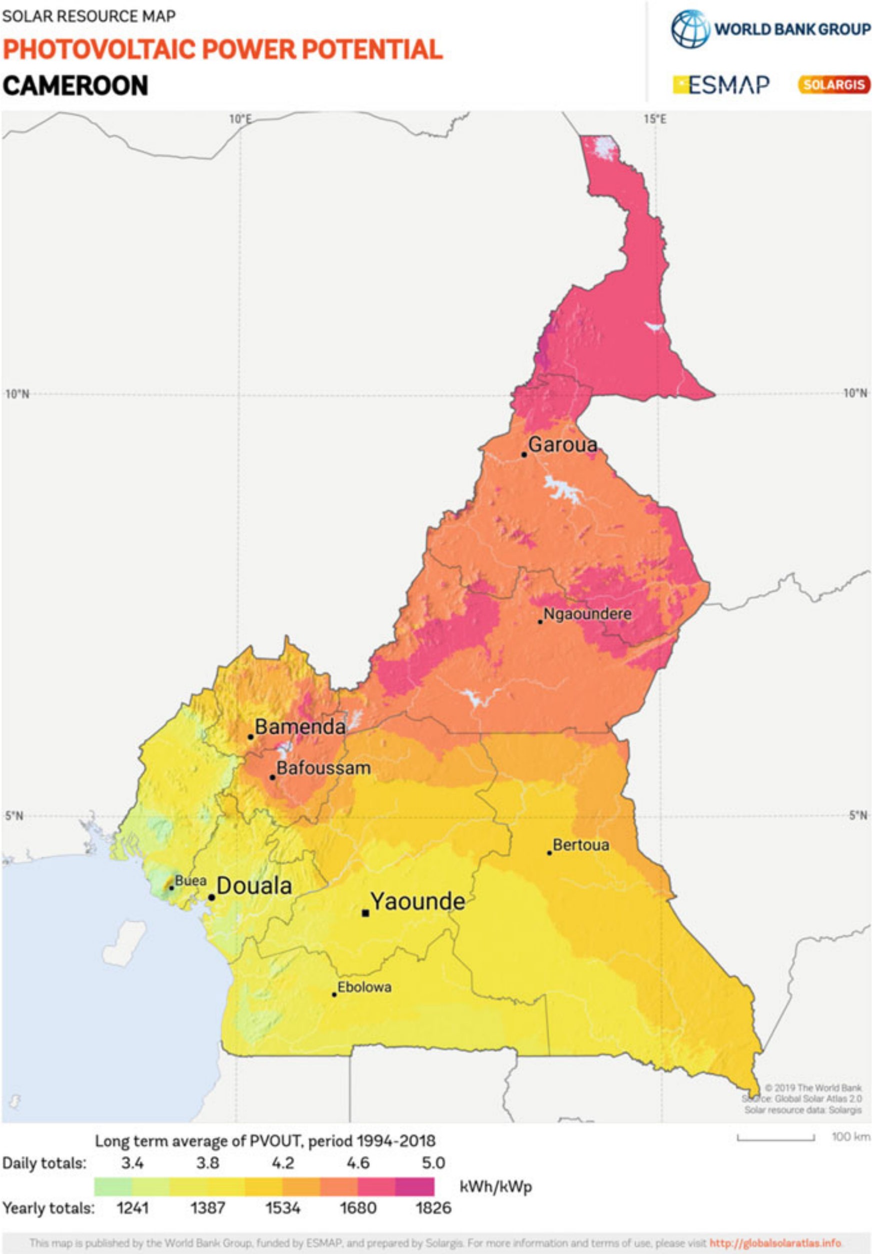


**Fig. 5** PV potential power potential of Cameroon. *Source* https://globalsolaratlas.info/download/cameroon

solar plants to a total capacity of capacity of 35 MW [23]. The first PV/diesel hybrid commercial hybrid plant was inaugurated in Djoum in the South Region on the 25th of January 2018 by the ENEO the national electricity supply company. The plant has 186 kilowatts peak and built on nearly 3500 $m^2$ of surface area [24] and is connected to 1115 KW thermal power plant. This project has given the villages the opportunity to have access to drinking water, basic health care, education and other essential services that rely heavily on electricity.

### *5.3 Problems Associated with Solar Energy Implementation in Cameroon*

One of the major problems faced by the solar industry in Cameroon is the absence of local manufacture of any of the components. All infrastructures are imported from China, Europe or America. This affects installation time and cost because after feasibility studies the equipment has to be imported. Supply takes about three months by sea and at times clearing from the major seaport in Douala takes a few weeks. Because very small quantities are imported at a time, the installation cost is bound to remain high. However, the scraping of the value added tax by the government in 2012 considerable reduced the cost of solar installation in Cameroon.

There is no quality control for solar products in Cameroon. It is not uncommon to see solar modules in the market that operate at peak values far below the values claimed by the manufacturers. There are lots of unreliable solar batteries in the local markets and some government sponsored projects like solar street lighting failed a few days after installation. Poor quality inverters and charge controllers also flood the local markets. All these problems have made some people to have very little confidence in solar energy as an option.

As in all other renewable energy options in Cameroon the lack of feed in tariffs has made private investment for grid connection impossible. Many private firms are willing to invest in grid connected solar energy investments but government has not established the purchase price per kWh of electricity from renewable sources.

## 6 Biofuels Potentials in Cameroon

### *6.1 Survey of Possible Crops for Biofuel Production in Cameroon and Their Yields*

The Cameroon government has in several instances indicated her willingness to embark on an elaborate biofuel program. This became necessary when the prices of petroleum products skyrocketed in 2008. However as usual, many African countries show spontaneous and sporadic interest in biofuels, and this usually dies down when the factors causing the interest die down. The government has planned biofuel production from cassava and palm oil. Earlier attempts have been made to produce biofuels from palm oil. However as Tangka et al. [18] caution that developing countries embarking on biofuel production must be sure of a local market. This often means the development or the acquisition of machines that use these biofuels. Some NGOs in Cameroon that attempted biofuel production of straight vegetable oils SVO, soon discovered that there was no immediate local market and the projects were abandoned. The interest in biofuels has remained in political speeches with no real action on the ground.

Cameroon is blessed with so many oleaginous crop varieties that can be very useful as biodiesel feedstock. The Renewable Energy laboratory of the University of Dschang is carrying out exploration to identify suitable plant species to serve as feedstock. The laboratory is also developing technologies that can use these fuels at the village level like biofuel fired ovens, and bi-carburation technologies for small engines etc.

Some plant species that are used commercially for biodiesel production in countries like India, Korea, Burkina Faso and Mali, are abundantly found in Cameroon and grow in the wild unattended to. Jatropha, Castor oil plant, hinder agricultural activities as they are the major weeds in some farm lands. Amongst the possible plant species identified are castor oil, jatropha, soybean, sunflower oil, cotton seed oil, melon seed, Njangsa (*Ricinodendron heudelotii*), palm kernel oil and hundreds of other plants growing in the wild unidentified. There are other possibilities of producing biofuels from insect larvae. The Renewable Energy Laboratory of the University of Dschang has recently completed research on the production of biodiesel from the larvae of raffia palm weevil (*Rhynchophorus phoenicis*) likewise the rapid production method for the of the larvae.

## 7 Environmental Issues Surrounding the Use of Sustainable Energy in Cameroon

### *7.1 Emissions and Environmental Protection*

Emission from the consumption of fossil fuels stood at 6.224 million tonnes in 2012 [14]. While Akom et al. [3] reported green house gas emissions of 82 Mt $CO_2$ e in 2013. Temperatures have increased in Cameroon since the 1930 where a net increase of 0.95 °C was registered between 1930 and 1999. Environmentally, Cameroon has a national policy for forest management and biodiversity conservation [16]. There are so many protected areas and also forest regeneration projects that planted more than 3 million trees. The creation of protected areas is helping in carbon sequestration and therefore contributing to mitigation of global warming.

Verification and certification in forest exploitation are compulsory in Cameroon. The signing of Voluntary Partnership Agreement (VPA) of the European Union Forest law enforcement, African Forests Law enforcement and trade as well as the Governance and Trade (FLEGT) program is clear indication that the Cameroonian government is environmentally conscious.

Energy consumption in the residential sector in Cameroon is up to 70% of total energy consumption, somehow higher compared to the world level of about 27% [11]. The consumption of energy by the residential sector has considerable environmental impacts. As built environment promises to expand in Cameroon the green house gas emission should be expected to rise.

### *7.2 Review of Legislations and Policies Affecting the Sustainable Exploitation of Energy in Cameroon*

The energy sector in Cameroon is governed by some laws that regulate the sector. The following are some sections of the energy law that give a picture of how the sector operates. It also shows the readiness of the government to protect the environment while serving power to the people.

The law on electricity promulgated on the 8th legislative period of the legislative year 2011 and precisely during the 3rd ordinary session (November 2011). The law governs the electricity sector with a view to ensuring its modernization and development. It is applied to the generation from any primary or secondary energy source, the transmission, distribution, supply, importation, exportation and sale of electricity by any corporate entity or individual in Cameroon.

In this regard, the law:

- lays down the conditions for storing water for electricity generation, the generation, transmission, distribution, importation, exportation and sale of electricity;
- establishes the basis for fair competition in the electricity sector so as to enhance its economic efficiency;
- lays down the procedures for checking the fulfillment of specific obligations incumbent upon operators engaged in non-competitive activities;
- specifies the rules governing environmental protection in the electricity sector;
- lays down the rules governing the protection of consumers' interests in terms of prices, conditions of supply and safety of the services; and the lastly
- guarantees the continuity and quality of services.

### *7.3 Analysis of the Energy Law in Cameroon*

A critical analysis of some of the sections of the energy law brings out some revelations.

- The energy law is designed only around electricity form hydro sources and as such, attempts to commercially produce electricity for sale to the national grid using other sources of renewable energies might have problems. This can be seen in section. 3
- Sections 3, 8 and 9 dwell at large on environmental protection showing that Cameroon is environmentally conscious in the quest for energy.
- In section 9 the environmental impact assessment is the responsibility of the operator. This brings about a serious bottle neck in the private sector investments in the renewable energy, because environmental impact assessment is a very expensive and sometimes a subjective activity. Getting such a document validated by competent government authorities can be an uphill task in Cameroon.
- In section 15 paragraph 2, and section 31, the use of the water stored by the holder of a license to store water for the generation of electricity shall be subject to the payment of a fee whose amount as well as conditions of collection and distribution shall be laid down by regulation. This is tricky because ever since the promulgation of this law, feed in tariffs have never been established in Cameroon. Therefore potential investors cannot even carry out feasibility studies.
- Equally sections 18, 19 20, 21, 22 and 41 as well as many other sections have no texts of applications. In Cameroon, a law without a text of application cannot be exploited by individuals against the state. Some laws have had their texts of application enacted after 10 years.
- Section 68 reveals that the government is conscious of energy efficiency which can contribute to mitigation of global warming.

## 7.4 Review of International Treaties Signed and Ratified by Cameroon on Energy and Environment Exploitation

The Cameroonian Parliament decided on 10th June 2016, to authorise the president of the republic to issue a decree to ratify the agreement which was signed by Cameroon on 22 April 2016 on climate change at the end of COP 21. In this agreement, Cameroon took the commitment of reducing by 32% its gas emissions by 2035, based on the reference date of 2010 [22].

Cameroon is equally signed and ratified the following international treaties.

- Biodiversity;
- Climate Change-Kyoto Protocol;
- Desertification;
- Endangered Species;
- Hazardous Wastes;
- Law of the Sea;
- Ozone Layer Protection;

- Tropical Timber 83, Tropical Timber 94;
- Wetlands; and
- Whaling.

## 8 Conclusions

In this chapter, we discussed the present day energy situation in Cameroon. It is seen that about 95% of conventional energy supply in Cameroon is from hydro sources while about 2.7% is obtained from the burning of fossil fuels. Cameroon has the largest hydro energy potential in Africa south of the Sahara (20 GW) and 115 Tera Watt hours, second only to the Democratic Republic of Congo. Only 3% of this is exploited. The energy mix shows 71.8% crude biomass, 21% oil and gas and lastly 7.2% electricity. The energy consumption pattern shows that 70.8% is used in residential area, followed by 14.49% in transportation while the industrial and public sectors take only about 8.2%. There are a number of thermal plants scattered all over the country some of which act as backup to the national grid. A few solar plants have been installed off grid to serve some communities. There are other potentials like wind, biomass, micro hydro and biofuels but they have largely been under tapped. Cameroon has a good number of energy laws that govern the sector but some of the laws are responsible for poor performance of the energy sector. Lastly, Cameroon has ratified a good number of international treaties which shows that the country is ready to exploit energy in an environmentally friendly manner.

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# Optimizing Energy Use Efficiency for Agricultural Sustainability

**Anirban Pal, Anirban Nandy, Shiladitya Dey, and Piyush Kumar Singh**

**Abstract** Energy is a critical prerequisite of modern society. Access to adequate energy resources shapes the socio-economic status, welfare of individuals and nations alike. However, ensuring efficient utilization of energy and its continued access for everyone is one of the most pressing issues that we face today. The agricultural sector consumes a sizeable portion of energy in terms of fossil fuels, chemical fertilizers, human labour, and electricity, which are used in production. Inefficiencies in production processes lead to over-utilization of these energy resources and generate undesirable outputs, such as agricultural wastes and greenhouse gas emissions (GHGs). A detailed farm-level energy analysis could provide insights regarding how to optimize energy consumption. The primary goal of the chapter is, therefore, to elaborate the concepts energy analysis and its importance in agriculture to gauge farm efficiency and discuss possible techniques for efficient energy management at the farm-level that will ensure the sustainability of agriculture in the context of developing countries. Lastly, we look at a case of paddy farmers from India and measuring their energy efficiency through the benchmarking approach to identify the best management practices employed by proficient farmers with the help of empirical data collected through field survey. This chapter provides actionable information for lawmakers to help us devise policies that can meet the increasing energy needs of their growing economies while reducing the adverse environmental effects of energy production systems.

**Keywords** Energy and environment · Energy efficiency · Energy management · Energy analysis · Energy indices · Energy optimization · Agricultural sustainability

## 1 Introduction

Energy is an indispensable necessity for existence in modern society. In today's world, access to energy can shape the level of economic development and overall

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well-being experienced by an individual. However, ensuring its access for everyone is a difficult task. Conversely, global energy systems tend to have severe environmental implications in the form of depletion of non-renewable resources and greenhouse gas (GHGs) emissions. Human activities have been estimated to be contributing nearly 8.1 billion tons of $CO_2$ into the atmosphere annually of which more than 80% is from burning fossil fuels and remaining 20% is due to large-scale deforestation [5]. Every economic activity, ranging from agriculture and industry to transportation and communication, requires energy. However, non-renewable sources (oil, coal and natural gas) primarily regulate our energy systems, which has raised concerns regarding their depletion in the near future, alongside creating severe climate change-related issues.

Rapid economic growth in countries around the world has bolstered the demand for commercial energy. As a result, the consumption of commercial energy has increased more than three times globally over the past three and a half decades. Sector-wise analysis done by the International Energy Association (IEA) in 2016–17 revealed that the share of the commercial energy consumed by the industrial sector has declined by 9%[1] since 1980–81. In contrast, the share of the agriculture sector has climbed up 5%[1] during the same period. Accordingly, energy use in the agriculture sector registered the highest growth in this period. High economic growth among developing nations of South Asia, like China and India, also has a direct impact on the global energy demand, which grew twice as rapidly in 2017 as compared to 2016[1].

Furthermore, the energy intensity (i.e. the ratio of energy use to GDP) of China and India, in particular, has been the highest in the world since 2000 as can be seen in Fig. 1. Though the rate of energy intensity improvement has slowed down to some extent, it is expected to keep growing. The United States of America stands out as an exception, with its energy intensity reducing in the year 2017–2018. Stringent energy policy regarding the use of non-renewable energy sources coupled with slow economic growth could be responsible for this change. However, the global energy intensity projections until 2040 are likely to remain positive for all regions, with India and China at the top. Consequently, policy measures will probably fail to contain the increasing rate of energy use intensity, in view of the Sustainable Development Goals (SDGs), if efforts are not directed towards energy conservation through the judicious allocation of energy resources.

South Asian countries house some of the largest populations in the world, with over 1.9 billion people spread across 5.2 million $km^2$ of land area. Within South Asia, India is the has the largest population which is set to cross over 1.35 billion people by 2025, and its population is projected to grow steadily in the future because of the high population growth rates. This exploding population has evident implications for

[1]Data has been taken from the World Energy Outlook (WEO) reports published by the IEA. The WEO reports provide extensive data on energy consumption and energy-related emissions based on market data, for countries and regions around the world (https://www.iea.org/reports/world-energy-outlook-2019).

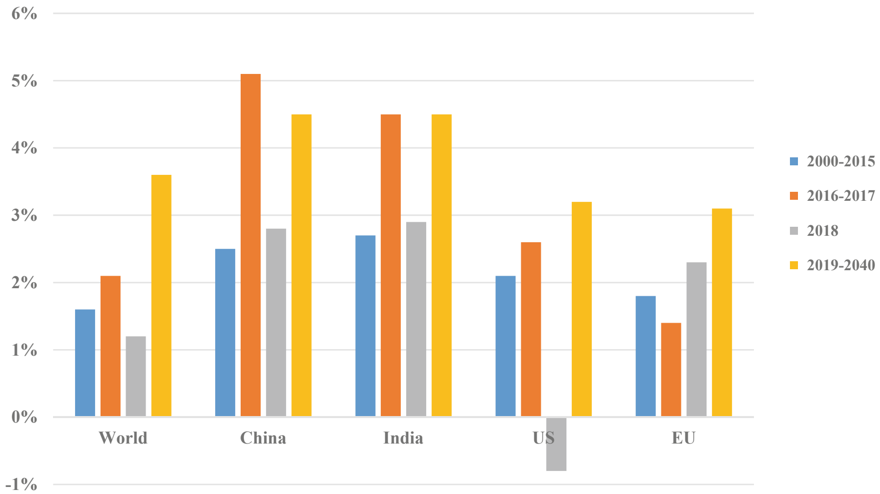


**Fig. 1** Annual average primary energy intensity improvement in key regions of the world under the Sustainable Development Scenario, 2000–2040[1]

national food and nutritional security. The Global Food Security Index[2] (GFSI) in 2018, ranked India at 76th position out of 113 countries assessed. UN-India reported that nearly a quarter of the world's hunger burden is borne by India alone which is reflected on the Global Hunger Index[3] (GHI) in 2019 as well, with India ranking 103rd out of the 119 countries on that list. Hence, apart from increasing agricultural productivity, ensuring the sustainability of natural resource inputs like land and water is also imperative to maintain adequate levels of agriculture in the region.

Energy is intricately interlinked with agriculture, and energy use within agricultural production systems plays a vital role in ensuring food security. Agriculture typically produces both desirable outputs in the form of biomass and undesirable outputs like GHG emissions due to fertilizer application, land-use change, electricity and fuel consumed, all of which contribute towards global climate change. Climate change, in turn, affects agriculture as well, especially small and marginal farmers from developing nations, with erratic rainfalls, natural disasters, accelerated soil erosion and a rise in sea-levels thus endangering global food security. Therefore, judicious use of energy in agriculture can not only help address environmental security concerns but ensure food security for the masses.

Farming utilizes energy directly from electricity and fossil fuels, bio-energy from seeds and organic manure, mechanical energy from human, animals and machinery,

[2]The Global Food Security Index (GFSI) formulated by the Economist Intelligence Unit (EIU) measures the drivers of food security in terms of affordability, availability, and quality, across both developed and developing countries.

[3]The Global Hunger Index (GHI) has been calculated based on the data from various UN and multilateral agencies to capture the multi-dimensional nature of hunger in terms of undernourishment, child mortality and child undernutrition.

as well as chemical energy stored in fertilizers and pesticides. The amount of energy consumed on-farm defines the scale and intensity of agriculture. With an increase in global population, usage of energy in the agricultural segment has improved considerably. Improvements in agricultural energy use have resulted in the maximization of agricultural yields while minimizing labour-intensive farming practices. Effective and efficient use of energy is, therefore, the key to sustainable agricultural production and development, as it meets the demand of the present population, alongside mitigating the harmful effects of agriculture and preserves the precious resources for the future generations.

The environmental footprint of high energy-intensive agriculture is another significant factor to be considered while trying to gauge the effects of energy use in agriculture. In order to assess the energy use efficiency of different agricultural inputs and outputs, a common unit is required against which different aspects of agricultural systems can be measured and compared. To this effect, all inputs and outputs could be converted in terms of energy equivalent. Energy use efficiency can then be calculated by comparing the amount of energy consumed with the amount of energy produced while cultivating a particular crop. Because of its inclusive approach, energy analysis can be implemented as a useful indicator of long-term and environmental sustainability. Sustainability of agricultural production systems can be ensured through effective energy management, which not only increases productivity, contributing to the economy but also enhances competition and profitability among rural communities with added environmental benefits.

The present chapter attempts to build on the extant research by first evaluating various inefficiencies of energy use within an agricultural production system and examining them from an energy management perspective. Insights regarding the sources of these inefficiencies will serve as the first step for farmers and policy-makers to improve the farm level energy utilization. In the following section, key theoretical concepts about energy and environmental footprint of agriculture have been elaborated, in the context of developing countries. Subsequently, the concept of energy analysis is operationalized, and methods used for its computation are described through a case study. Finally, the optimization method is applied to the collected primary data, and the results are objectively analyzed to draw valid conclusions.

## 2 Energy Security in Agriculture

Economic forces largely govern the nature and amount of energy used in any sector, including agriculture. Profit-driven agriculture of the modern era is moulded by the interactions of demand and supply forces, in developed and developing countries alike. The difference lies in the fact that agriculture in developed countries, is mostly technology-driven, which constitutes only a fraction of agriculture in developing countries. In developed nations around the globe, energy and its complementary inputs are cheaper, and hence, they have substituted land and labour inputs. On the other hand, in developing countries, labour is notably cheaper compared to the capital-intensive energy-based machinery—causes of high real prices of energy-related technology range from import constraints to pricing distortions through commodity-related policies. As a result, the majority of power generation in developing countries is fossil-fuel driven, which is not only detrimental to the environment but also unsustainable from an energy security perspective.

Conversely, it is also found that agriculture in developed parts of the world is more energy-intensive than their less-developed counterparts. This difference is attributable to the interactions amongst decision-making and economic forces, compared to the initial supply of various energy resources available and their prices in these two sets of countries. A study conducted by the World Bank in 1998 identified pricing strategies that restrain the adoption of yield-increasing technologies had been employed in more than two-thirds of the developing countries. The abundance of cheap labour and low investment in human capital in developing countries has resulted in prices of human labour to be much cheaper than the prices of fuel and mechanization. Small and marginal farmers in rural areas of India have scarce resources at their disposal in terms of natural resources like land, water, fertilizers, fuels and the human resources [7], which is why they have to allocate these resources efficiently and economically to earn profits.

Human energy is one of the costliest forms of energy if we consider the energy equivalent of the amount of food a man consumes daily on an average. Similarly, animal energy is also expensive if the opportunity costs of feeding the cattle are taken into account. Thus, despite financial constraints, the share of farm energy obtained from fuels and mechanization has been rising in developing nations lately, which makes improving the efficiency of energy consumption in agriculture more necessary in order to address the issues related to energy access, energy security and environmental security [17]. Therefore, energy management from the perspective of agriculture among developing countries like India should be aimed towards judicious utilization of available resources to maximize energy use efficiency rather than substituting costlier energy resources with cheaper options as in the case of developed nations.

## 3 Overview of the Energy Sector in India

The total energy required in an economy is dependent on the energy use intensity of the producing sectors as well as the rate of economic growth. Energy use intensity, in turn, is sensitive to the level of technological advancement in a particular sector. Despite the capital-intensive nature of commercial energy infrastructure, public investments in the energy sector have been steeply increasing since the fourth five-year plan. As a result, the domestic power generation capacity has quadrupled since the 1990s, and the per capita energy use has also doubled within the same time-span [15]. However, the overall energy generated still falls short of the demand due to rapid population growth and industrialization with a shortage of around 2.6%

in the country [16]. Even though the IEA data shows current electrification status in India to be at 99.6%, millions of households still do not have access to electricity [1].

Apart from its domestic energy resources, the Indian economy is dependent on fossil fuel imports to meet its domestic energy requirements. Figure 2 shows the source-wise share in electricity generation, and it can be seen that coal dominates the power generation scenario, which is not ideal on multiple levels. First, emissions from fossil fuel-based power generation and consumption have led to unhealthy spikes in air pollution levels across India in the last couple of years, which is a growing environmental concern. Secondly, the share of imported coal has grown briskly to over 30%, despite having high coal reserves of our own. The increase in imports is mainly due to inadequacies in production processes and the quality of coal available [15]. Thirdly, the share of renewable sources like hydro, solar and wind energy in power generation has declined from 26.59% in 1990–91 to 19.75% in 2016–17[5]. This shift in the energy mix does not bode well from an energy security viewpoint, as growing dependencies on fossil fuel imports to meet the domestic energy demands increases energy vulnerability as well.

Other developing nations in the region like Pakistan and Bangladesh have also been struggling to meet their domestic energy demands. Excessive reliance on imported fossil fuels, poor pricing policies related to generation and distribution of energy, and other bottlenecks have stifled private investments in the power business. This shortage of investment, in turn, has contributed to an impending energy crisis. As a result, per-capita energy use in Pakistan has grown at a sluggish rate of 2–3% rate in the past two decades. Likewise, the per capita electricity consumption in Bangladesh remains one of the lowest (320 kWh in 2014–15) in the world. In comparison, India has performed better with its per capita energy consumption that

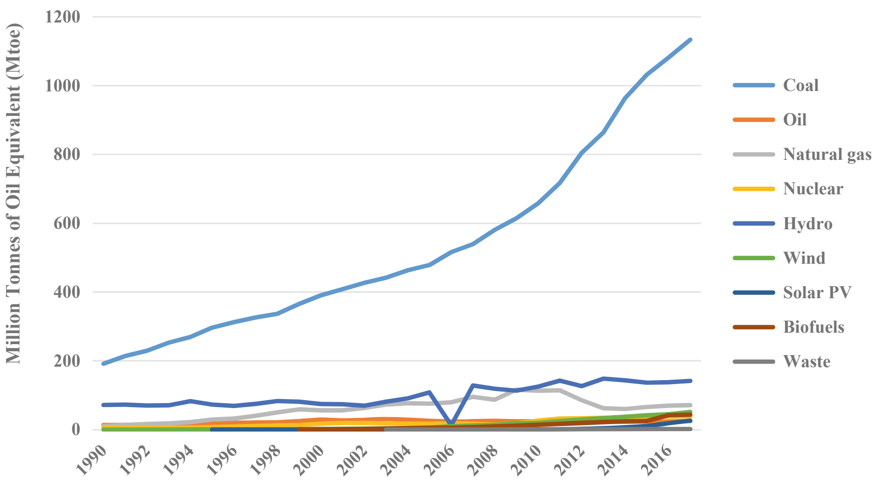


**Fig. 2** Electricity Generation in India by Source, 1990–2017 (The data has been obtained from IEA website (https://www.iea.org/data-and-statistics))

grew more than 53% since 2000, but its still just a third of the global average. Large-scale public investments in the energy sector and augmenting renewable sources for energy production has helped India to keep up with its increasing energy demands.

The agriculture sector in India contributes approximately 15% to the GDP and employs more than 43% of the workforce. Consequently, the pattern of energy consumption in Indian agriculture has also altered considerably over the past few decades, witnessing an exponential shift from human labour and animal-based agriculture to modern mechanized farming. Figure 3 shows the energy consumption by the agricultural sector in India from 1990–2017. In the pre-modernization period, agricultural workers and draught animals accounted for a sizeable portion of the total energy used in agriculture (nearly 15% and 45%, respectively). In comparison, energy from electricity and oil products contributed minorly (around 40%). In the following decades, the share of energy used has changed drastically with electricity and fossil energy accounting for more than 86% of the total energy consumed in 2017 and the contribution of agricultural workers and draught animals reducing to a mere 6% and 8%, respectively [20]. However, the available energy is not utilized efficiently.

India ranks second in the world in terms of paddy, wheat, cotton and sugarcane production, and it is also one of the largest producers of rice, vegetables and fruits, accounting for nearly a tenth of the world's total production. In order to reduce energy in agriculture, the use of high-energy inputs like synthetic chemicals and fertilizers must be cut down. The energy value for individual inputs includes the direct energy required for its production and the indirect energy used for processing and transporting that input to the field. Koeijer et al. [21] showed that the differences

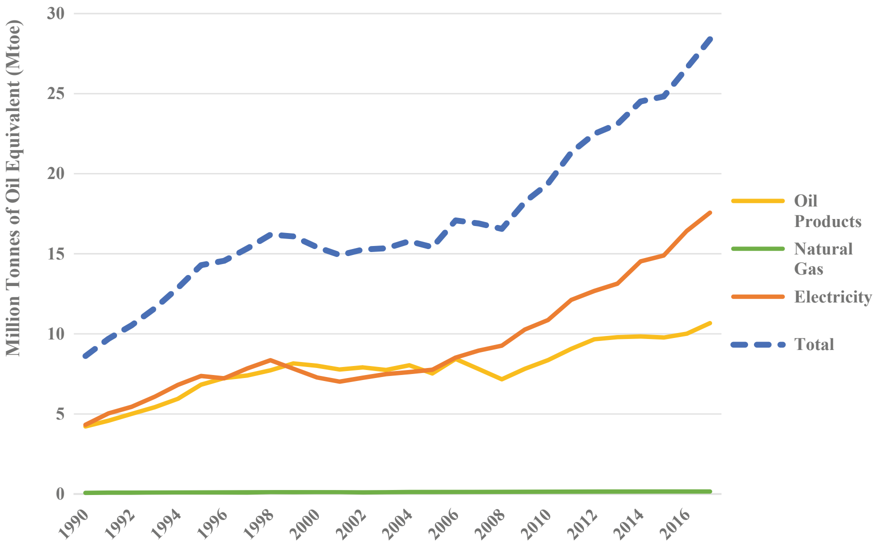


**Fig. 3** Total energy consumption (TEC) in Indian agriculture sector by source, 1990–2017[2]

in fertilizer and pesticide application among Dutch arable farmers affected their farm efficiency. Additionally, the efficiency of individual farmers differed over time as well as across different fields within a year. If the physical conditions are considered to be relatively constant for all farmers, then the variations in the efficiency could then be attributed to differences in farm management. Hence, the central issue examined in this chapter is whether differences in the efficiency of indirect energy use could be explained through differences in farm management. With this insight, keys could be found to improve management in order to reduce the use of direct and indirect energy.

## 4 Energy and Environmental Foot-Print of Agriculture

Energy is both fuel and feedstock for agriculture: primary energy is the fuel, while solar energy is the feedstock material. Energy utilization in an agricultural production system starts with field preparation, sowing, fertilizer application and continues until the harvesting, processing and transport of the crop to the market is complete. Simultaneously, crops capture solar radiation through photosynthesis and harness bio-energy to produce biomass. However, the relationship between energy consumption and agricultural yield is not linear. The crop production or yield improves with the increase in energy input only up to a certain level [29]. Consequently, if energy resources are cheap and abundant, farmers use energy inputs inefficiently and wantonly in order to maximize production with minimal risk. Furthermore, when the farmers are not able to achieve attainable yields, they consistently overexploit the available input resources. Efficient and appropriate use of energy inputs in agriculture is, therefore, a central aspect of consideration for agricultural sustainability, as evidenced by the research carried out on the topic.

On the other hand, among developing nations like India, where the majority of the agriculturists are smallholders, farmers' access to inputs resources are often limited due to financial and locational constraints. Distribution of land and capital is highly inequitable in India. Small and marginal farmers, having less than two hectares of land individually, constitute nearly 86% of the farmers but own merely 47% of the total cultivated area [36]. Effective management of input resources, in this case as well, can help maximize their energy use efficiency, thereby reducing production costs. To achieve this, we must precisely identify the energy relationships that exist within agricultural production systems and measure the flow of energy across different stages of crop production, processing, distribution and preparation, correctly. Such a study is usually referred to as an energy analysis of a particular agricultural system.

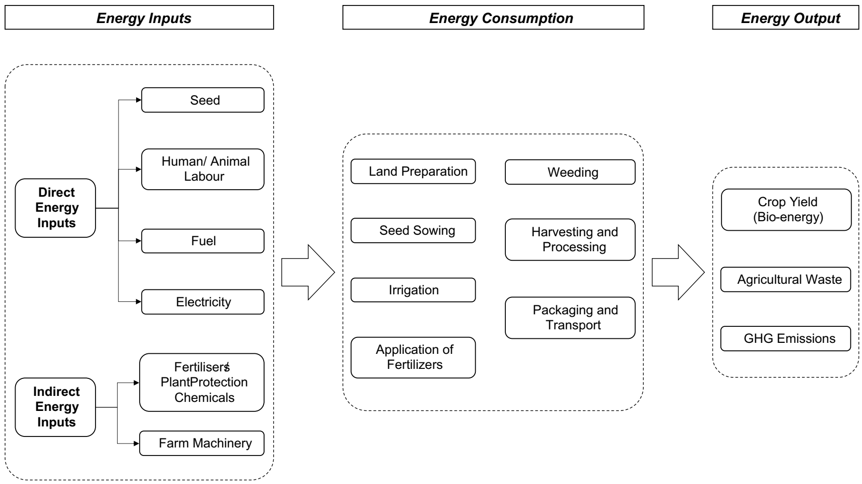


**Fig. 4** Conceptual framework of energy flow within a typical agro-ecosystem

## 4.1 *Energy Analysis and Agriculture*

Energy analysis is defined as the process of measuring how much energy is embodied in goods and services in physical units. This measure is also referred as the Gross Energy Requirement (GER), and it includes the energy used directly for the process of production along with the energy required to make available the raw materials and equipment needed for the process, tracing them back to their primary source [42]. Agriculture utilises broadly two types of energy, solar and non-solar. Non-solar energy can be further classified into direct and indirect energy. Direct energy refers to energy from electricity and fuel used directly for mechanisation and irrigation purposes, whereas indirect energy refers to the energy required for the production of agricultural fertilisers and plant protection chemicals from their primary sources. Figure 4 below shows the conceptual energy analysis framework for any crop with different energy inputs, energy conversion and energy outputs.

## 4.2 *Direct Energy*

The land used for agriculture is an invaluable resource, and land size, together with the pattern of land-use, significantly affect the energy-input requirement and the overall energy use efficiency. Large farms have been found to demonstrate better energy ratios and lower GHG emissions compared to the small and medium-sized farms [37]. The Green Revolution in India, circa 1974, not only led to systematic farming practices with a high rate of chemical application and farm mechanization but also fostered the development of high yielding seed varieties and genetically modified crops. Thus, the seed is also another important direct input in crop production, and seed energy is the total energy expended in the process of crop production. As discussed earlier, marginal farmers in developing countries like India still depend heavily on human and animal labour at different stages of production. The energy equivalent of human labour, in that case, is calculated as the amount of menial work required in field operations for crop production. Direct energy can be broadly expressed as:

$$Direct\ Energy = Seed\ Energy + Fuel\ Energy + Electricity\ Energy + Human\ Labour\ Energy$$

where,

$$Human\ Labour\ Energy = \frac{Work\ Duration(t)}{Size\ of\ Farm\ (ha)} \times Energy\ Coefficient\ (MJ/t)$$

While diesel fuel energy and electrical energy are measured directly in terms of their calorific values, the seed energy component can be calculated in terms of the seed-rate. The energy coefficients represent the amount of energy that is typically consumed from primary production to final usage of each input.

## *4.3 Indirect Energy*

Use of indirect energy inputs is equally prevalent in modern agriculture starting from electricity used for running irrigation pumps and the fuel used in machinery, transport, to the production of fertilizers and other plant protection chemicals. Energy equivalents for farm machinery and irrigation consist of sequestered energy in fuels and electricity, in terms of their enthalpy, i.e., the energy consumed in the production of their different components as well as the additional energy needed for the end-users to avail them. Thus, in order to calculate the energy equivalent of irrigational water, the sum total of the energy consumed for manufacturing the materials for the pipes, channels, dams, pumps and equipment and the energy needed for construction of the entire on-farm irrigation systems, as applicable, would be considered [21]. Similarly, the energy embodied in agricultural machinery comprises of the energy consumed for the production of the tractors and harvesters depreciated throughout their economic life. While the energy equivalents of synthetic fertilisers and plant protection chemicals (PPCs) include the energy directly used in their production, packaging and distribution, the energy equivalents of organic farmyard manure are derived from the mineral fertilizer equivalents corresponding to the fertilization effect of the applied manure. Indirect energy can thus be broadly expressed as:

$$Indirect\ Energy = Farm\ Machinery\ Energy + Fuel\ Energy + Chemical\ Energy$$

where,

$$Farm\ Machinery\ Energy(MJ/ha) = \frac{Weight\ of\ Machinery(kg) \times Working\ Time(t)}{Size\ of\ Farm(ha) \times Useful\ Life(t)} \times Energy\ Coefficient(MJ/kg)$$

$$Fuel\ Energy = \frac{Fuel\ volume(L)}{Size\ of\ Farm(ha)} \times Energy\ Coefficient(MJ/L)$$

$$Chemical\ Energy = \frac{Quantity\ of\ Chemical(kg)}{Size\ of\ Farm(ha)} \times Energy\ Coefficient(MJ/kg)$$

Globally, several investigations have been piloted to identify energy use under different crop production systems [4, 43]. Soddy [38] provided the initial outline for an exhaustive accounting of the different forms of energy used within a crop production system, which served as a template for later studies. For example, in cotton production diesel, fertilizer and machinery play a most potent role in energy consumption [46], while irrigation and fertilizer are the strong contributors in energy intake [40]. Similarly, the use of machinery and advanced farming technology was found to improve the energy input used in the production systems [47]. Except for a handful of comprehensive energy analyses, most of the studies have only considered the direct fuel inputs that can be measured easily, and the system boundaries have been defined restrictively avoid calculations pertaining energy from indirect sources. Likewise, environmental and biomass related energy inputs have been excluded in the majority of the research and the energy expended through human or animal labour has also often been discounted.

Devising energy use based indicators could help us measure the long-term viability of existing agricultural practices [23]. Holistically speaking, global sustainability indicators could be expanded to include energy and agriculture. This would enable us to establish the benefits of improved energy services for agriculture definitively through different indicators of progress. In this direction, FAO has been developing energy indicators of sustainable agriculture [14]. From a policy standpoint, such measures would help bridge the gap between the rural energy sector and agricultural policy dimensions, incorporating agricultural energy needs in the overall energy planning process. Last but not least, proposed indicators should integrate the environmental dimension of energy use as well, taking into account the undesirable outputs of agricultural systems as elaborated in the next section.

## *4.4 Environmental Impact of Agricultural Inefficiencies*

As input energy consumption in the agricultural sector grows, the depletion of natural resources is accelerated, along with an increasing amount of GHG emissions in the atmosphere. Agriculture accounts for 10–12% of the total humanmade GHG emanation [22]. Among the gases, Nitrous oxide ($N_2O$) and methane ($CH_4$) are the most potent ones. As per the Biennial update report on climate change, the energy sector in

India contributes most to the atmospheric emissions with about 71%[5] of total emissions, whereas the agricultural sector contributes to 18%[4] of the total emissions and stands second in the list. Intensive farming practices through the use of mechanization during different tillage operations, fertilizer and pesticide application, supplemental irrigation practices, harvesting, and residue management emit $CO_2$ and other GHGs into the atmosphere. Additional emissions, due to agricultural responses elsewhere, also include potential emissions from land-use changes, including deforestation.

Nevertheless, multiple studies have highlighted that chemical fertilizers and fossil fuels used in farm machinery contribute considerably towards agricultural GHG emissions [12, 37]. Variations in soil, climate, and economic conditions across different farms can influence the direct and indirect impacts of GHG emissions. Thus, the amount of carbon savings from agricultural energy mitigation options are determined by the regional primary energy mix. However, the adoption of energy-efficient management practices can effectively mitigate the harmful effects of GHG emissions to a certain extent. For instance, better farmyard manure (FYM) management reduces indirect consumption of fossil fuels used in the preparation of chemical fertilizers, while simultaneously decreasing $N_2O$ and $CH_4$ emissions [24, 44]. Hence, optimizing the farm-level energy use efficiency can serve dual objectives: offsetting the harmful environmental effects of GHG emissions and improving overall energy security.

## *4.5 Energy Management in Agriculture*

Inefficiencies in the allocation of energy resources produce undesirable outputs in agriculture. Abatement in such technical inefficiencies attracts financial as well as environmental benefits through efficient resource use and reductions in emissions and waste. Hence, efficiency-related literature often refers to management as an important factor in explaining inefficiencies in production. However, the relationship between management and efficiency is layered and complex [34]. Management broadly encompasses the art and science of formulating, implementing and evaluating strategic decisions through analysis and synthesis of evidence to achieve desired outcomes. This concept of strategic management is appropriate for analyzing the complex interlinkages between variables and characterizing farm management to improve the technical efficiency of smallholders. Energetic improvements in agriculture can primarily be achieved through (i) optimization of energy inputs, (ii) technological advancements, (iii) input substitution and (iv) demand-driven strategies.

[4]The Biennial Update Report to the United Nations Framework Convention on Climate Change (UNFCCC) is prepared by Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India (GoI) highlighting India's adherence to the sustainable development goals in different sectors.

Farm operations require significant amounts of energy inputs. Energy analysis of an agro-ecosystems provides us with useful insights regarding factors affecting farm energy use efficiency. Optimum quantities of these inputs within a specific farm setting can be obtained by comparing data from adjacent farms. Frontier approaches like Data Envelopment Analysis (DEA) is particularly useful to benchmark and compare relatively homogenous sets of farmers and finally obtain recommendations regarding the optimum quantities of various inputs in order to maximize productivity [21, 21]. Providing farmers with management support, to analyze their individual farm data against best performers, can help them formulate an appropriate strategy to reduce energy use and maximize production.

Technological advancements can be attained for all major agricultural inputs. Key strategies include genetic modification of plants and livestock [45], use of proficient farm machinery [3], improved irrigation systems [35] and enhanced plant-related chemicals. Genetic engineering of plant species reduces their input requirements, improve their yields, or increase their resistance to different types of stress. Robust and more fuel-efficient farm machinery help incur energy savings through better fuel-efficiencies and lower maintenance costs [28]. Another strategy could be to adopt precision cropping techniques [33] wherein site-specific irrigation and micro-nutrient requirements are estimated and managed effectively [11], to cut excess inputs.

Input substitution can reduce agricultural energy consumption within the framework of existing technologies [13]. From an econometric standpoint, technological advancement moves the equilibrium position along a given production possibility frontier, driven by forces of demand and supply, while substitution of inputs shifts the entire frontier outward, driven mainly by the cost of energy [31]. Examples of input substitution typically involve a systematic intensification of agriculture through changes in fertilization techniques [41], alterations in tillage and irrigation patterns [32], changes in the degree of farm mechanization [27] and integrated pest management [10]. Thus, substituting scarce or expensive energy inputs with cheaper or more abundant alternatives might increase the energy use per unit area. However, a sufficient increase in crop yields, through proper implementation of these techniques, can decrease the overall energy intensity per unit of agricultural produce [41].

The market demand for agricultural commodities governs their volume of production and thus, the total energy consumed in the process. Hence, moulding the demand towards an organic, local, more seasonal, vegetarian diet could promote environment-friendly crop management methods, which fall under the broader umbrella of low external input based agriculture (LEISA) framework [18]. Similarly, creating a demand for renewable energy and products among the general public through awareness could be another example. Demand-driven strategies are largely governed by market prices and policies. Policies related to energy prices, removal of trade barriers, or stringent environmental policies could all encourage the adoption of energy-friendly agricultural commodities. Thus, energy management comprises of a heterogeneous and complex set of strategies, all of which enhance the mitigation potential of agro-ecosystems.

# 5 A Case Study of Indian Paddy Farmers

As discussed in the previous sections, the total energy consumption in Indian agriculture increased nearly six times, from 425.38 billion Mega Joules (MJ) in 1980–81 to 2592.82 billion MJ in 2006–07 [20]. If we compare the amount of energy used in total production, coarse cereals are the biggest consumers, followed by pulses and oilseeds. Among cereals, the energy cost for paddy was found to be the maximum at the rate of INR 13,529/ ha.[5] The share of total commercial energy used for the production of rice is highest in the state of West-Bengal, among the major rice-growing states of India [8]. Hence, we have restricted our study to the estimation of energy use efficiency in paddy production and focussed on the state of West Bengal.

## *5.1 Research Methods and Data*

The present study was carried out in the state of West Bengal of India, where about 65%[6] of the population depends on agriculture, of which nearly 95%[7] are smallholders. West Bengal ranks highest among the paddy producing states in India [8]. Huge amounts of input resources are utilized in paddy production since it is a resource-intensive crop. Therefore, averting wastage of energy from input sources in the case of paddy production is of utmost importance. This study used primary data collected from the villages of Darjeeling district of West Bengal. The data was collected from 50 paddy producers by using a face-to-face questionnaire for the production year 2017–2018. In DEA efficiency estimation, human labour (differentiated into adult man and woman), diesel, fertilizer and electricity were selected as the input variables, while the paddy yield was defined as the only output variable.

## *5.2 Energy Equivalents of Inputs and Output*

The inputs and output associated with paddy production were converted into energy equivalent by utilizing the available standard procedure which involves the multiplication with the equivalent energy coefficients [8, 26]. The energy equivalents may vary to some extent over time, based on exogenous factors. However, the coefficients were obtained. Table 1 indicates the energy equivalents of the agricultural inputs and output in paddy production. These equivalent energy coefficients for different inputs and output have been obtained from previous research work conducted under

[5]Relevant data has been obtained from multiple reports published by the Directorate of Economics and Statistics (DES) under the Ministry of Agriculture & Farmers' Welfare (MoAFW), Govt. of India (GoI). The DES reports provide year-wise information on key agricultural statistics.

[6]Data retrieved from 'Status Paper on Rice in West Bengal' published by the Directorate of Rice Research (DRR), Govt. of India (GoI).

**Table 1** Energy equivalents of different inputs and output

| Particulars | Unit | Energy equivalent (MJ/ha) |
|---|---|---|
| Inputs | | |
| Adult man | Man-hour | 1.96 |
| Adult woman | Woman-hour | 1.57 |
| Diesel fuel/machinery | Litre | 56.31 |
| Fertilizer | Kilogram (kg) | 77.8 |
| Electricity/irrigation | Kilowatt-hour (kWh) | 11.93 |
| Output | | |
| Paddy | Kilogram (kg) | 14.7 |

similar conditions and then utilised to estimate the energy inputs and output data. The estimated energy data was then applied to derive the energy use efficiency, energy productivity, specific energy, and net energy [19, 26, 30]. Mathematically the formulae can be explained as:

$$Energy-use\,efficiency = \frac{Energy\,output\,(MJ/ha)}{Energy\,input\,(MJ/ha)}$$

$$Energy\;productivity = \frac{Output\,(kg/ha)}{Energy\,Input\,(MJ/ha)}$$

$$Net\,energy = Output\,energy(MJ/ha) - Input\,energy(MJ/ha)$$

$$Specific\,energy = \frac{Energy\,Input\,(MJ/ha)}{Output\,(kg/ha)}$$

### *5.3 Efficiency Estimation Using Data Envelopment Analysis (DEA)*

In this study, the DEA method was employed to identify the relative efficiency in paddy production and derive the value of energy savings. In this method, the input-oriented DEA approach was used as farmers have comparatively less control over the output. The efficiencies obtained in DEA are known as technical efficiency (TE), pure technical efficiency (PTE), and scale efficiency (SE). Technical efficiency is a measure that helps a farmer to receive maximum output with certain input levels [6, 25]. Estimation of TE assumes constant returns to scale (CRS). It can be measured by the ratio of the sum of weighted outputs to the sum of the weighted inputs, expressed as:

$$TE = \frac{u_1 y_{1j} + u_2 y_{2j} + \cdots + u_n y_{nj}}{v_1 x_{1j} + v_2 x_{2j} + \cdots + v_m x_{mj}} = \frac{\sum_{r=1}^{n} u_r y_{rj}}{\sum_{s=1}^{m} v_s x_{sj}} \quad (1)$$

Here, $u_r$ represents the weight given to the $rth$ output, $y_r$ represents the quantity of the $rth$ output, $v_s$ gives the weight to the $sth$ input and $x_s$ represents the quantity of $sth$ input; $r$ is the number of individual outputs ($r = 1, 2, \ldots, n$), $s$ gives the number of individual inputs ($s = 1, 2, \ldots, m$), and $j$ represents the DMU under consideration ($j = 1, 2, \ldots, k$). Banker et al. [2] developed another DEA approach called the BCC model for estimating the pure technical efficiency. This approach considers variable returns to scale (VRS) as opposed to the constant return of scale assumed in the CCR model. Mathematically, the PTE can be expressed as:

$$Maximize\, z = u \times y_i - u_i$$

Subject to,

$$v \times x_i = 1$$

$$-v \times X + u \times Y - u_0 \times e \leq 0$$

$$v \geq 0, u \geq 0 and u_0 is free in sign \quad (2)$$

Here, $u$ and $v$ represent the weight of output and input matrixes, and $Y$ and $X$ represent corresponding output and input matrices. The $x_i$ and $y_i$ give the inputs and outputs for the $ith$ DMU. Scale efficiency indicates the impact of DMU size on the efficiency of the system. It can be expressed as follows [9]:

$$Scale\ Efficiency = \frac{Technical\ Efficiency}{Pure\ Technical\ Efficiency} \quad (3)$$

In this study, to analyze the efficient and inefficient farmers, the energy-saving target ratio (ESTR) has been measured to find out the inefficiency for each farmer based on their energy utilization. The ESTR can be mathematically expressed as:

$$ESTR_j = \frac{(Energy\ saving\ target)_j}{(Actual\ energy\ input)_j} \quad (4)$$

Here, energy-saving target ratio of a $jth$ farmer is the percentage of input energy that could be saved without reducing output energy.

## 6 Results and Discussion

The existing energy use efficiency and energy productivity were estimated as 0.86 and 0.059 kg/ MJ, respectively. The inefficiency present in the data probably results from the improper management of input resources such as diesel, fertilizer, and electricity. The resultant specific energy was 16.92 MJ/kg. The net energy was calculated as −4081.74 MJ/ha. The net energy showed a negative value signifying that there is a loss in energy in paddy production. Best-performing farmers were identified to estimate the optimum quantity of each input accounting for scale efficiency. The theoretically estimated improvements for different energy indices have been derived and provided in Table 2. Enhancement in energy ratio was estimated as 0.92, indicating an improvement of 6.97%. The improvements in energy productivity and specific energy were revealed as 0.063 kg/ MJ and 15.82 MJ/ kg with a difference of 6.77% and −6.50% respectively. The loss in net energy has been improved to −2216.56 MJ/ ha with a stark difference of 45.69%.

The DEA results for three efficiency measurement techniques are shown in Table 3. The results indicated that the mean values of TE, PTE and SE values were 0.76, 0.85 and 0.89, respectively. In the present study, the TE varied from 0.60 to 1, and the standard deviation is 0.10. It is evident that the difference between frontier efficient and inefficient farmers was measured high. These results also suggest inefficiency in energy utilization. This wide variation in the farmers' efficiencies revealed that the farmers were unaware of proper input allocation as well as the optimum amount.

The PTE value of a DMU below one showed that the farmer is consuming more energy than the optimum value. Hence, it is crucial to recommend realistic levels of input energy for all the sources required for proper utilization by inefficient farmers. This process helps to prevent energy waste by keeping the output level constant. In Table 4, the percentages of energy savings possible through optimum input recommendations, for 42 inefficient farmers, have been presented. These suggestions would

**Table 2** Improvement in energy indices for paddy production using DEA model

| Particulars | Unit | Present Qty | Optimum Qty | Difference (%) |
|---|---|---|---|---|
| Energy-use efficiency | – | 0.86 | 0.92 | 6.97 |
| Energy productivity | kg/MJ | 0.059 | 0.063 | 6.77 |
| Net energy | MJ/ha | −4081.74 | −2216.56 | 45.69 |
| Specific energy | MJ/kg | 16.92 | 15.82 | −6.50 |

**Table 3** Average technical, pure and scale efficiency of paddy farmers

| Particulars | Mean | SD | Min | Max |
|---|---|---|---|---|
| Technical efficiency | 0.76 | 0.10 | 0.60 | 1.00 |
| Pure technical efficiency | 0.85 | 0.12 | 0.62 | 1.00 |
| Scale efficiency | 0.89 | 0.08 | 0.64 | 1.00 |

**Table 4** Actual and recommended values of energy-use from different input sources for inefficient farmers (based on BCC Model)

| Farmer number | PTE | Actual energy-use, MJ/ha | | | | | Recommended optimum energy-use, MJ/ha | | | | | ESTR (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Adult man | Adult woman | Machinery | Fertilizer | Irrigation | Adult man | Adult woman | Machinery | Fertilizer | Irrigation | |
| 1 | 0.98 | 1202 | 1914 | 4883 | 1687 | 1390 | 1181.57 | 1881.47 | 4691.36 | 1658.33 | 1069.9 | 5.36 |
| 3 | 0.97 | 1265 | 1905 | 4917 | 1670 | 1480 | 1239.66 | 1852.67 | 4817.13 | 1636.55 | 1199.5 | 4.37 |
| 6 | 0.99 | 1181 | 1854 | 4824 | 1694 | 1311 | 1160.3 | 1846.43 | 4804.29 | 1671.7 | 1038.6 | 3.15 |
| 8 | 0.99 | 1281 | 1862 | 4843 | 1696 | 1415 | 1160.48 | 1846.69 | 4803.17 | 1671.59 | 1038.75 | 5.19 |
| 11 | 0.96 | 2490 | 3779 | 9313 | 3845 | 1734 | 2128.56 | 3375.21 | 8659.31 | 3191.81 | 1681.09 | 10.04 |
| 12 | 0.89 | 2475 | 3684 | 9790 | 3346 | 1964 | 2029.29 | 3191.37 | 8110.08 | 2981.32 | 1715.47 | 15.2 |
| 13 | 0.74 | 2396 | 3727 | 9890 | 3668 | 1797 | 1624.69 | 2580.86 | 6774.92 | 2426.63 | 1344.65 | 31.32 |
| 15 | 0.72 | 2407 | 3695 | 10,000 | 3658 | 1962 | 1663.68 | 2696.47 | 7189.58 | 2607.84 | 1431.79 | 28.23 |
| 16 | 0.98 | 2390 | 3732 | 9541 | 3487 | 1742 | 2179.75 | 3455.92 | 8850.77 | 3269.56 | 1715.27 | 6.8 |
| 17 | 0.72 | 2454 | 3717 | 9795 | 3656 | 1931 | 1700.8 | 2713.38 | 7121.81 | 2570.46 | 1409.62 | 28.01 |
| 18 | 0.68 | 2333 | 3781 | 9570 | 3584 | 1935 | 1586.71 | 2523.31 | 6508.72 | 2348.62 | 1316.03 | 32.64 |
| 19 | 0.87 | 2410 | 3791 | 9404 | 3515 | 1981 | 2054.22 | 3253.68 | 8224.47 | 3043.63 | 1620.68 | 13.76 |
| 20 | 0.7 | 2340 | 3624 | 9834 | 3281 | 1943 | 1600.71 | 2521.48 | 6316.52 | 2297.27 | 1360.44 | 32.94 |
| 21 | 0.89 | 2400 | 3660 | 9696 | 3314 | 1988 | 2011.97 | 3162.78 | 8036.93 | 2952.21 | 1708.64 | 15.13 |
| 23 | 0.77 | 3389 | 5430 | 14,036 | 5028 | 2579 | 2607.44 | 4130.63 | 10,525.26 | 3897.36 | 2008.05 | 23.94 |
| 24 | 0.89 | 3472 | 5500 | 14,176 | 5071 | 2573 | 3017 | 4777.19 | 12,203.65 | 4476.91 | 2295.62 | 13.06 |
| 25 | 0.94 | 3474 | 5498 | 14,025 | 5390 | 2579 | 3207.82 | 5078.43 | 12,985.62 | 4746.92 | 2429.59 | 8.13 |
| 26 | 0.86 | 3411 | 5592 | 13,980 | 5042 | 2820 | 2919.26 | 4622.9 | 11,803.12 | 4338.61 | 2226.99 | 16 |
| 27 | 0.74 | 3466 | 5491 | 14,345 | 4999 | 2500 | 2402.65 | 3807.35 | 9686.07 | 3607.59 | 1864.27 | 30.63 |
| 28 | 0.88 | 3445 | 5553 | 14,000 | 5369 | 2899 | 3036.72 | 4819.08 | 12,340.79 | 4528.15 | 2321.87 | 13.5 |

(continued)

**Table 4** (continued)

| Farmer number | PTE | Actual energy-use, MJ/ha | | | | | Recommended optimum energy-use, MJ/ha | | | | | ESTR (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Adult man | Adult woman | Machinery | Fertilizer | Irrigation | Adult man | Adult woman | Machinery | Fertilizer | Irrigation | |
| 29 | 0.66 | 3470 | 5504 | 14,141 | 5085 | 2742 | 2276.75 | 3599.85 | 9154.99 | 3397.21 | 1813.14 | 34.58 |
| 30 | 0.64 | 3404 | 5569 | 14,083 | 5000 | 2733 | 2187.47 | 3453.03 | 8778.27 | 3247.71 | 1775.2 | 36.86 |
| 31 | 0.66 | 3441 | 5568 | 13,970 | 5391 | 2861 | 2278.31 | 3625.89 | 9249.62 | 3444.15 | 1795.72 | 34.7 |
| Farmer Number | PTE | Actual energy use, MJ/ha | | | | | Recommended optimum energy use, MJ/ha | | | | | ESTR (%) |
| | | Adult Man | Adult Woman | Machinery | Fertilizer | Irrigation | Adult Man | Adult Woman | Machinery | Fertilizer | Irrigation | |
| 32 | 0.94 | 3452 | 5450 | 14,420 | 5148 | 2507 | 3128.7 | 4953.52 | 12,661.39 | 4634.97 | 2374.04 | 10.41 |
| 33 | 0.86 | 3405 | 5525 | 14,425 | 5363 | 2811 | 2929.8 | 4747.54 | 12,411.84 | 4587.77 | 2358.99 | 14.25 |
| 34 | 0.7 | 3389 | 5556 | 14,276 | 5081 | 2623 | 2376.44 | 3766.02 | 9586.38 | 3568.26 | 1846.61 | 31.63 |
| 35 | 0.84 | 3447 | 5519 | 14,199 | 4968 | 2928 | 2802.91 | 4439.21 | 11,326.31 | 4173.96 | 2145.3 | 19.87 |
| 36 | 0.61 | 3393 | 5599 | 14,408 | 5260 | 2811 | 2098.88 | 3375.94 | 8784.21 | 3253.79 | 1714.89 | 38.9 |
| 37 | 0.66 | 4661 | 7281 | 18,555 | 6996 | 3783 | 3068.19 | 4858.01 | 12,413.44 | 4549.35 | 2331.56 | 34.05 |
| 38 | 0.92 | 4679 | 7249 | 18,735 | 6969 | 3547 | 4209.5 | 6705.6 | 17,330.6 | 6263.79 | 3185.8 | 8.46 |
| 39 | 0.96 | 4593 | 7306 | 18,615 | 6879 | 3396 | 4408.58 | 6974.03 | 17,906.33 | 6446.05 | 3272.68 | 4.37 |
| 40 | 0.78 | 4588 | 7285 | 18,880 | 6844 | 3627 | 3587.47 | 5718.37 | 14,754.03 | 5372.21 | 2743 | 21.95 |
| 41 | 0.77 | 4585 | 7354 | 18,598 | 6637 | 3640 | 3505.68 | 5548.65 | 14,206.26 | 5168.41 | 2638.73 | 23.88 |
| 42 | 0.76 | 4700 | 7299 | 18,648 | 6745 | 3893 | 3519.64 | 5570.69 | 14,263.48 | 5188.17 | 2648.54 | 24.45 |
| 43 | 0.76 | 4522 | 7389 | 18,575 | 6694 | 3669 | 3467.5 | 5496.96 | 14,094.73 | 5133 | 2621.82 | 24.57 |
| 44 | 0.79 | 4621 | 7278 | 18,971 | 6709 | 3445 | 3635.99 | 5754.38 | 14,740.29 | 5352.82 | 2730.23 | 21.48 |

(continued)

**Table 4** (continued)

| Farmer Number | PTE | Actual energy use, MJ/ha | | | | | Recommended optimum energy use, MJ/ha | | | | | ESTR (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Adult Man | Adult Woman | Machinery | Fertilizer | Irrigation | Adult Man | Adult Woman | Machinery | Fertilizer | Irrigation | |
| 45 | 0.97 | 5722 | 9192 | 23,829 | 8283 | 4404 | 5567.45 | 8803.5 | 22,655.39 | 8085.91 | 4086.36 | 4.34 |
| 46 | 0.76 | 5712 | 9075 | 23,373 | 8182 | 4183 | 4259.65 | 6738.91 | 17,296.01 | 6235.31 | 3168.11 | 25.39 |
| 47 | 0.76 | 5747 | 9182 | 23,367 | 8486 | 4189 | 4296.88 | 6797.69 | 17,448.59 | 6288 | 3194.26 | 25.4 |
| 48 | 0.94 | 5712 | 9068 | 23,672 | 8428 | 4223 | 5390.58 | 8539.86 | 22,012.2 | 7869.44 | 3980.16 | 6.48 |
| 49 | 0.85 | 5653 | 9153 | 23,860 | 8173 | 4397 | 4799.52 | 7591.2 | 19,508.42 | 6999.26 | 3547.18 | 17.16 |
| Avg | 0.81 | 3534.37 | 5606.9 | 14,439.47 | 5215.85 | 2788.62 | 2828.19 | 4482.86 | 11,508.62 | 4188.1 | 2192.48 | 19.53 |
| SD | 0.11 | 1241.82 | 2018.1 | 5172.18 | 1834.97 | 882.08 | 1112.86 | 1763.69 | 4530.92 | 1624.15 | 763.86 | 10.75 |

help the farmers to minimize their energy consumption. The mean energy-saving target ratio was revealed as 19.53%. The maximum and minimum energy saving target ratio was 3.15% and 38.90% belong to the most and least inefficient paddy producers with a standard deviation of 10.75. Hence, the recommended energy use for inefficient farmers if adopted, could prevent the over-exploitation of resources, especially in terms of diesel, fertilizer, and electricity energy inputs.

## 7 Conclusion

The agriculture sector in the modern era continues to be highly resource and energy-intensive, growing exponentially to meet the global food demand. Nevertheless, agriculture has a bifold role as an energy user and as an energy supplier. This interesting aspect of agriculture can be channelled to mitigate the effects of climate change, ensure food and energy security for all. The first and foremost way to ensure sustainability is to conserve energy at each stage of production through efficient management of energy resources. First, the energy use efficiency of a farm is calculated through energy-ratios and specific energy indices. Managerial interventions like improving the energy efficiency of production and distribution processes through less energy-intensive methods, more efficient machinery, de-centralization of crop production systems and organized food transportation can all contribute towards better energy management in the agricultural sector.

Apart from energy management, augmenting and substituting renewable forms of energy in place of non-renewable fuel-based energy generation could also help. Subsidizing solar, wind and bio-energy based technologies can make them accessible to a broader population of medium and small-scale farmers. In this study, results have been obtained for the current consumption of energy by paddy farmers in West Bengal, India. The results imply that there is a difference between the present amount of energy resources being used by the farmers and the optimum amount of resources required to achieve a fixed level of crop yield. Shifting towards the optimum quantity of energy inputs can significantly boost the farms' production efficiency. However, local socio-economic and environmental conditions should guide solutions to energy-related problems.

Thus, the formulation of energy-related policies should integrate national energy management perspectives with the locally perceived priorities emphasizing on a shift towards renewable alternatives for the provision of energy services in agriculture in developing countries. However, mobilizing the transitions occurring in the energy and agricultural sector in order to the benefit rural communities and their livelihoods is a daunting task. Rural populations are faced with the danger of being left behind unless national energy policies are explicitly designed around their needs and requirement. It is clear from the analysis presented in this chapter that energy-related decision-making must be appropriately considered and integrated into agricultural and rural development programmes, which will provide sustainable energy to the masses in order to sustain and improve their standard of living while maintaining the delicate balance between economic development and environmental sustainability.

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# Floating Photovoltaic System Technology—Prospects of Its Implementation in Central Asian, South Asian and South East Asian Region

**Muhammad Abid, Zaineb Abid, and Muhammad Umer**

**Abstract** Sustainable supply of energy and access to water are among the major issues facing the Central Asian and South Asian countries due to climate change. There is a need of an environmental friendly and cost-effective energy production technology to achieve reasonable energy production without affecting climate by release of any kind of greenhouse gases. This renewable and sustainable source of energy can be provided by floating photovoltaic systems/technology (FPVS) which also helps in achieving sustainable supply of clean water. This chapter discusses the working of Floating Photovoltaic (FPV) technology and its technical, economic and ecological feasibility over the land-based PV systems. It also discusses the prospects of implementing this technology in Central Asian, South Asian and South East Asian region by providing the case studies of already implemented systems in different parts of the world. The implementation of FPVS in Indus Basin, Kabul River Basin and water resources in Central Asian Countries, South Asian and South East Asian Countries can prove to be greatly effective by controlling huge amount of evaporation and precipitation and can prevent climate change in this region at bigger scale.

**Keywords** Renewable energy · Floating photovoltaic systems · Feasibility · Central Asia · South Asia

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## 1 Introduction

Enormous demand for increased energy production due to explosive rise in world population along with depletion of fossil fuels, high levels of greenhouse gas emissions and climate change have necessitated the shifting of energy production systems from conventional non-renewable sources to renewable sources [1]. Among renewable energy sources, solar energy is of the prime interest due to several competitive advantages over other resources which despite having high production potential require complex setups and conditions [2]. Solar energy is widely available all over the world and thus, solar power generation units i.e. photovoltaic (PV) units can be deployed very conveniently in every geographic region without any special arrangements [3]. Photovoltaic units can last up to 25 years without maintenance with easy replacement and relocation. Moreover, damage or disruption in any of the units requires replacement or repairment in only that unit rather than disturbing all the other units in an arranged system without affecting their output. However, photovoltaic systems conventionally applied on land have certain limitations which affect their energy efficiency such as dense soiling effect, higher humidity levels and high altitudes with less light time [4].

In order to overcome the limitations of land-based PV systems, Floating Photovoltaic Systems (FPVS) have been developed for the implementation of sunlight utilizing photovoltaic systems on water bodies such as lakes, oceans, lagoons, fish farms, canals, rivers, irrigation ponds and waste water treatment plants etc. FPV Systems are a combination of Photovoltaic plant technology and floating technology and are a new concept with the implementation of only a few demonstrator projectors worldwide [5]. FPV technology is especially useful in regions with less area of land for land-based PV installations such as Japan, Korea, Singapore, Philippines etc. and high evaporation rates due to increased temperatures since these systems can be installed on water reservoirs and can prevent excessive water evaporation. Moreover, areas having difficulties in accessing portable water and stable energy supply have great potential for implementation of this technology [6]. The potential associated to the application of FPV units can be realized from the fact that if only 1% of natural basin surfaces of the world get covered by FPV units, 25% of the global electricity demands will get fulfilled [7].

The first pilot floating PV plant was installed in California in 2008 immediately after the completion of the pilot study of the technology in 2007. One of the first FPV plants was built for research purposes in Aichi, Japan with the capacity of 20 kilo Watt (kW) [8]. A total of 22 FPV plants with the installed capacity of 0.5–1157 kW had been built worldwide by the end of the year 2014 [9]. Many countries are realizing the potential and advantages of this technology and incorporating the implementation of this technology in their policies. However, there are certain limitations to this technology such as effects of corrosion on the panels etc. Research on these effects and PV configuration and its link with energy efficiency is underway.

## 1.1 Components of Floating Photovoltaic System

Floating PV system consists of the following components:

1. **PV modules**: Standard crystalline and aluminum frame PV modules are generally used. However, there are various humidity and corrosion risks in water bodies which pose a need for an alternative polymer based modules.
2. **Floating platform or pontoon**: This is a floating platform holding a suitable number of modules according to the requirement and availability of space in series parallel combination. The platform has enough buoyancy to float itself even with heavy loads. The floats of the system are usually made of high density polyethylene (HDPE) which has high tensile strength, does not require maintenance and is Ultra Violet (UV) light and corrosion resistant.
3. **Anchoring and mooring system**: A mooring system is a permanent structure that keeps PV modules in a fixed position and keeps them from turning over or floating away. The system usually consists of nylon wire rope slings tied to bollards on banks and at the corners.
4. **Inverters**: These are centralized structures converting the form of current from alternative current to direct current for the commercial use.
5. **Cables and connectors**: Electricity is transported to land from the PV system and the energy is stored in grid or the batteries. This requires the use of high temperature resistant, water proof and robust Alternate Current (AC) and Direct Current (DC) cables. The standard for cables is IP68. See Fig. 1 [10].

This chapter provides an extensive discussion on floating photovoltaic technology in comparison to land-based PV systems. Technical, economic and environmental advantages of floating PV systems over land-based PV systems have been mentioned along with the case studies of the countries that have implemented this technology and the benefits they are receiving to support their implementation worldwide. Lastly, the need and potential of this technology in Central Asian, South Asian and South East Asian countries have been discussed in detail.

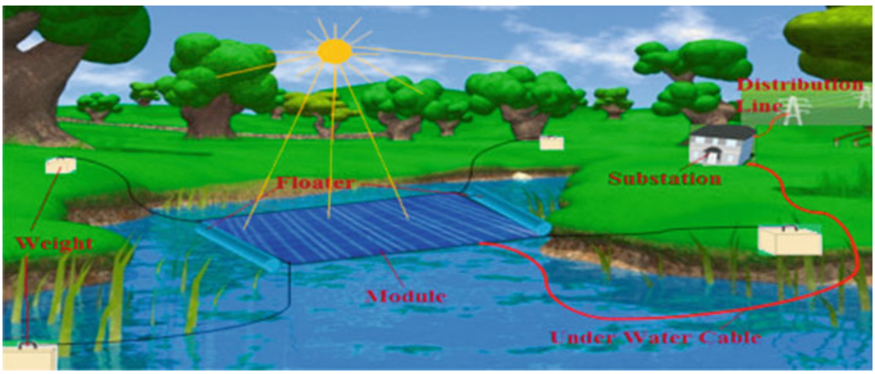


**Fig. 1** Overview of FPV plant (*Source* Sahu et al. [10])

## 2 Case Studies of Presently Implemented FPVS in Different Parts of the World

Governments of many countries all over the world are realizing the potential benefits and efficiency of FPV technology and are implementing it such as Italy, Spain, France, South Korea, Singapore, Brazil, India, UK, USA and Japan. Following are some of the case studies of presently implemented FPV systems throughout the world:

- Preliminary simulations of a 240 kW FPVS on a pool in Khuzestan province of Iran showed that about 380 Mega Watt (MW) power can be produced and added into the main power supply system annually by FPVS. FPVS can further reduce evaporation and can store about 13,950 $m^3$/year, which makes up about 24% of the reservoir's storage capacity. Thus, increased power production and reduced evaporation makes FPVS an efficient technology for agro-energetic policies and for water pumping due to availability of sufficient amount of solar radiation over larger area all over the world [11].
- To study the benefits of the technology for the local farmers of Spain where most of the farmer have water reservoirs for irrigation, a prototype of FPVS has been developed. The study showed that the technology remains highly attractive and economical even during the conditions of fluctuating feed-in-tariffs in the country with microencapsulated phase change material further improving the energy output. Moreover, near Alicante, Spain, one-to-one plant was built in an agricultural system to study the performance. The static solar system covered only 7% area of the total reservoir having an area of 4700 $m^2$ [12].
- In Agosto Alicante, Spain, scientific and monetary investigations of a 20 kW prototype of FPVS covering an area of 350 $m^2$ showed a successful performance of the system which lead to the implementation of a large-scale FPV plant consisting of 1458 PV panels supported on 750 pontoons covering an area of 4490 $m^2$. The result is the production of 300 kW power.
- Being one of the largest coal-based thermal power generating countries, China realized the importance of renewable energy sources and implemented 40 MW floating solar power plant which is the largest floating solar plant in the world (Fig. 2) [13].
- The German SUNdy structure consisting of a hexagonal-shaped structure has been implemented by Det Norske Veritas which provides interesting properties such as easy arrangement of modules, flexibility, resistance to waves and ability to retain its shape.
- In 2015, 50% of the overall market share of FPVS was accounted for by Japan. At Kato city of Japan, larger installations have been made to withstand typhoons. However, since these systems are designed for water, corrosion is one of the major issues that needs to be observed. Moreover, the Japanese government has further planned the installation of over 100 FPV plants in the next 5 years. The political factor is also contributing to the growth of technology in Japan.
- India installed its largest floating solar power plant with the power generation capacity of 100 kW in Kerala and further plans to install a 10 kW plant in Kolkata

**Fig. 2** World's largest 40 MW floating solar power plant at Huainan, China (*Source* Brandon [13])

and Banasura Sagar reservoir in Wayanad [10]. Moreover, the feasibility research of installing 1 MW plant was done in two different places in India. It showed that power generation efficiency at Kota barrage and Kishore Sagar Lake was 18, 38, 519 kilo Watt hour per year (kWh/year) and 18, 58, 959 kWh/year respectively.

- Installation of FPV panels was investigated on four different lakes of Rajasthan, India through four cases of covering panels. It has shown that this system has the potential to produce 3–27 MW power in these lakes [14, 15].
- In Korea, two floating PV test plants were installed. These plants had the generation capacities of 2.4 kW and 1000 kW respectively. Their analysis showed a 10% increase in the generation capacity due to the cooling effect of water. Similarly, in Colignola power plant known as Floating Tracker Cooling Concentrator (FTCC), PV panels are coupled with the reflectors. The result is an increased efficiency of the system due to cooling effect of water and reflection of mirrors, leading to a 20% decrease in the cost as compared to the overland PV systems.
- The evaluation of a thin-film flexible floating PV array technology implemented on water reservoirs in Sudbury, Canada showed a 5% increase in system's efficiency due to the cooling effect of water [16].
- In China, the potential of a floating PV plant, covering an area of 2500 $km^2$ of water surface, can reach up to 160 Giga Watt (GW) and can save up to 2054 $m^3$ of water from evaporation annually. Thus, the competition for land can greatly be reduced especially in the eastern region of China. In comparison with traditional terrestrial PV systems, the floating PV plants show an increased efficiency of 1.58–2.00% as observed by 3-dimensional finite element analysis based on the water cooling effect [9].
- The energy generation of FPVS is estimated in relation to the ground-based PV systems. In China, the energy generation of FPVS is generally higher during the months of June to August but lower from September to October.
- It has been observed that the integration of floating solar panels with overland systems can be useful. In Maltese islands, the offshore location was used as a launching pad for PV panels floating on the surface of the sea and the resulting

yield was combined with traditional system of electricity production based on gas and steam turbines.

- The assessment of the deployed crystalline PV systems with pontoon type structures in offshore environments showed that the thin-film based PV systems are reasonably inexpensive for offshore wind power activities. Moreover, thin-film PV had higher output (in $GWh/km^2$) and specific installed capacity (in $MW/km^2$) than tidal barrage systems, wind and wave.
- Hydroelectric facility with the generation capacity of 227 kW can be operated together with 60 kW PV modules as revealed by the Homer software that is used for pre-feasibility study. Thus, the present generation capacities of the dams can be coupled with PV modules floating on the surface of water reservoirs. In addition, the water can be used for drinking purposes as well. In Santa Maria in Southern Brazil, about 60% of the population receives drinking water from Val de Serra.
- Universidad Politecnica de Valencia and CELEMIN ENERGY jointly developed an FPV system composed of polyethylene floating units that not only functioned as elastic fasteners and tension producers but also adjusted the system according to changing level of water reservoirs. The system covered the entire area of the reservoir i.e. 4490 $m^2$ at 300 kilo Watt power (kWp) and saved 5000 $m^3$ of water [17].
- Fish-eye-type lens camera and modeling approach i.e. digital elevation model (DEM) was used on FPVS on Pit Lake in mines of Korea to group the zones suitable for FPV system's shading. The array spacing of panels and most favorable tilt angle was kept in mind while designing the FPV system. System advisory model (SAM) by National Renewable Energy Laboratory, USA, was used for energy simulations based upon system design and weather data. The studies predicted that the future PV models would be able to produce 971.57 MWh/year by covering an area of 87,650 $m^2$ of water surface and total cost will be US$897,000 with the return time period of 12.3 years. The annual reduction in greenhouse gases will be 471.21 tonnes of $CO_2$ ($tCO_2$) [18].
- In Australia, the feasibility of the application of FPV on wastewater basins has been evaluated by Rosa-Clot et al. [19]. They have concluded that fixed panels are more suitable than tracking panels for wastewater basins.
- Artificial Neural Networks (ANNs) are implemented for forecasting power generation of big-scale PV plants. Moreover, the potential of FPV systems can be enhanced and determined by integrating GIS-based techniques with remote sensing technology [10].
- A feasibility study conducted in China shows that $151 million floating solar plant can produce 150 MW electricity which is enough to power around 50,000 homes.

## 3 Technical Feasibility of FPVS Over Land-Based PV Systems

Floating PV systems have many technical advantages over land based PV systems which make them a much better option for energy production. FPV systems are convenient and provide increased energy efficiency which makes them highly feasible. It is observed that the energy density of FPVS is higher than a land-based system. However, the utility-scale implementation doesn't involve increased cost. Choi [20] states that the efficiency of FPVS is 11% higher than overland PV systems while some studies also show that the efficiency of PV systems is 15% higher [7].

Energy produced by the FPV in any hour can be estimated as;

$$W = I \times A \times \eta$$

where, I is a mean hourly insolation, A is an area and η is a degree of efficiency of the power plant in the analyzed hour.

Efficiency of a PV power plant is determined as;

$$\eta = \eta_{module} \times \eta_{temp} \times \eta_{invertor}$$

where, $\eta_{\text{module}}$ is the degree of efficiency of a module; $\eta_{\text{temp}}$ is the efficiency of PV conversion due to the influence of deflection of the PV panel temperature from the Standard Test Conditions (STC) values; $\eta_{\text{invertor}}$ is the efficiency of the invertor [21].

In Skadar Lake at Montenegro, a study was conducted to compare the production of three power plants: first, overland PV plant with fixed azimuth angle (0°) and fixed optimal tilt angle (30°); second, base conceptual FPPP with fixed azimuth angle (0°) and fixed optimal angle (12°); third, the proposed FPPP with variable azimuth angle and fixed optimal angle (44°). Table 1 shows that the production of proposed FPPP was found to be 31.29% greater than that of the land-based PV system while the rise of insolation was observed to be 22.91% [22].

Modules of FPV can be either be fixed or equipped with the tracking system depending upon the external conditions. Thus, they can also adjust to the changing water levels to maximize the energy output. Hence, modules of FPVS can be easily arranged which is one of the greatest advantages of this technology. A study of a proposed floating photovoltaic power plant conducted by Vladan and Zeljko [23]

**Table 1** Comparison of ground PV, Base FPPP and proposed FPPP

| | Ground PV plant | Base FPPP | Proposed FPPP |
|---|---|---|---|
| Production of energy (GWh) | 141.71 | 145.72 | 186.05 |
| Annual insolation (kWh/m$^2$/day) | 5.02 | 4.66 | 6.17 |

*Source* Vladan and Zeljko [22]

showed the capability of the system to produce almost 186.05 GWh/year power annually and provide for about 20.78% electrical energy needs.

Evaporation in open reservoirs can lead to the loss of up to 40% water. However, FPV systems can reduce the evaporation of water from reservoirs by up to 70% and preserve the water levels during extreme summers. The PV panels and pontoons provide an effective cover to reservoirs resulting in decreased evaporation. According to Vladan and Zeljko [22], FPVS reduce evaporation in water bodies by up to 5.41 million $m^3$ per year. In South Australia, it has been observed that the FPVS reduce evaporation by 90% [19] while in India, 1 MW FPVS has been found to save 37 million liters of water [14, 15]. Moreover, evaporation in natural lakes and ponds can be reduced by 33% while in man-made facilities, 55% evaporation can be prevented [20] leading to efficient supply of drinking water. Thus, implementation of floating Photovoltaic systems is an effective option for conservation of water bodies, waste water treatments, wineries and fish farms.

A feasibility study of FPV systems in Skadar Lake in Montenegro in 2017 showed that the greatest amount of evaporation of the lake occurs in July at 9.27 mm daily while lowest evaporation occurs in December at the level of 1.19 mm per day. However, the reduction of 5.41 million $m^3$ was observed after implementation of floating photovoltaic power plants (Fig. 3) [22].

Following are the benefits of FPV systems in comparison to land-based PV systems;

- This floating system is durable, cost effective, and supple.
- The implementation of FPV systems is easy in comparison with overland-PV systems. Their installation is easy and not time consuming. The system can be

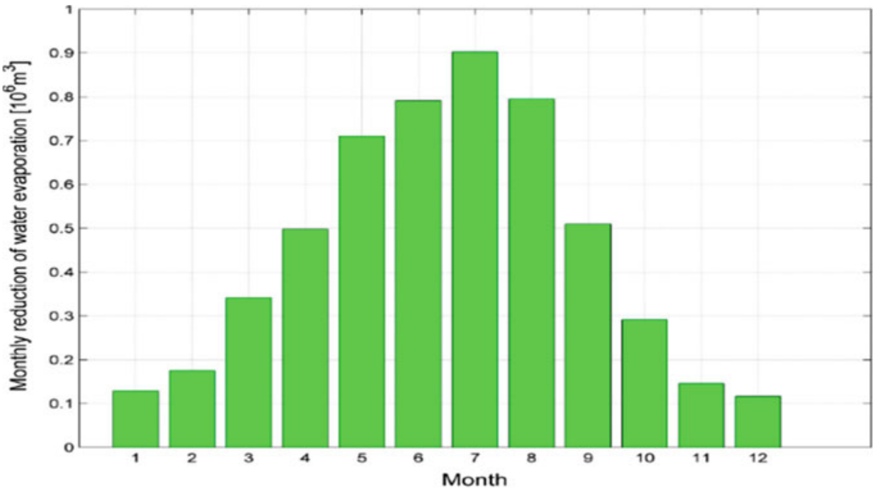


**Fig. 3** Monthly reduction of water evaporation at Skadar Lake after implementing FPPP (*Source* Vladan and Zeljko [22])

made firm by using old tires and bamboo in a short time of up to three months. Floating PV systems can be easily rolled up and transported by inserting flexible solar panels on a floating foil.

- Having shape-retaining properties and flexibility to resist waves, FPVS can withstand typhoons [6].
- The floating PV systems are 100% recyclable since they utilize high-density polyethylene which can withstand corrosion and ultraviolet rays [10].
- The marine sites are envisioned to comprise coated thin film PV which allows the arrangement to be supple while submergible arrays are inundated in unkind weather situations. By submerging photo voltaic (PV) panels at different depths, temperature difference of 30 °C degrees can be achieved due to the reduction of light reflection and absence of thermal drift. This can lead to an increase in efficiency by 20%.
- The FPVS systems have easy and cheap cleaning and maintenance system due to easy availability of water required for cleaning and less dust experienced by FPVS compared to land-based PV systems which continuously experience the soiling effect. Having less impact on land, FPV proves to be environmental friendly technology.
- This technology can be helpful in establishing a solar friendly real estate on industrial ponds, inland freshwater bodies, mine lakes, hydroelectric dams and irrigation reservoirs with its successful implementation.

### *3.1 Factors for Technical Feasibility of FPVS*

The technical and economic feasibility of FPV systems can be assessed by determining the weather conditions, water depth, solar radiation distribution, solar pathfinder, flow modeling, system connection, connectivity with power system, and a mooring method to ensure the adaptation of buoyant materials to substantial changes of water level.

It has been observed that the performance of the floating PV system depends on the number of factors including:

- type and size of modules,
- phase-change material (PCM),
- floating and support structure,
- construction of modules (single or multilayer),
- thickness of modules,
- temperature of modules,
- Optimum inclination of modules,
- Wind loads on PV modules.

The use of two microencapsulated phase change material (MEPCM) layers on the backside of the PV panels greatly contributes to the technical benefits of FPVS. It was observed that the energy output increased by 1.48% when two 3 cm thick

MEPCM layers having the melting points of 30 °C and 26 °C respectively were used. However, the power generation increased by 2.03% during summer when two 5 cm thick MEPCM layers with same melting points were used. The increase was observed due to the effects of MEPCM layers on the temperature control of PV cell and energy production efficiency of PV unit during the day [9].

The temperature of the modules plays an important role in higher energy efficiency of FPVS. A typical PV module, depending on the type of solar cells and climatic conditions, converts about 4–18% of the incident solar energy into electricity while the rest of the energy is converted into heat and this increases the temperature of the module [23]. This lowers the energy efficiency of the land-based PV systems. However, in case of FPV systems, the cooling effect of water keeps the temperature of the modules lower increasing their energy efficiency [24]. Operating temperature of FPVS has been found to be 3.5 degrees lower than the operating temperature of the land-based PV panels [9]. The use of aluminum frames for supporting PV modules can be especially useful for conducting the cooling effect of water. Moreover, the electricity generation efficiency can also be increased by the use of reflectors which increase the efficiency of solar energy capture during different times of the day [6].

Vladan and Zeljko [22] calculated the monthly energy output of a Floating PV plant at Skadar Lake in Montenegro keeping in mind the cooling effect of water, mean monthly water temperatures and mean daily insolation for each month. The biggest energy output was obtained for July and lowest for January with annual energy production of 178.34 GWh. This is shown in Fig. 4 and Table 2.

Depending on configuration of modules, the energy efficiency can change as well. Having fixed installation maximizes the coverage of the available area while tracking installation maximizes the energy collection [10]. Similarly, submerged configuration of PV panels is 20% more efficient than conventional panels exposed to air in summers [7, 10].

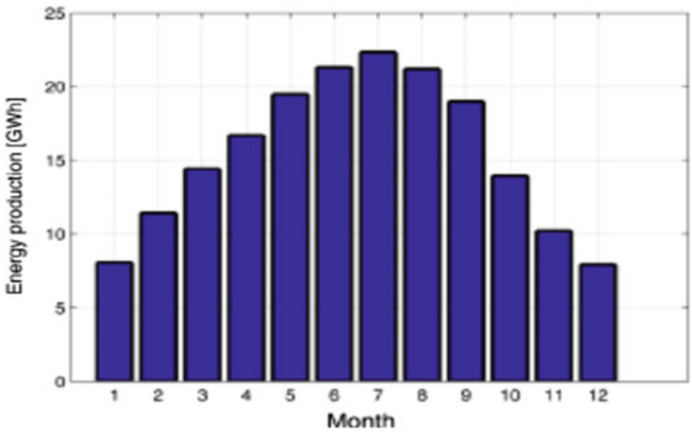


**Fig. 4** Monthly production of FPPP (*Source* Vladan and Zeljko [22])

**Table 2** Monthly production and insolation of the FPPP at Skadar Lake

| Month | Energy (GWh) | Insolation (kWh/m$^2$/day) |
|---|---|---|
| January | 7.50 | 2.82 |
| February | 10.48 | 4.37 |
| March | 13.65 | 5.15 |
| April | 16.16 | 6.30 |
| May | 19.02 | 7.55 |
| June | 20.82 | 8.71 |
| July | 21.81 | 8.89 |
| August | 20.63 | 8.38 |
| September | 18.26 | 7.32 |
| October | 12.93 | 4.87 |
| November | 9.51 | 3.70 |
| December | 7.53 | 2.84 |
| Total | 178.34 | Annual-Average: 5.91 |

*Source* Vladan and Zeljko [22]

The optimal azimuth angle for each FPV platform is determined according to the azimuth angle of the sun while PV panel tilt angle is determined according to maximum daily insolation for a year. According to the calculations done by Vladan and Zeljko [22], an optimum tilt angle of 44° is necessary for an average daily insolation at the level of 5.914 kWh/m$^2$/day as shown by Fig. 5.

In FPV systems, the wind pressure can produce great mechanical loads in the form of lift and drag forces on the panels and other components causing the movement of the system across the reservoir. This is because in FPV systems, wind pressure is transferred to the entire system unlike land-based PV systems in which the wind carriers are only in certain spots [25]. To mathematically determine the effect of the influential parameters on the resulting force of wind F affecting the platform, following formula can be used:

$$F = 0.5 \times C_F \times A_w \times v^2$$

where, $C_F$ is coefficient of force, $A_w$ is the surface affected by wind (m) and $v$ is the wind speed in m/s [22].

According to Santafe et al. [17], the force of the wind is directly proportional to the tilt angle and the size of the PV panel i.e. $A_{w.}$ However, to prevent the effect of large wind forces on the system, the system should be installed in such a manner that in case of strong winds, the panel aborts tracking the sun and starts rotating so that the azimuth angle of the wind in relation to the module becomes 0° (Fig. 6). By placing the system at this angle, the effect exhibited by the lift and drag forces is decreased.

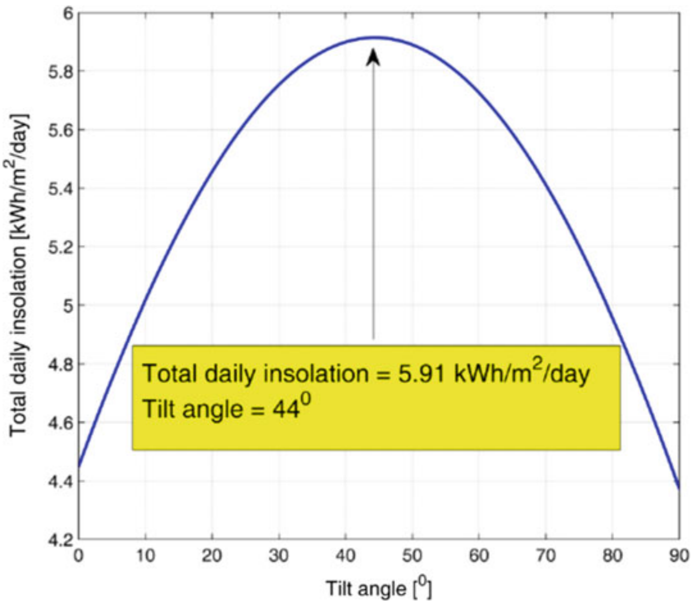


**Fig. 5** The calculation of an optimal tilt angle of a PV panel (*Source* Vladan and Zeljko [22])

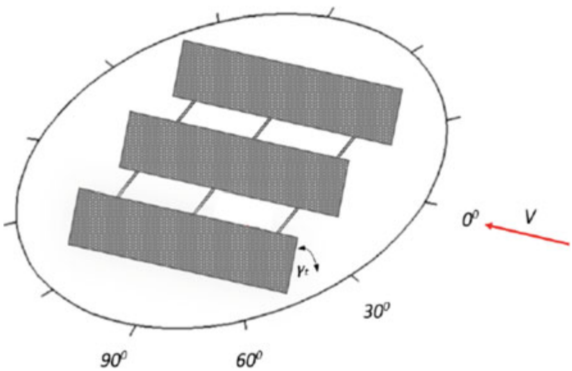


**Fig. 6** Positioning of PV panels during strong winds (the assumed wind direction is indicated by red arrow) (*Source* Vladan and Zeljko [22])

## 4 Economic Feasibility of FPVS

The cost associated to the installation of the FPV system consists of three components i.e. Balance of System (BoS), modules and inverter.

The balance of system costs includes a wide array of components ranging from technical considerations to soft skills. BoS is primarily divided into three categories including the hardware costs, installation/deployment costs and soft costs. Firstly, the hardware expenses include components like racking, mounting, cabling, grid

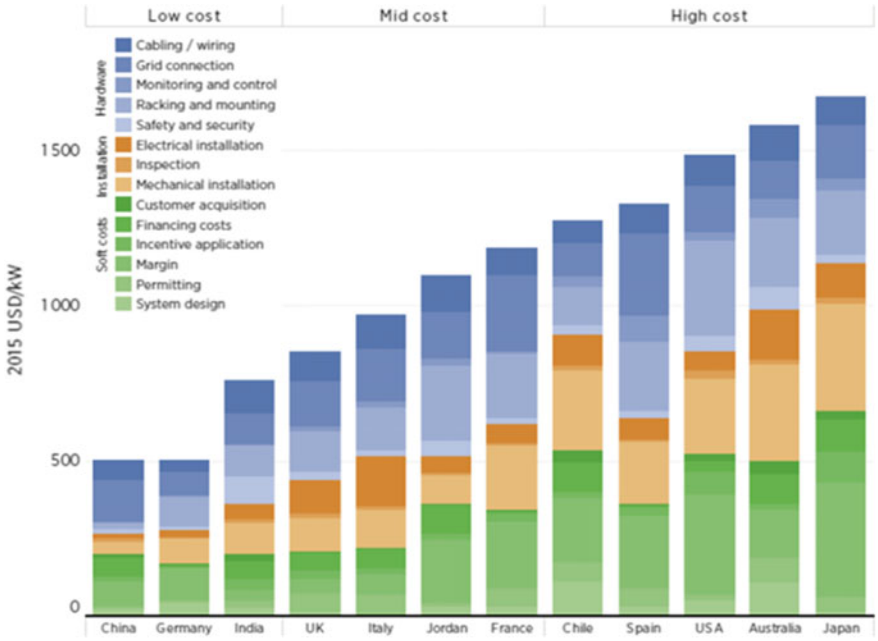


**Fig. 7** Balance of system country comparison (*Source* IRENA [26])

networking, safety and security and the monitoring system. Secondly, the installation costs reflect the mechanical and electrical part of the deployment as well as the technical supervision carried out during the construction phase. Lastly, the soft costs comprise of the designing of the system, financial plans, deployment permits and the supporting policies. The costs associated to the BoS and its regarding components vary from region to region thus, giving a comparative overview of the regions which have attained technical efficiency and cost effectiveness in comparison to other regions as shown in Fig. 7 [26].

The modular costs include all the mechanical part of the FPV system that just requires the application of designated technical skills to assemble and deploy them. Solar PV systems have been observed to depict a high learning rate of up to 22% in the past few years. An annual increase of 40% growth in the PV market in past decade has caused a significant decline in the prices of the modules by up to 80% by 2015. Referred to which, the average price per module ranged from 0.52 $/W for India and China to $0.72 $/W for Japan. The trends are shown in Fig. 8 [27].

The inverters are the central functioning component of PV systems as these convert the direct current produced by the PV units into the grid compliant alternating current for consumer utilization. PV inverters are divided into three categories including micro inverters that can be installed for each PV unit with capacity up to 360 W, string inverters having operational capacity of 100 kW and the central inverters used for systems functional beyond 100 kW. For large scale deployments, the utilization

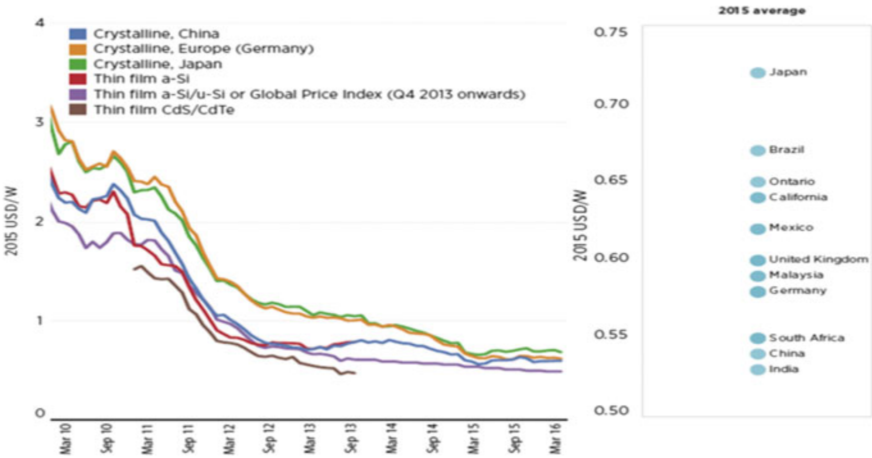


**Fig. 8** Modular price global trends [27]

of central inverters is in the lead while the micro and string inverters remain utilized in small and domestic scale applications.

According to a research conducted by Vartiainen et al. [28], 55% of the total cost is attributed to the modular components and inverters, while 45% of the total cost is attributed to the balance of system as shown by the Fig. 9.

According to Masters et al. [21], if the operation costs are taken as costs per produced kWh of electrical energy, then the production costs can be calculated as:

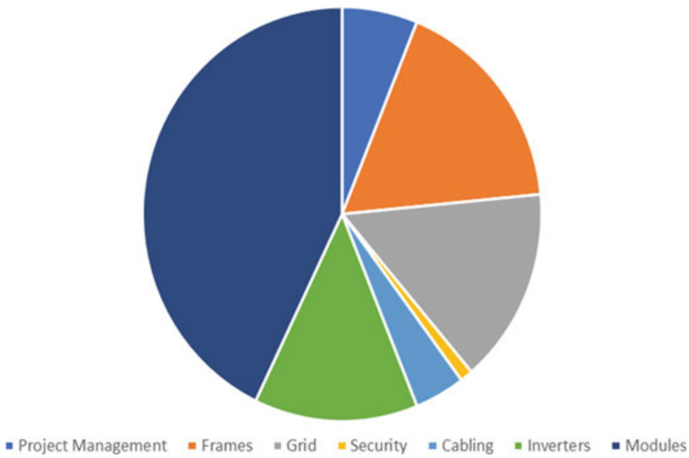


**Fig. 9** Solar PV Global average cost (*Source* Vartiainen et al. 2019 [28])

$$c = \frac{\left(\frac{i \times (1+i)^n}{(1+i)^n - 1}\right)}{A_v \times E} \times I_{tot} + m$$

where, $c$ denotes the price of 1 kWh produced electrical energy, $I_{tot}$ is the total investment, $A_v$ denotes the availability factor for FPVS, E is the annual energy produced by FPVS in kWh, m is the operation cost, $I$ is an interest rate and $n$ stands for amortization period for the power plant.

Following are the economic benefits that FPVS have over land-based PV systems:

- Cost of implementation of FPV systems is less since no heavy equipment such as boilers or chimneys are required. Moreover, the FPV panels can also be mounted on a rigid pontoon structures. This reduces the amount of steel structures in the plants. Similarly, the cost of building the supporting floating structure is lesser than the cost of buying and preparing the equivalent area of land i.e. civil works and seismic proof foundations for land-based PV systems. As per a study, the supporting floating structure of FPVS accounts for up to 25% of the total cost of the project. Kim et al. [29] conducted the cost analysis for the construction of 1 MWp FPV system on the bases of construction materials used and concluded that for lighter structures made of fiber-reinforced polymer, the investment costs were greatly lowered. The investment costs are further lowered with the growth of total installed capacities as well of unit power.
- FPVS reduce the saving cost of land and operating cost for power generation expenses since a large number of giant water bodies are readily available all over the world [5]. Unexploited and non-revenue generating water surfaces can be converted to commercial solar power plants by implementation of FPVS. This can lower the energy generation expenses and can lead to significant savings on land prices [10].
- Operation and maintenance cost of FPVS is lesser than that for land-based PV systems. This is because the water required for cleaning is readily available at source and components are less likely to overheat. Similarly, FPV technology is less prone to dust and saltwater corrosion is not normally a problem since most FPV systems are installed on freshwater bodies such as lakes and reservoirs. In addition, no maintenance is spent on clearing away terrestrial vegetation as FPV is less prone to shading and other obstacles that block the sunlight.
- On contrary to the capital expenditure the operational expenditure varies exponentially from region to region. Thus, there can't be an exact figure depicting the global average. The operations and maintenance are based upon regular activities requiring continuous availability of human and technical resources. It must be taken into consideration that though the administrative and cleaning costs almost remain the same through the lifetime of a system, yet the replacement cost of technical components is bound to increase with time (Fig. 10).

- The payback period of 1 MW Floating Solar Power Plant (PSPP) was calculated. The plant consisted of 4000 modules of capacity 250 each with minimum plant life of 25–30 years and the payback period was only 5 years. Its economic

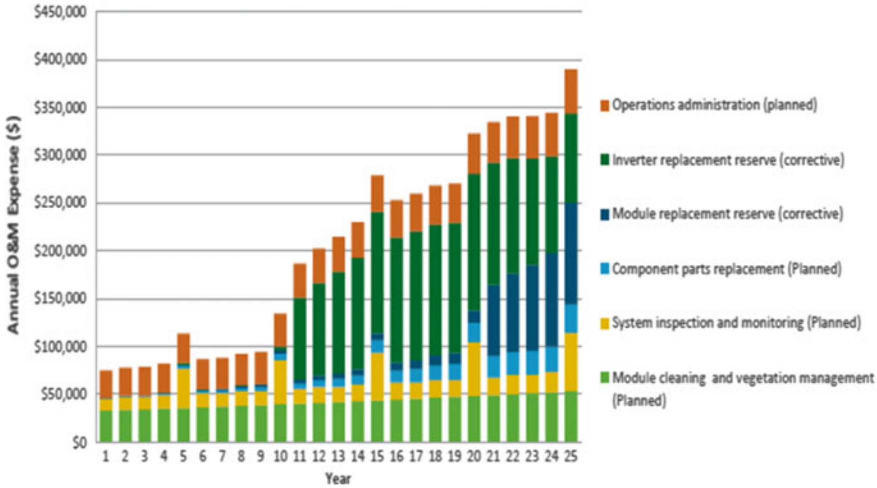


**Fig. 10** PV operational and maintenance cost trend [28]

feasibility was also highlighted. Total Installation Cost taken was crore 8; Selling Cost per Unit Rs/kWh 9; Total Generation Hours 1920; Total Generation (MU) MU/per Day 0.008. Earning per Year Crore 1.728; hence providing Savings after 10 years of Crore 9.28.

The payback period is calculated as:

***Payback period = Total cost of PV system with all auxiliary equipment/Total annual cost saving after installation of PV system***

- Due to the growth of this technology, FPV technology, just like land-based PV technology, is applicable for federal grants, subsidies and incentives in many countries. Similarly, increased implementation of Floating photovoltaic technology in many parts of the world is providing new job opportunities in business, design and pre-construction departments. In 2016, there were more than 3 million people employed in solar PV technology. This was more than the number of people employed in any other renewable energy sector.

## 5 Ecological Feasibility of FPVS

FPV technology presents many advantages to the environment which are discussed below;

- Being a green technology, FPVS can significantly reduce carbon dioxide gas emissions by 83.42 kt $CO_2$/year thus, greatly mitigating the issue of climate change [22].
- The reduction in greenhouse gas emissions can be obtained by the following formula:

$$G_t = E_s \times G \times (1 + \beta)$$

- where, $G_t$ is an amount of GHGs reduced annually ($tCO_2$/year), $E_s$ is annually production of electricity by a FPVS (MWh/year), G is a standard value of Greenhouse Gas (GHG) emissions from each country ($tCO_2$/MWh) and $\beta$ is an average loss rate of the power transmission and distribution systems.
- Where land-based PV systems require about 2.2–12.2 acres/MW area of land for implementation of the system, FPV systems are implemented on water bodies and thus, conserve land for agriculture, mining, tourism and other land-incentive activities. FPV is an environment friendly technology with less impact on land. In addition, the implementation of FPVS on water bodies reduces the need for deforestation and encourages reforestation. The increased deforestation required for land-based solar plants leads to increased runoff and soil erosion resulting in increased intensity of the storms and floods etc. It further emits a greater amount of $CO_2$ into the atmosphere. FPV systems reduce the loss of habitat and conserves biodiversity.
- Implementation of FPVS on water bodies reduces the penetration of sunlight in water thus, reducing the rate of photosynthesis in water. Consequently, formation of algae in the water bodies is also decreased. FPVS lead to improvement in quality of water [10].
- In the water bodies where FPV systems are installed, reduced evaporation and more retained water are beneficial for animals and vegetation. In the proposed floating photovoltaic power plant planned on an isolated and shallow part of Skadar Lake whose water level in the summer months decreases to a critical height that isolates it from the rest of the lake, the effect of evaporation reduction has been observed to have a very positive effect on the survival of living organisms in this part of the lake [22].

## 6 Challenges for the Implementation of FPVS

The development of system design that adjusts to surrounding conditions and stays afloat is one of the major challenges in the commercialization of this technology. Following are some of the major challenges that need to be researched upon:

- Being surrounded with water, the structure of the system may be affected by corrosion due to high moisture levels and adverse environmental conditions [12]. Moreover, many other environmental factors affect FPV systems such as water quality, variation in water depth, water currents, tides, temperature fluctuations, oxygen, evaporation, fish, algae and many other living organisms. Also, FPV systems must be able to withstand erratic movements caused by floods, cyclones, typhoons and high winds [6]. These forces of nature pose vibration and stress issues which may lead to micro-crack formations in the modules. Consequently, electricity production might be decreased and durability results might occur.

- The implementation of FPV technology on seas has been especially found to be unsuccessful due to the sea tides and high speed winds which continuously disturb the positioning and azimuth angle of the panels. Moreover, saltwater increase the threat of corrosion as well [30].
- Floating systems require mooring systems providing directional control to maintain the azimuth angle of the panels otherwise, the power output can be reduced.
- The initial installation of FPV systems requires high costs. The initial investment cost of FPVS is 1.2 times higher than the conventional solar power plants [10]. Moreover, the cost of energy production of solar panels is about 10 times higher than energy production costs of fossil fuel based technologies during the recent years.
- The quality of water may be degraded by the construction material of the modules such as silicon modules and High-Density Polyethylene (HDPE) thermoplastic floats.
- The transport of the power generated from water to the land area presents a safety risk. Due to the presence of underwater cables, increased number of electrical accidents may occur which might kill aquatic animals. Hence, flora and fauna might be affected leading to biodiversity loss, and hindrance in transportation activities and fishing [6].
- Birds might be killed by being attracted to the panels and hitting them. Moreover, by the optical reflection of the sunlight with the panels, a glare might be produced which might be uncomfortable for the surrounding fauna and the residents of the area.

## 7 Recommendation of Implementation of FPVS in South East Asia, Central Asia and South Asian Countries and Others in the Region

Asia is the most populous region of the world with a population of 4,601,371,198 people forming about 59.7% of the world population [31]. Among Asian regions, South Asia contributes a population of 1,918,211,381 (24.9% of the world population) while South East Asia contributes about 662,011,806 population (8.6% of the world population). Furthermore, the population of Central Asia is 73,212,100 (1.0% of the world population). Being one of the most populous regions of the world, the energy demands in these areas are also tremendously high and are likely to increase even further.

## *7.1 South East Asia*

According to Enerdata [32], the energy consumption of South East Asia rises by an average 3% per year and is expected to reach 1.6 Gtoe (tonne of oil equivalent) in 2050. About 17% of the total energy consumption in the region was provided for by electricity in 2017 and is expected to increase by 30% in 2050. South East Asia's energy demand will be increased by two-thirds by 2040 as mentioned in World Energy Outlook 2018 with installed capacity increasing from 240 to 565 gigawatts. Moreover, the energy demands are likely to increase by double digits per year for the region's poorest countries such as Myanmar, Laos, and Cambodia etc. while 6–10% annual growth in energy consumption has been projected for Philippines, Vietnam and Indonesia etc. [26]. The region's major source of energy is coal with about 35% of the region's energy coming from coal [32]. Top 10 ASEAN (Association of South Asian Nations) countries are among the top 20 investors of new coal capacity which proves that the current energy generation mechanisms of South East Asia are not environment friendly and run counter to the clean energy production targets of most of the countries. The energy profile and population profile of the Southeast Asian region for the years 2000, 2010 and 2018 are provided in Fig. 11. The three bars for each category represent year 2000, 2010 and 2018 respectively.

Moreover, the climate of Southeast Asian region is mostly tropical and the weather remains hot and humid year round due to which the region experiences high rates of evaporation from the water bodies. In addition, there is an increasing competition of solar companies for land due to expanding population and rising demands for agriculture and industry. In this situation, floating solar technology can be an attractive alternative which can help solve Southeast Asia's energy crisis and environmental issues [33].

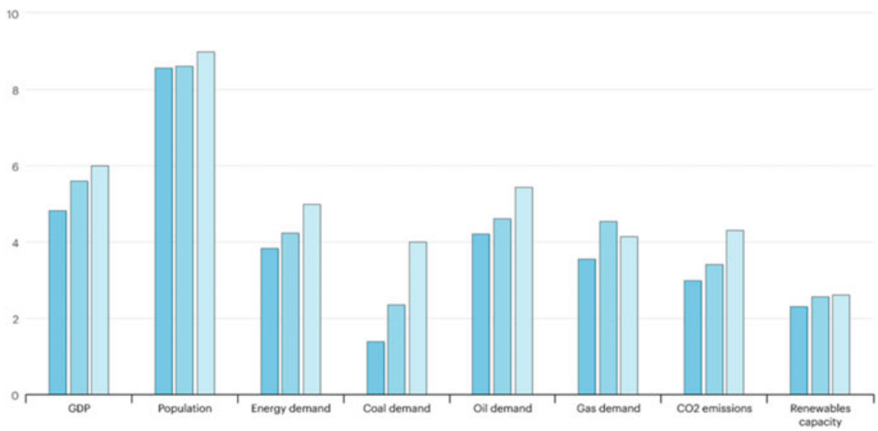


**Fig. 11** Share of selected global economic and energy indicators in Southeast Asia, 2000–2018 (*Source* International Energy Agency [26])

## 7.2 Central Asia

Central Asia is a region consisting of Uzbekistan, Kyrgyzstan, Kazakhstan, Tajikistan and Turkmenistan with Uzbekistan being the most populous country in the region. Though the region is rich in natural energy resources such as oil, gas and coal, there is uneven distribution of these resources among the countries due to breaking up of Soviet Union. Tajikistan and Kyrgyzstan have high hydropower potential but low amounts of fossil fuels while Kazakhstan has huge amounts of oil, coal and gas reserves. In Uzbekistan and Turkmenistan, there are great amounts of gas reserves with little amounts of oil and coal reserves. In view of these scenarios, fossil fuel rich countries such as Kazakhstan have high energy export potential and have approached markets outside the Central Asian region. However, countries such as Kyrgyz republic and Tajikistan which get hydropower surpluses in summer have to face the major energy shortages during the winter and have not been able to secure energy export markets for their summer energy surpluses. Thus, the major source of energy generation in Central Asia is fossil fuels which worsen the impacts of climate change and are not efficient since up to 10% of the energy can be lost during power transmission. Moreover, the energy consumption of the region is greater than the production levels. Consequently, there is a need for a clean and cost-effective energy production source in Central Asia to meet these energy demands. This has shifted attention towards renewable energy sources especially solar energy since price of panel producing 100 watts of electricity has continuously decreased from $37 in 2016 to $24 by the end of 2018.

Central Asia's geographical conditions are especially favorable for the implementation of FPVS due to the availability of large number of rivers and other water bodies. The region also receives an average of 250 sunny days a year. The Central Asia receives solar radiations of about 1300–2200 kWt/hour on one square meter, which makes the region suitable for enforcement of PV technologies as mentioned in Fig. 13 by Winarso [34]. FPV can also help store water in Central Asian water bodies since the level of evapotranspiration is larger than the level of precipitation, P/PET < 0.5 (150/500) in different regions especially in arid and semi-arid locations. Most of the water collection technologies are related to the open surface water reservoirs in Central Asia; therefore desertification over its territories is becoming a complicated issue. There are considerable water losses in open reservoirs via salty water creation and evaporation. Keeping and recharging the water in aquifers is an alternative solution for reducing the rate of evaporation from water bodies. During Central Asian summers, the water resources continue to dry up, thus giving rise to irrigation issues. Thus, implementation of FPVS can be highly feasible in Central Asia in terms of energy production and water resource conservation. A feasibility study was conducted for assessing the potential of FPV technology in Central and West Asia. Lake Boyukshor and Toktogul reservoir have been identified as potential installation sites for FPVS in Azerbaijan and Kyrgyzstan respectively. Lake Boyukshor is a highly saline dumping site which has the power production potential of 500 MW while Toktogul reservoir is the largest reservoir in Central Asia having the potential of producing over 20 GW.

### 7.3 South Asia

In 2014, the electricity consumption in South Asia was 707 kWh per capita while oil, gas and coal sources accounted for about 80.03% total electricity production in the region. Energy use in the region was measured as 576 kg of oil equivalent per capita. Renewable resources, on the other hand, accounted for only 16.8% of the total energy production. Gaseous fuel consumption was found to be the source of about 8.11% of the total carbon dioxide emissions while liquid fuels produced 626,745 kt of $CO_2$. From 1971 to 2014, electricity consumption in India grew from 97.773 to 804.514 kWh per capita while energy consumption in Pakistan increased from 93.48 to 447.501 kWh per capita. The rise of energy consumption from 57.657 to 531.091 kWh per capita was observed for Sri Lanka from 1971–2014. Energy consumption grew from 6.005 kWh per capita in 1971 to 146.468 kWh per capita in 2014 in Nepal while in Bangladesh, electricity consumption increased from 10.834 kWh per capita in 1971 to 320.204 kWh per capita in 2014 [35]. South Asian countries are now starting to work on renewable energy resources to produce clean energy and these projects are being successful as shown by the implementation of FPVS in India and other countries mentioned above.

Keeping in mind the success of this technology in India and many other regions of the world, such implementations should be extended to Pakistan and Afghanistan etc. Implementation of this sophisticated technology in Pakistan, Afghanistan, and Central Asia was discussed in Indus Basin Knowledge Forum held in Colombo, Sri Lanka and included in the Ten Point Agenda Actions for the future. Indus Basin which originates from Tibetan Plateau in China and shared by China, Pakistan, India and Afghanistan is an ideal reservoir for the implementation of FPVS in South Asian region. Travelling through these countries, the basin is nourished by tributaries of Hindu Kush, Himalayan and Karakoram regions and is a source of food and energy for almost 300 million people living along its territories. The forum also shed light on Central Asia's experiences related to climate change, flood, droughts and snowmelt processes and highlighted the importance of FPV technology in Pakistan, Afghanistan and Central Asia [6].

Having the current electricity generation capacity of 33,836 MW, Pakistan in South Asia faces energy deficit of 2500 MW. Most of the energy generation sources of the country are non-renewable with hydel sources, RLNG (Compressed Natural Gas), gas, oil, nuclear sources and other renewable resources accounting for about 27%, 26%, 20%, 16%, 5% and 5% power generation respectively. Pakistan is among the countries most suitable for installation of FPV systems since the country is attributed with one of the highest insolation values in the world i.e. an average of 8.5 h of daylight availability. According to a research, the monthly mean daily GHI (Global Horizontal Irradiance) of the country is 4.44–5.83 kWh/m$^2$ thus, averaging the annual mean at 5.27 kWh/m$^2$. On the minimum, annual mean daily GHI has been 4.44 kWh/m$^2$, which still is more than the global annual mean daily GHI being valued at 3.61 kWh/m$^2$. In terms of power generation, the solar energy potential associated to the various regions of the country commendably ranges from 2.0 up to

8.5 kWh/$m^2$ per day. Despite the availability of ideal conditions, the adaptation of the technology has been relatively slow in comparison to other countries [36]. Even though the country has a potential to produce the astounding 2.9 million MW of clean energy by utilizing the solar PV technology, it is currently delivering a mere output of only 1556 MW. In Pakistan, Baluchistan has the highest photovoltaic potential of 5.8 kWh per day with Sindh and Southern Punjab having the potential to produce 4.5–5.4 kWh per day. The areas of Northern Punjab, Khyber Pakhtunkhwa and Gilgit Baltistan have the referred potential valued between 3.4 up to 4.4 kWh per day. Substantial efforts have been observed in recent years from the governmental as well as private bodies to adapt the solar power as an alternate to the conventional energy sources which suggests that Pakistan will soon make significant contribution in the field by doubling up its current solar energy output by 2022 [37]. Keeping in view the current solar energy adaptation trend within the country, various land-based projects have already started to deliver and many are on way to be accomplished.

Another suitability factor for deploying FPV in Pakistan is the canal system of the country which is one of the best in the world. At present there are a total of 57 canals included in the system of which 45 are regular canals while 12 are linked ones. The referred canal system runs through 3 large dams and 85 small dams within the country with a total length of 56,073 km. The canal system is divided into three types; perennial canals that have the running supply of water throughout the year; non-perennial canals that have supply of water only through the summers or rainy season; inundation canals that are only active through the rainy season. Among these, perennial canals are the best fit for the deployment of FPV systems which are abundant in Pakistan. The potential of solar PV technology in Pakistan and all over the world in terms of solar irradiance is shown by the Figs. 12 and 13 respectively.

To implement and obtain benefits of FPV technology, the countries in Central, South and South East Asia need to generate their own databases to own all pertinent datasets such as available data in GIS (Geographic Information system) surroundings and web-based GIS. This is important in understanding the hydrological settings of an area. Moreover, it guides and helps in accessing agreements to use facilities, preparing safety fences, and installing floating solar panels on small water bodies and reservoirs in selected areas and in providing awareness and training sessions to scientific community and people. At the later stages, generated databases and GIS data help determine the spatial relationships between the acquired datasets, and develop sound conceptual models which are then used for developing surface–groundwater modeling to be used in prediction analyses. This highlights the criteria for installing the floating solar plants with sustainable water supply and clean energy production perspectives.

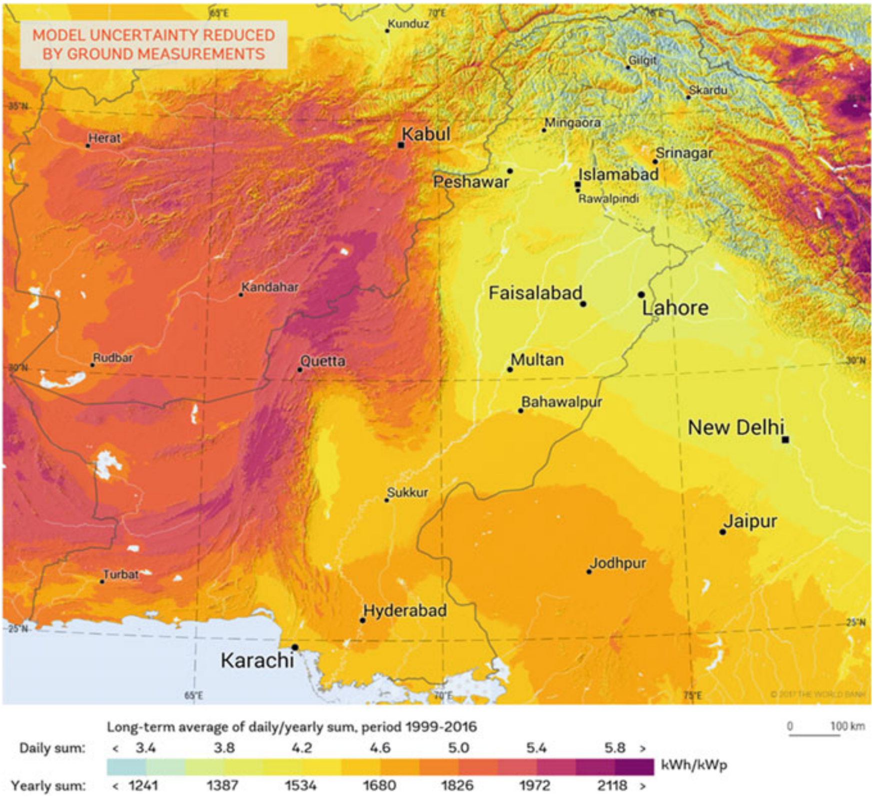


**Fig. 12** Solar potential in Pakistan (*Source* Stokler et al. [38])

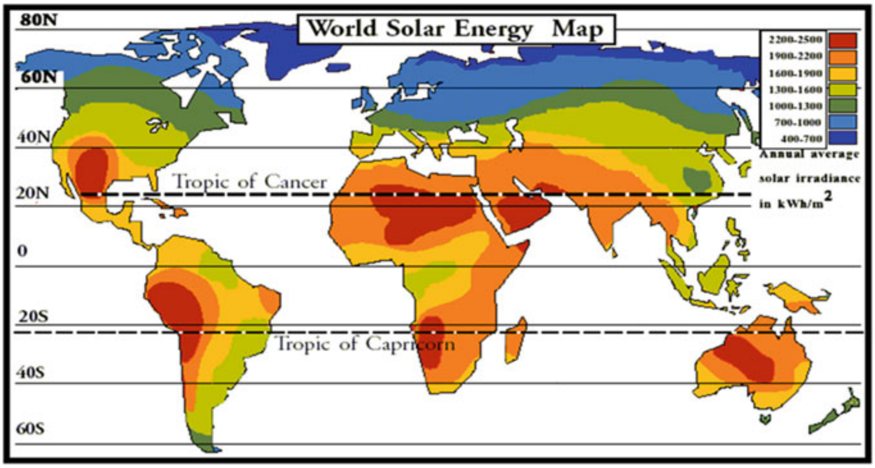


**Fig. 13** Global solar resource for PV technologies (*Source* Winarso [34])

## 8 Conclusions

The tremendous increase in world population and climate change issues are presenting an enormous demand for increased clean energy production and sustainable supply of freshwater. This poses the necessity to shift from non-renewable resources to renewable resources of energy production among which floating photovoltaic technology can be of great interest since it has greater energy efficiency, reduces evaporation from the water bodies, improves water quality, increases aquatic biodiversity, eliminates the need for land acquisition and provides economic benefits. In view of these benefits, many countries around the world such as Spain, India, China, Japan, South Korea etc. have initiated FPV megaprojects to fulfill their energy needs. However, world's most populous regions with higher energy demands i.e. South Asia, Southeast Asia and Central Asia, which need a sustainable alternative the most, are still lagging behind in implementing this technology. These regions lose a large amount of water by evaporation from their reservoirs due to high temperatures and have highly saline water and soil posing issues of water supply. They also have power transmission problems. The countries in these regions especially Pakistan and Afghanistan have a high potential for deploying this technology due to large number of water reservoirs in these regions and sufficient insolation. Hence, the new FPV technology can be a way forward for these countries to solve their energy, water and food crisis. Being a new technology, however, there are certain parameters of this technology that need to be studied in detail. Further research is needed to monitor the effect of salt water corrosion on modules as well as the effect of high winds, tsunamis etc. on the orientation of the panels. Similarly, solar tracking system to check and maintain the tilt and angle of solar radiation needs to be focused while designing the systems. In this regard, GIS based techniques integrated with remote sensing can be potentially useful. Hence, it is concluded that the developed and developing countries must come together and carry out an extensive research of the newly emerging FPV technology so that all the developing and underdeveloped regions of the world can get their basic right i.e. access to clean energy and sustainable supply of water.

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# Towards a Shared Future

**Muhammad Asif**

## 1 Commonality of Challenges

It has been over 50 years now that Marshal McLuhan used the term global village which describes the idea of global coexistence with influences from international communication, culture, travel, and trade and commerce. The COVID-19 pandemic has most recently cemented the planet's status of a global village as the virus originating from the Chinese city of Wuhan has virtually paralyzed the whole world. The global energy and environmental scenario is another befitting indicator to manifest the concept of a global village.

Climate change, as a result of global warming, is leading to wide-ranging problems such as seasonal disorder, a pattern of intense and more frequent weather-related events such as floods, droughts, storms, heatwaves, wildfires, health problems, and financial loss [1]. The United Nations (UN) warns that climate change can also lead to a global food crisis [2]. It has been reported that since the advent of the twentieth century, natural disasters such as floods, storms, earthquakes, and bushfires have resulted in an estimated loss of nearly 8 million lives and over $7 trillion of economic loss [3]. Future projections suggest that by the year 2060 more than one billion people around the world might be living in areas at risk of devastating flooding due to climate change [4]. A recent study suggests that by 2070 up to 3.5 billion people will be living in areas too hot for them [1].

Global warming is one of the most pressing factors advocating for the shared future of the planet in terms of the faced challenges and the potential solutions. Eminent scientists and scholars are expressing their concern about global warming. In a survey, 50 Nobel Laureates described climate change as the biggest threat facing mankind

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ahead of issues like disease, nuclear war, and terrorism [5]. Stephen Hawking repeatedly raised alarm bells as "Climate change is one of the great dangers we face, and it's one we can prevent if we act now. We are close to the tipping point where global warming becomes irreversible." He also described energy as one of the key factors that will "lead to the end of life on Earth" [2]. According to Noam Chomsky, "we have entered a new geological era, the Anthropocene, in which the Earth's climate is being radically modified by human action, creating a very different planet, one that may not be able to sustain organized human life in anything like a form we would want to tolerate." [6].

Global warming is a threat to the whole planet, its intensity however is not uniformly distributed. Climate change is affecting the whole world, but the poorest countries are suffering the earliest and the most. The majority of the global population suffering from climate change are from developing countries with limited resources to mitigate the challenges and to rebuild their lives after extreme environmental events. It is the low lying and small island countries, also termed as small island developing states (SIDS), which are being hit harder. The UN Secretary-General Antonio Guterres also acknowledges that "Climate change is happening now and to all of us. No country or community is immune. And as is always the case, the poor and vulnerable are the first to suffer and the worst-hit" [7]. For small island developing states (SIDS), global warming poses an enormous set of challenges for their livelihood, safety, and security. Since most of the infrastructure in these countries is on the coast, the damage from consequent erosion and flooding is likely to be hugely burdensome for their typically modest economies. Owing to their smaller land area compared to other countries, they cannot afford to lose land due to surging sea levels. For some, for example, Maldives, it threatens their very existence. One of the significant heartbreaks of global warming is that developed and industrialized countries are acutely responsible for the phenomenon but the heavier price is to be paid by the poor and developing nations. For example, the average value of the per capita energy consumption—an index to measure the contribution towards global warming—in industrialized and developed countries is almost six times greater than that in developing countries [8].

It is projected that unabated climate change could cost the global economy at least 5% of GDP each year and in worst case scenario the cost could be more than 20% of GDP" [9]. The situation demands collective and cohesive global efforts to mitigate the implications of climate change, and in doing so climate justice should be taken care of. Focus on climate change should be embedded in development policies at all levels. Rich and industrialized countries such as the Organisation for Economic Co-operation and Development (OECD) nations should share the responsibility for their emissions by helping the vulnerable and resource-deficient nations in the fight against climate change.

## 2 Energy and Environmental Security: A Balancing Act

In the modern age, energy is closely linked to the environment. Energy security and environmental security are thus becoming increasingly intertwined, especially in the wake of the global drive for sustainable development. They have commonalities both in terms of the challenges faced and the potential solutions. The energy and environmental securities have strong economic dimensions as well. Not only that the energy and environmental problems adversely affect the economy of a society, to address them also requires significant financial resources. Energy, environment, and economy are therefore interwoven factors. The energy-environment-economy triangle is quite complex and dynamic in its very architecture.

Despite all the realization about the importance of energy in the socio-economic uplift and advancement of societies, the global energy landscape continues to face numerous challenges, above all, acute energy security issues facing large proportions of the population around the world. The nature of challenges for countries at different socio-economic and technological strata can hugely vary. While a considerable segment of the population in the developed countries continue to experience fuel poverty, electricity deprivation remains a challenge for many in Africa and Asia. Although globally there has been a significant improvement in recent years in terms of grid penetration, quality of grid, and affordability of energy remain to be critical issues for many in developing countries. Issues like poor grid quality, power outages, and breakdowns, planned load shedding, and brown shedding is a regular phenomenon even in major cities in these countries. Lack of access to reliable and refined energy resources can also be gauged from the fact that around 2.6 million lack access to refined cooking fuels. The situation is even more alarming when energy security is looked at from the 4As perspective: availability, adequacy, affordability, and acceptability.

Developing countries are typically reliant on fossil fuels, largely imported, to meet their energy requirements, especially for power generation. Fossil fuels are typically extremely localized in terms of their existence and well over 80% of the countries in the world rely on imports, especially in the case of oil and gas, to help meet their requirements. Consumption of fossil fuels entails environmental emissions besides affecting energy security in terms of import dependency and higher energy prices for consumers. The import bill can also be a massive burden on the developing and poor economies. In South Asia, for example, over 90% of the oil and gas supplies are imported with similar consequences. Developing countries experience further challenges, such as aging and inefficient energy infrastructure, resulting in additional monetary and environmental burdens. With the fast growth in energy demand, in the coming decades, they face the task of large capital investments in the energy sector. It is important to channel the investment towards sustainable energy projects focusing on renewables, distributed generation, and energy efficiency to better address the energy and environmental challenges. Renewable and energy efficiency projects however due to their very nature are capital-intensive, making them a difficult choice for weak economies. Over the years several international bodies including United

Nations Environmental Program (UNEP) has launched several programs to support renewable energy and energy efficiency projects in developing countries. One such program was the International Advisory Facility (IAF) under UNEP's Global Environment Facility (GEF) initiative with the aim to "help project financiers make informed business decisions on renewable energy and energy efficiency investment in developing and transition economies".

## 3 A Renewable Pathway

The environmental footprint of fossil fuel-based energy systems contributing to almost 80% of the global supplies, is an issue needing urgent and meaningful attention [10, 11]. Though there has been a global drive to shift away from coal and oil-based power generation, the energy sector remains to be one of the biggest contributors to GHG emissions. In recent decades renewable energy has come of age as a strong candidate to help address the energy and environmental security. Renewable energy has also emerged on the global energy landscape as the flag bearer of a sustainable energy transition. It offers a promising solution to help address the global energy and environmental problems. Renewable resources—i.e. solar energy, wind power, hydropower, and biomass—are abundant and inexhaustible offering environmentally clean energy [12, 13]. Another major advantage renewables have in comparison to other types of energy resources is their vast distribution. Unlike fossil fuels, for example, renewable resources are widely distributed across the world. Almost every country has some form of renewable energy available within its geographic borders thus offering a kind of energy freedom. In recent years renewable energy has overtaken the supplies from fossil fuels and nuclear power both in terms of investment and capacity addition. The fast expansion of the renewable energy base has been mainly propelled by the success of solar energy and wind power. Factors like conducive policies, technological advancements, and economy of scale have contributed to the accomplishments of renewable energy. The global renewable power capacity including hydropower at the end of 2019 stood at 2,588 GW. For the fourth year in a row, increment in the installed capacity of renewables has outpaced the net capacity addition of fossil fuel and nuclear power combined. Solar photovoltaic (PV) is one of the most promising and fast-growing renewable technologies, accounting for 58% of the total renewable capacity addition. With 115 GW of new capacity addition in 2019, its total installed capacity stood at 627 GW at the end of the year [14].

Over the last couple of decades, renewable energy has made fast inroads into the global energy landscape despite its intermittency issues. The intermittency issue can be helped by employing diverse renewable resources. Renewable technologies are gradually maturing in terms of efficiency and performance. Large scale deployment of renewable energy, however, comes with its own set of challenges—it is capital intensive as well as it requires significant changes in the existing energy markets, institutions, infrastructure, and political and cultural practices. The cost trends in energy markets are favoring renewables with solar and wind power already becoming economically competitive in many places. The price of PV projects for example has experienced a dramatic fall in recent years—power purchase agreements have been signed at prices as low as US Cents 2.34/kWh. Intermittency is, however, a major shortcoming of renewables like solar energy and wind power which can lead to grid integration issues with their increased penetration in the system [15].

Renewable energy offers an appealing package to the developing countries in terms of indigenous supplies, scalability and flexibility of projects, decreasing cost trends, and environmental friendliness. It can help curtail import dependency, reduce environmental emissions, create jobs, and foster economic activities. Through distributed systems, renewable energy can help control transmission and distribution losses. Renewable energy can also offer an optimum solution for electrification as over one billion people still lack access to electricity in these countries. Developing regions have abundant potential for renewable energy. South Asia, for example, is estimated to have a potential of 350 GW and over 200 GW for hydropower and wind power respectively while the daily solar radiation level in most of the countries in the region is over 5 kWh/$m^2$. Sub-Saharan Africa is estimated to have a potential of over 850 GW from modern renewables. In recent years, techno-economic advancements in the field of renewable energy have been complimented by conducive energy policies. Developing countries are also transforming their energy policy landscape to support renewables. The block of Southeast Asian countries, for example, has set a target of 422 GW of renewables by 2025 [16]. A combination of technical and policy developments can significantly help developing countries advance their renewable energy portfolio. There have been some success stories in this respect. India, for example, has made significant progress in renewable energy—with a respective installed capacity of 37 GW, 33 GW, and 85 GW India stands 4th, 6th, and 5th in wind power, solar energy, and renewable energy deployment in the world. The country has set a target of having 175 GW of renewables by the year 2022 of which 85 GW has been installed [17]. South Asia has also seen several small-scale renewable energy programs initiated, to provide modern energy services to rural and remote communities. Grameen Shakti, a micro-generation renewable energy program in Bangladesh, for example, has installed 1.7 million solar home systems, 33,500 biogas systems, and around 1 million improved cooking stoves. Latin America is the leading region in the world in terms of share of renewables thanks to hydropower. The region has also an abundance of bioenergy, wind power, and solar energy. Between 2010 and 2015, the region invested over US$80 billion in modern renewables [18].

## 4 Build Back Better

The COVID-19 pandemic has shaken the world to its core. The United Nations Secretary-General describes the pandemic to be the greatest challenge the world has faced since World War II. It has driven the world into unchartered territories triggering monumental and far-reaching impacts on the human race and the planet. At the start of August 2020, the pandemic was adding over 100,000 new cases every day to the tally of around 19 Million infections, while having resulted in over 700,000 deaths [19]. The consequent global economic recession is being tipped to be unparalleled. The US and Germany economies, for example, respectively plunged by 32.9 and 10.1% in the second quarter of the year recording the worst ever drop either country has experienced [20]. The socio-economic cost of the pandemic both at the macro- and micro-level is huge. The exact scope and intensity of the wider implications would depend upon how quickly and effectively vaccination is made available. Even if a cure is available by the end of 2020, the psychological impact, the fear factor, and uncertainties around it will remain there for a considerable time. The world has to live with a new normal as there will be many things that may never return to the pre-COVID-19 era. While the World Health Organization (WHO) warns that there will be no return to the old normal for the foreseeable future [21], it is also being widely tipped that the world has changed forever [22, 23].

The energy sector is also feeling the impact of COVID-19. Oil prices have plunged due to the diminished demand with the United States having recorded negative prices in April 2020. The energy sector is also experiencing supply cuts, disrupted trade flows, mounting debts, and bankruptcies. The full and long-term impact of the pandemic is hard to predict. The Energy Information Administration (EIA) estimates that in the second quarter of 2020 the global demand for petroleum and liquid fuels will average 83.8 million barrels per day (b/d), compared to 100.4 million b/d at the same time last year. EIA forecasts that consumption for the full 2020 will average 92.5 million b/d compared to the figure of 100.8 million b/d from 2019. EIA expects the consumption to rise to 99.7 million b/d in 2021 [24]. Other challenges of the COVID-19 will include and managing curbed revenue, liquidity shortage, and mounting debt obligations. Another implication of COVID-19 on the energy sector is the disruption in the supply chain, especially around renewables. China—the biggest manufacturer of renewable energy components especially when it comes to solar technologies and wind turbines—being the epicenter of the COVID-19, saw its manufacturing base almost halted for several months. The delays in the supply chain could result in an increase in prices for renewable materials and components in the short term. The International Renewable Energy Agency (IRENA) is concerned the pandemic may have an impact on the sustainable energy transition [25]. According to the International Hydropower Association (IHA), the prevalent uncertainty combined with liquidity shortages has put financing and refinancing of many hydropower projects at risk. New and upgrade projects have are also being halted, contributing to a fall in confidence regarding future investments and operations [26]. PricewaterhouseCoopers (PWC) has surveyed industry leaders to determine their major concerns about the impact of COVID-19 on the energy sector. 71% of the respondents expressed their main concern as the financial impact, including effects on results of operations, future periods, and liquidity and capital resources. Other major concerns recorded are potential global recession; the effects on workforce/reduction in productivity; decrease in consumer confidence reducing consumption; supply chain disruptions; difficulties with funding; not having enough information to make good decisions; and impacts on tax, trade, or immigration [27].

COVID-19 is set to have major implications for developing countries. Besides the loss of lives, the financial fallout is going to be colossal for the developing and underdeveloped economies. There will be micro- and macro-level implications on many fronts. According to the UN Labor Agency, around half of the global workforce could see their livelihood destroyed [28]. Hundreds of millions are already facing the financial heat—in the form of job losses, reduced working hours, and pay slashes—many of whom are likely to be pushed below the poverty line. Fuel poverty is set to rise across the world especially in the developing world. While energy affordability is a major problem in the developing countries in the pre-COVID scenario, those directly and indirectly affected by the financial implications of the pandemic will find the energy prices even more challenging. The situation is bound to impact the affordability of energy. The situation is also going to affect the governments' capacity to focus on addressing energy and environmental issues. In the wake of financial difficulties people are facing, energy security situations especially in terms of affordability will become more critical.

The COVID-19 crisis has underpinned the importance of access to sustainable energy services. From the deep economic recession the pandemic has plunged the world into, it requires a huge rebuilding effort. Given the track record and positive impact of sustainable energy solutions especially renewable technologies and energy efficiency, as observed over the last couple of decades, has become ever more important. Energy and environmental security through sustainable energy systems should be embedded in the global economic recovery plans. The United Nations has called on governments to seize the opportunity to "build back better" by creating more sustainable, resilient, and inclusive societies in the planning for a post-pandemic recovery. The United Nations Secretary-General António Guterres calls upon the nations: "We need to turn the recovery into a real opportunity to do things right for the future", while the UN Climate Chief states more specifically as: "With this restart, a window of hope and opportunity opens, an opportunity for nations to green their recovery packages and shape the 21st-century economy in ways that are clean, green, healthy, safe and more resilient". According to the UN Secretary-General, "The recovery must also respect the rights of future generations, enhancing climate action aiming at carbon neutrality by 2050 and protecting biodiversity. We will need to build back better." The United Nation Development Program Administrator emphasizes that "As we work through response and recovery from the shocks of the pandemic, the SDGs need to be designed into the DNA of global recovery" [29]. The pandemic has provided governments a unique opportunity to reset their economies, develop new business streams, and create jobs with a focus on sustainable energy and environmental future [30].

## 5 Concluding Remarks

Sustainable development is regarded to be one of the cornerstones of the global priorities in the twenty-first century. Energy and environmental security is a critical aspect of sustainable development. Meeting the growing energy requirements without inflicting damage to the environment is one of the biggest challenges the world faces today. In the backdrop of a growing realization about sustainable development, developing countries in regions like Southeast Asia, South Asia, Sub-Saharan Africa, and Latin America face a wide range of energy and environmental challenges. South Asia and Sub-Saharan Africa, jointly home to almost 40% of the global population, face serious energy challenges in the form of lack of access to electricity and refined cooking fuels, fragility of grid, and high energy prices. In these two regions alone, over 850 million and nearly 2 billion people lack access to electricity and clean cooking fuels respectively. Energy issues need to be addressed to improve the socio-economic prosperity in developing countries and to help meet the Sustainable Development Goals. Climate change, widely regarded to be a consequence of anthropogenic emissions in the post-industrial-revolution era, is arguably the most important threat facing mankind. Ironically, the poor and developing countries, despite having a marginal contribution towards the greenhouse gas emissions, are mainly at the suffering end when it comes to the implications of climate change. Climate change-driven extreme weather disasters, water scarcity, and seasonal disorder are exacerbating the food and water security situations in these countries. Low-lying small island and developing states (SIDS) are particularly facing serious challenges form the rising sea level.

The grave implications of global warming and climate change call for an urgent and paradigm shift in human activities and use of resources. Through the Paris Agreement, 196 countries have adopted the first-ever universally legally binding global climate deal to avoid dangerous climate change by limiting global warming to well below 2 °C. A recent Intergovernmental Panel on Climate Change (IPCC) report, however, has warned that the world is seriously overshooting this target, heading instead towards a higher temperature rise. It concludes that there is a need for major changes in four big global systems: energy, land use, cities, and industry. The report warns that to limit warming to 1.5 °C, the world needs to invest around $2.4 trillion in renewable and energy efficiency initiatives every year through 2035 [31]. The progress made in the world at national and international levels is falling short of what is needed to fight climate change. Developed and industrialized nations need to help the poor and developing countries in the fight against climate change. There is a need to amplify international support in terms of capacity building, technology, and knowledge transfer, financial assistance.

The COVID-19 pandemic has severely dented the broader economic and socio-political fabric of the world. In the age of globalization, all nations, irrespective of their developmental status have been affected by the pandemic. As Winston Churchill said “Never let a good crisis go to waste”, the crisis should be capitalized to cultivate energy and environmental positives. The world needs to come together as a united international community. Sustainable development and climate risks should be incorporated into policymaking, financial system, and infrastructure development mechanisms. The post-COVID-19 recovery should be based upon build back better approach. It is time to explore a more resilient lifestyle based on sustainable technologies and practices. Human interaction with nature and natural resources needs a reset.

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# Correction to: Energy and Environmental Security in Developing Countries

**Muhammad Asif**

## Correction to:
## M. Asif (ed.),
## *Energy and Environmental Security in Developing Countries*, Advanced Sciences and Technologies for Security Applications, https://doi.org/10.1007/978-3-030-63654-8

The original version of this book was inadvertently published with incorrect country name and without Dedication, Foreword, Preface, and Acknowledgement pages. These have now been updated.

Dedication, Foreword, Preface, and Acknowledgement pages have been included in the book front-matter and the country name has been updated from UK to Kingdom of Saudi Arabia.

The updated version of the book can be found at
https://doi.org/10.1007/978-3-030-63654-8



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