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Hassan Qudrat-Ullah
Aymen A. Kayal *Editors*

Climate Change and Energy Dynamics in the Middle East

Modeling and Simulation-Based Solutions

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Editors

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ISSN 1860-0832 ISSN 1860-0840 (electronic)
Understanding Complex Systems
ISBN 978-3-030-11201-1 ISBN 978-3-030-11202-8 (eBook)
https://doi.org/10.1007/978-3-030-11202-8

Library of Congress Control Number: 2019934773

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To My Grandfather

Raja Munawwar Khan (late)

—Hassan Qudrat-Ullah

To My Parents, Wife, and Children

—Aymen A. Kayal

Preface

Global climate change and global warming has the potential to severely impact both the production and consumption of energy across the globe. The Middle East region with even slightly warmer weather can result in an increased demand of energy (e.g., for more air conditioning use and energy-intensive methods for water supply), lower labor productivity (e.g., relatively few hours are available during the day), and less supply of energy (e.g., hydro generation can suffer due to none or less availability of water due to rising temperature). The potential imbalance of energy demand and supply can often lead to rising electricity costs and power outages which, in turn, can have severe impact on the socioeconomic welfare of the population of these countries. Although more sunny days can help in harnessing solar power, the predominant use of fossil-based electricity generation by this region and the resulting environmental emissions are major concerns to be addressed. Consequently, for the decision-makers, to better understand the sustainable production and consumption of energy and the related socioeconomic dynamics requires a systematic and integrated approach. Modelling and simulation in general and system dynamics and optimization modelling in particular have the capabilities to deal with the complexity of climate change and energy dynamics. Therefore, the primary aim of this book is to present, in the context of the Middle East region, the latest decision-making tools, techniques, and insightful and innovative solutions that the decision-makers can utilize to overcome the challenges that their energy systems face. Furthermore, we hope to encourage further theoretical and empirical research that perhaps may be interwoven by the works presented herein and in advancing new methodological perspectives to include multilevel and cross-level analysis to better understand the dynamics of sustainability-focused supply chains.

Unified by the common goal of making better decisions in the sustainable production and consumption of energy, we invited potential authors to submit and showcase their work related to the major theme of this book, *Climate Change and Energy Dynamics in the Middle East*. In addition to relevance of their work to the Middle East, we sought both theoretical (only state-of-the-art reviews) and empirical chapters with a focus on system dynamics, econometric, optimization, and conceptual modelling. It is our hope that this book will stimulate a new way of thinking as a proclamation of a new era of resource constraints and renewed focus on "integrative" solutions for the challenges in climate change and energy policy-making.

Content Overview

The integrating theme of this book is modelling-based solutions to deal with dynamics of climate change and energy domains. The book contains five parts. Part I presents the introduction and preview of Climate Change and Energy Dynamics in the Middle East. Part II of this book, "Dynamic Modelling in Service of Climate Change and Energy Decisions," examines the dynamic modelling-based approaches to better understand the dynamics of climate change and energy-related issues in the Middle East. Five state-of-the-art applications of dynamic modelling include Socioeconomic and Environmental Implications of Renewable Energy Integrity in Oman: Scenario Modelling Using System Dynamics Approach, Energy and Emissions Modelling for Climate Change Mitigation from Road Transportation in the Middle East: A Case Study from Lebanon, Climate Change and Energy Decision Aid Systems for the Case of Egypt, Control Strategy and Impact of Meshed DC Micro-Grid in the Middle East, and The Energy-Water-Health Nexus Under Climate Change in the United Arab Emirates – Impacts and Implications. Part III of this book, "Understanding the Dynamics of Climate Change and Energy Using Optimization and Econometric Modelling," showcases four unique contributions addressing the challenges of climate change and energy dynamics utilizing optimizing and econometric modelling approaches: (i) Leapfrogging to Sustainability: Utility-Scale Renewable Energy and Battery Storage Integration – Exposing the Opportunities Through the Lebanese Power System, (ii) Climate Change and Energy Dynamics in the Middle East: Challenges and Solutions, (iii) Greenhouse Gases Emissions and Alternative Energy in the Middle East, and (iv) Quantitative Analysis Methods Used in Modelling Power Systems and Climate Change for Saudi Arabia. Part IV of this book highlights the role of conceptual modelling in a better understanding of climate change and the energy dynamics of the Middle East. In this category, we have two chapters: (i) Transformation Toward Clean Energy in the Middle East: A Multi-Level Perspective and (ii) Global CO_2 Capture and Storage Methods and the New Approach to Reduce Emission for Geothermal Power Plants with High CO_2 Emission: Turkey Case Study.

Finally, Part V of this book overviews the key insights and learning points as well as the future research avenues contained in this book.

Acknowledgments

We would like to thank everyone, mentioned herein or not, for their continued support in helping to bring this book project to completion. Most importantly, I am sincerely grateful to the contributing authors of this book. Their support of this endeavor enabled us to platform the collective lessons presented in the book. We also acknowledge the work and knowledge of the members of our review panel. My thanks also go to all the people at Springer, USA, especially Christopher and HoYing with whom we corresponded for their advice and facilitation in the production of this book. I would like to thank Taub Jeffrey, Chandhini Kuppusamy, and the production team from Springer for their help in the final production of this book. We are grateful to my families for their encouragement and support throughout this endeavor.

Finally, the editors would like to acknowledge the financial support provided by the Deanship of Scientific Research (DSR) at King Fahd University of Petroleum & Minerals (KFUPM) for funding this work through project No. BW171006.

Dhahran, Saudi Arabia
December, 2018

Hassan Qudrat-Ullah
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Part I
Introduction

Chapter 1
Introduction: Climate Change and Energy Dynamics in the Middle East

Hassan Qudrat-Ullah and Aymen A. Kayal

Abstract The use of modeling and simulation-based solutions for a better understanding of climate change and energy dynamics has seen phenomenal growth during the past several decades. The primary focus of this modeling activity has been to study energy-economy interactions and impacts. On the other hand, we are witnessing a global trend in climate change mitigation efforts, increasingly focusing on the sustainable supply of energy. These renewed concerns about climate change and global warming pose unique modeling challenges. Therefore, the primary aim of this book is to disseminate the roles and applications of various modeling approaches aimed at improving the usefulness of energy policy models in public decision-making in the context of the Middle East. In this chapter, we present the preview of 11 unique contributions we have in this volume.

Keywords Energy policy · Modeling and simulation approaches · System dynamics · Dynamic modeling · Optimization and econometric models · Electricity supply and demand · Climate change · Environmental emissions · Sustainability · Decision-making · Policy assessment · Energy markets · Renewable energy · Electricity

1 Introduction

Global climate change and global warming have the potential to severely impact both the production and consumption of energy across the globe. In the Middle East region, even slightly warmer weather can result in an increased demand for energy (e.g., for more air conditioning use and energy-intensive methods for water supply), lower labor productivity (e.g., relatively few hours is available during the day), and less supply of energy (e.g., hydro generation can suffer due to none or

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H. Qudrat-Ullah, A. A. Kayal (eds.), *Climate Change and Energy Dynamics in the Middle East*, Understanding Complex Systems,
https://doi.org/10.1007/978-3-030-11202-8_1

less availability of water due to rising temperature). The potential imbalance of energy demand and supply can often lead to rising electricity costs and power outages which, in turn, can have severe impacts on the socioeconomic welfare of the population of these countries. Although more sunny days can help in harnessing solar power, the predominant use of fossil-based electricity generation by this region and the resulting environmental emissions is a major concern to be addressed. Consequently, for the decision-makers, to better understand the sustainable production and consumption of energy and the related socioeconomic dynamics requires a systematic and integrated approach. Modeling and simulation in general and system dynamics and agent-based modeling, in particular, have the capabilities to deal with the complexity of climate change and energy dynamics.

The primary aim of this book, therefore, is to present, in the context of the Middle East region, the latest decision-making tools, techniques, and insightful and innovative solutions that the decision-makers can utilize to overcome the challenges that their energy systems face. Specifically, we are interested to showcase the innovative modeling-based solutions including the application of system dynamics and other dynamic modeling approaches, the optimization and econometric models, conceptual models and frameworks, and specific case studies in the context of the Middle East.

Thus, in an attempt to provide some viable solutions for Climate Change and Energy Dynamics of the Middle East, we issued the call for contributions in this volume. Specifically, we sought help from the system dynamics and dynamic modeling community. Consequently, several different examples of modeling approaches and models to provide solutions to various issues related to climate change and energy dynamic are provided in this volume.

1.1 Methodology

In our call for contributions on “Climate Change and Energy Dynamics of the Middle East,” we went through various email lists of professional bodies. We also posted the call for chapters at the message boards of a few international conferences on the related topics. Personal invitations were sent to target authors as well. We received 17 “one-page” abstracts as the expression of interests. Based on the initial screening by our review panel, the authors of 14 chapters were invited to submit the complete chapter. All 14 chapters received from the contributors went through a double-blind process. The reports from the independent reviewers were sent to the authors to address the issues and incorporate the suggestions made by the reviewers. Only 11 chapters made it to the final stage of acceptance. The final versions of these 11 chapters have been edited and included in this volume.

1.2 Research Categories

The chapters thus compiled are classified into five categories following the structure of the book. The first category, the current one, presents the introduction and preview of "Climate Change and Energy Dynamics of the Middle East." The second category examines the dynamic modeling-based approaches to better understand the dynamics of climate change and energy-related issues in the Middle East. Five state-of-the-art applications of dynamic modeling include *Socio-economic and Environmental Implications of Renewable Energy Integrity in Oman: Scenario Modeling Using System Dynamics Approach*; *Energy and Emissions Modeling for Climate Change Mitigation from Road Transportation in the Middle East: A Case Study from Lebanon*; *Climate Change and Energy Decision Aid Systems for the Case of Egypt*; *Control Strategy and Impact of Meshed DC Micro-grid in the Middle East*; and *The Energy-Water-Health Nexus Under Climate Change in the United Arab Emirates: Impacts and Implications.*

The third category showcases four unique contributions addressing the challenges of climate change and energy dynamics utilizing optimizing and econometric modeling approaches: *(i) Leapfrogging to Sustainability: Utility-Scale Renewable Energy and Battery Storage Integration – Exposing the Opportunities Through the Lebanese Power System*; *(ii) Climate Change and Energy Dynamics in the Middle East: Challenges and Solutions*; *(iii) Greenhouse Gas Emissions and Alternative Energy in the Middle East*; and *(iv) Quantitative Analysis Methods Used in Modeling Power Systems and Climate Change for Saudi Arabia.* The fourth category in this book highlights the role of conceptual modeling in a better understanding of climate change and the energy dynamics of the Middle East. In this category, we have two chapters *(i) Transformation Toward Clean Energy in the Middle East: A Multilevel Perspective* and *(ii) Global* CO_2 *Capture and Storage Methods and the New Approach to Reduce Emission for Geothermal Power Plants with High* CO_2 *Emission: Turkey Case Study.*

The final category, finally, overviews the key insights and learning points as well as the future research avenues contained in this book.

2 Dynamic Modeling in Service of Climate Change and Energy Decisions

2.1 Exploration of Renewable Energy Policy Decisions in Oman

Al-Sarihi and Bello (in press), authors of Chap. 2, "*Socio-economic and Environmental Implications of Renewable Energy Integrity in Oman: Scenario Modeling Using System Dynamics Approach*," make the case for renewable energy (RE) in Oman where oil and gas resources have played a crucial role in boosting Oman's economy as well as meeting domestic energy needs. They posit that (i) the increasing domestic energy demands have created pressure on national energy supplies and made the search for alternative energy sources such as renewables ever more important and (ii) socioeconomic and environmental implications of RE, which could boost its uptake. Using system dynamics approach, they develop three RE integrity scenarios – i.e., (i) business-as-usual, (ii) moderate, and (iii) advanced and ambitious. By examining these scenarios' long-term implications on economy, society, and environment, they found (i) that, under moderate, advanced, and ambitious scenarios, new renewable energy jobs can be created by 2040, (ii) natural gas consumption for electricity generation was estimated to decline by more than 60% by 2040 compared to the business-as-usual scenario, and (iii) if no renewables are considered in the future energy mix, however, the total CO_2 emissions are expected to significantly rise by 2040 compared to 2010.

2.2 Energy and Emissions Modeling for Climate Change Mitigation from Road Transportation in the Middle East: A Case Study from Lebanon

Continuing the use of system dynamics modeling, Marc Hadad and Charbel Mansour (in press), in Chap. 3, provide an assessment framework and a case study of the potential savings in energy use and CO_2 emissions from alternative fuel vehicle technologies compared to existing conventional vehicles, including the dynamic modeling of different mitigation strategies at the fleet level. They did their case study in an urban area of Lebanon's Greater Beirut Area which has one of the most unsustainable road transport systems in the region. The developed framework highlights the need to account for real-world driving and weather conditions since poor roads, congested traffic, and extreme weather conditions common in the developing countries of the Middle East can reduce the benefits of these vehicles. In their results, they show that:

- Introducing micro-hybrid vehicles to make up 35% of the fleet in 2040 reduces energy use and emissions by 19% compared to the business-as-usual scenario, thereby stabilizing growth trends in 2040 as compared to 2010 figures.
- The addition of 10% hybrid electric vehicles by 2040 to the first strategy leads to 11% additional savings compared to 2010.

They allude to future research by highlighting the need to incentivize cleaner fuel vehicles and to systematically explore additional strategies for reducing energy consumption and emissions in road transportation.

2.3 Climate Change and Energy Decision Aid Systems for the Case of Egypt

In Chap. 4, "Climate Change and Energy Decision Aid Systems for the Case of Egypt," Aya Sedky Adly (in press) demonstrates the use of "TIMES" energy model. She argues that "the growth of energy production and consumption is strongly affecting and being affected by climate change in many aspects. In warmer countries, such as Egypt, climate change is expected to have an even larger impact on different energy forms demand. However, since economic, technical, and environmental energy concerns change from country to another, addressing the impact of both current climate and future climate changes on demand should be worked out by decision makers by the country policies and geographical conditions." She addresses the research question: how should experts best characterize such uncertainties for decision-makers of climate change scenarios including changes in mean climate characteristics as well as changes in the frequency and duration of weather events in Egypt? She presents with a modeling-based decision aid in developing climate action plans and selecting the most suitable mechanisms in correspondence to energy demands.

2.4 Control Strategy and Impact of Meshed DC Micro-grid in the Middle East

Using dynamic modeling with Matlab/Simulink, Barara et al. (in press) posit that "the installation of Micro-grid provide as a viable solution to the problem of energy efficiency and environmental in the world, this is especially true for countries in the Middle East which have an abundance of natural sunlight. The interest is due to several advantages in comparison to AC Micro-grids regarding efficiency, a minimum number of devices, no need for frequency/phase control, modularity and reliability. Moreover, it enables easy integration of renewable energy resources, particularly photovoltaic ones." In their study, they target meshed DC micro-grid, while most of the literature papers concern radial DC micro-grids wherein in meshed DC grids, the control strategy of current or power becomes a critical issue, particularly if a modular and generic solution is researched. Their study focuses on the use of smart nodes controlling the power flow in the grid. They conclude that reduced scale tests based on dSPACE DS1103 have been provided to validate experimentally the proposed control scheme.

2.5 The Energy-Water-Health Nexus Under Climate Change in the United Arab Emirates: Impacts and Implications

Dougherty et al. (in press), in this final chapter of this section Chap. 6, apply scenario-based approach and climate change modeling at the regional spatial scale to address energy-water-health nexus. They assert that “Climate change poses serious energy, water and health challenges for the United Arab Emirates (UAE). While closely interconnected, the development of sustainable energy, water, and health policies has typically been viewed as independent, sector-specific planning challenges. However, changing demographics, a rapidly growing economy, dependence on desalination, and worsening air quality – all taking place as climate change unfolds – suggest a need for a more integrated approach to risk management. Accounting for the interactions between an ‘energy-water-health nexus’ is one way to ensure that development strategies are considered within a framework that addresses the range of potential tradeoffs, risks, and synergies.” They addressed the energy-water-health nexus under a changing climate by undertaking research activities as part of the Local, National, and Regional Climate Change Programme (LNRCCP) of the Abu Dhabi Global Environmental Data Initiative (AGEDI) where climate change modeling at the regional spatial scale (Arabian Peninsula; Arabian Gulf) was first carried out to establish the atmospheric and marine physical conditions that will underlie energy, water, and health challenges in the future. They used the results of this modeling as inputs to an analysis of policies that account for linkages across the energy-water nexus on the one hand and the energy-health nexus on the other. They present the key results as:

- That climate change will render an extreme hyper-arid climate even more so, while the waters of the Arabian Gulf will experience heightened salinity, changing circulation patterns, and higher temperatures as desalination activities intensify.
- That energy efficiency and renewable energy can lead to significant reductions in annual greenhouse gas (GHG) emissions at negative to modest societal cost while leading to substantial decreases in premature mortality and health care facility visits in the urban environment.

3 Understanding the Dynamics of Climate Change and Energy Using Optimization and Econometric Modeling

In this section, we will present four state-of-the-art applications of optimization and econometric modeling. The focus of these modeling and simulation applications is to assess the socioeconomic and environmental impact energy policies of some Middle Eastern countries.

3.1 *Leapfrogging to Sustainability: Utility-Scale Renewable Energy and Battery Storage Integration* – Exposing the Opportunities Through the Lebanese Power System

In the opening chapter of this section, the authors, Ahmad Diab et al. (in press), present the Lebanese power system as a case in point to showcase the importance of shifting the foundations of conventional thinking in power system planning into a new paradigm where renewable energy is adopted as priority choice. They studied the technical and economic feasibility of wind farms, solar PV, and battery energy storage systems. Using HOMER Pro-based simulations to optimize for the lowest cost of electricity, they show that:

- *Incorporating utility-scale renewable energy systems and battery energy storage can decrease the overall levelized cost of electricity (LCOE) to $c7/kWh.*
- *Without the integration of considerable storage capacity, an economic limit of approximately 20–25% renewable energy penetration is reached.*

They performed sensitivity analysis while adopting various values for the cost of natural gas and internalizing the social cost of carbon. Their results confirmed (i) a positive correlation between the cost of carbon and the price of natural gas on the one hand and system renewable energy fraction on the other and (ii) introducing demand-side management and increased grid flexibility also showed a high level of sensitivity to both system LCOE and the renewable energy fraction.

3.2 *Climate Change and Energy Dynamics in the Middle East: Challenges and Solutions*

Applying an optimization model, HOMER Pro software, Nandi et al. (in press), in Chap. 8, share an analysis of solar wind hybrid power plant in an area of Egypt. They identify the issue and set the goal of their study as, "to model and simulate a hybrid power system based on renewable which may solve the problems regarding the power generation due to climate change." They conducted case studies taking the real-time data regarding renewable energy and also the load data of the areas. They posit that optimization of the hybrid model using those real-time data will give us an idea about to what extent there will be the generation of power, the actual cost that will be required to set up the hybrid power plant, and most importantly the per unit cost of energy consumption.

3.3 Greenhouse Gas Emissions and Alternative Energy in the Middle East

In Chap. 9, utilizing econometric techniques including cointegration tests and Ganger tests, Uğurlu (in press) investigates the relationship between GDP per capita and renewable energy use and CO_2 emissions in the Middle East countries, namely, Algeria, Iran, Iraq, Israel, Jordan, Lebanon, Libya, Saudi Arabia, and Turkey. Before the empirical application was investigated, she presented and discussed the outlook of the economy, greenhouse gas emission, and renewable energy use of the Middle East countries. What she used a panel Granger causality test is in the empirical application section, and the preliminary tests are done before the model where the period used in the analysis is 2000–2014. Her results show that:

- *The GDP per capita has positive and renewable energy use has a negative effect on carbon dioxide emission.*
- *The variables have a cointegration relationship, and there is one way Granger causality from GDP per capita to carbon dioxide emissions and total primary energy consumption, foreign direct investment net inflows, and GDP.*

3.4 Quantitative Analysis Methods Used in Modeling Power Systems and Climate Change for Saudi Arabia

In Chap. 10, the final chapter of this section, Kayal and Al-Khars (in press) showcase a state-of-the-art review of the applications of the quantitative methods in studying the power systems and climate change dynamics for Saudi Arabia. They provide the background of the study and their main results as:

> The relationship between energy consumption, as well as economic growth and emission reduction, is considered sustainable development, and it has been the subject of intense research in the last couple of decades. The authors believed that balancing emission reduction while satisfying growing energy demand is an important issue for both policymakers and researchers alike in the Kingdom of Saudi Arabia (KSA). This seriousness in sustainable development in KSA should be evident in the literature through the increasing number of articles found in top journals related to the area. In order to ascertain our assumptions, the authors of this chapter conducted a sample review of publications that focused on quantitative modeling of the dynamics of both power and environment aspects in Saudi Arabia. Analysis of the sample of articles understudy revealed an exponential increase in the use of quantitative models for analyzing the integration of power generation and emission reduction dimensions in KSA. This growth indicates an increase in the propensity of research to evolve from descriptive energy studies to systems modeling that focus more on KSA's energy mix and emission reduction.

4 Understanding the Dynamics of Clean Energy Using Conceptual Modeling Approach

4.1 Transformation Toward Clean Energy in the Middle East: A Multilevel Perspective

Here, in Chap. 11, "Transformation Toward Clean Energy in the Middle East: A Multilevel Perspective," the author, Ismaeel (in press), contributes with an elegant socio-technical change conceptual model for transformation toward clean energy in the Middle East. First, he provides a background to the issue and then advances sever assertions:

> The global energy sector is going through a radical change of its well-established systems. Global efforts to mitigate climate change effects, changes in the economics of Hydrocarbon energy sources, and technological developments led to a global transition to renewable energy sources. The Middle East region is not an exception. During the last decade, the region witnessed the launch of successful renewable energy projects, especially in the electricity sector. They are mainly solar energy projects. The decline in the cost of solar panels and the good potential for solar energy in the region, in addition to economic challenges because of low oil prices and increasing population and urbanization, contributed to the case of transformation toward clean energy in the region. However, this transformation is in its early stages and requires careful planning and coordination of actions and policies from various parties at different levels.

He concludes that (i) transformation toward clean energy in the Middle East is discussed as a socio-technical change and analyzed through the multi-level perspective theoretical approach, and (ii) different factors affecting the transformation are identified at the three levels of landscape, regime, and niche that need to be coordinated and aligned to ensure a successful transition.

4.2 Global CO_2 Capture and Storage Methods and the New Approach to Reduce Emission for Geothermal Power Plants with High CO_2 Emission: Turkey Case Study

In the final chapter of this section, Chap. 12, Haklidir et al. (in press) present a case study on global CO2 capture and storage methods. First, they provide the review of current status CO_2 gas production and capture in the world and Turkey and then highlight the key issue as, "One of the general problems of the world is to the capturing of CO_2 gas and its storage or convert to another product, and it has been studying by the researchers for a long time. One of the solutions may include biofuel production from geothermal based CO_2 in a high CO_2 emission producer geothermal power plant like Turkey, Italy countries." They conclude with a new approach, "the conceptual design of the Helioculture process is applied to geothermal power plants to produce biofuel by CO_2. A helioculture process is a new approach, and it is possible to produce biofuel or ethanol by a photo-biocatalytic process with this method. The process uses solar energy and waste CO_2 to catalyze the direct-to product synthesis of renewable fuel, and it is evaluated applicable technology for high-CO_2 producer geothermal power plants like Kızıldere (Denizli) geothermal field in Turkey." The main result of their studies is, "Helioculture based fuel production looks five times higher than traditional biodiesel production in the region."

5 Finally

In the final chapter of this book, Chap. 13, Kayal and Al-Khars (in press) conclude with key insights gleaned from the showcased contributions in this book. These insights are presented in a three-thematic structure: environmental, economic, and social. Then they present the future research avenues as highlighted by the authors of the respective chapters. Both the researchers and the practitioner can get a quick glimpse of this book by reading this finally.

6 Concluding Remarks

For this book project, we started our journey in search of "modeling approaches and models" for a better understanding of climate change and energy dynamic in the Middle East, the fossil energy hub of the world. In this quest, we are successful in presenting 11 unique contributions. With regard to the theme of "modeling approaches" for the climate change and energy dynamics, we have five leading contributions on "system dynamics and dynamic methodology," four unique applications of "optimization and econometric models," and two chapters using "conceptual modeling and case studies." Consistent with the objective of this volume "the in the context of the middle east," we have six state-of-the-art applications of system dynamics and agent-based models.

It is worth noting that most of the model-based contributions in this volume have addressed "future research" explicitly. By utilizing the identified research gaps summarized in the final chapter of this book, researchers in energy systems domain can continue their research on important issues related to climate change and energy dynamics.

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Part II
Dynamic Modelling in Service of Climate Change and Energy Decisions

Chapter 2
Socio-economic and Environmental Implications of Renewable Energy Integrity in Oman: Scenario Modelling Using System Dynamics Approach

Aisha Al-Sarihi and Hafiz Bello

Abstract Oil and gas resources have played crucial role in boosting Oman's economy as well as meeting domestic energy needs. However, increasing domestic energy demands have created pressure on national energy supplies and made the search for alternative energy sources such as renewables ever more important. Aware of this challenge, investors, researchers and government have developed few renewable energy (RE) initiatives. However, RE accounts for less than 1% of total power generation in Oman. Importantly, socio-economic and environmental implications of RE, which could boost its uptake, are still under-researched. Using system dynamics approach, this chapter develops four RE integrity scenarios – i.e. business-as-usual, moderate, advanced and ambitious – and examines its long-term implications on economy, society and environment. The findings gained from long-term energy scenario analysis reveal that, under moderate, advanced and ambitious scenarios, new renewable energy jobs can be created by 2040 and natural gas consumption for electricity generation was estimated to decline by more than 60% by 2040 compared to the business-as-usual scenario. If no renewables are considered in the future energy mix, however, the total CO_2 emissions are expected to significantly rise by 2040 compared to 2010.

Keywords Oman · Fossil fuels · Renewable energy · Fuel mix · Scenarios · System dynamics · Socio-economic · Environmental implications

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H. Qudrat-Ullah, A. A. Kayal (eds.), *Climate Change and Energy Dynamics in the Middle East*, Understanding Complex Systems,
https://doi.org/10.1007/978-3-030-11202-8_2

1 Introduction

Like its neighbouring countries of the Gulf Cooperation Council (GCC) – Bahrain, Kuwait, Qatar, Saudi Arabia and the United Arab Emirates – Oman's economy has been highly reliant on oil and gas export revenues. Since their discovery, fossil fuel resources, namely, oil and gas, have been accounting for nearly 99% of total energy mix to meet the domestic energy needs. In recent years, however, the GCC states have exhibited signs of unsustainable[1] energy use such as energy security associated with increasing domestic energy demands and increasing per capita carbon emissions due to heavy reliance on fossil fuels. Despite GCC's vast resources of renewable energy, the use of renewable energy in total electricity installed capacity did not exceed 1% of total power capacity in 2014 (El-Katiri 2014; IRENA 2016).

The abundance of oil and gas resources has restricted the attention of investors, researchers and governments to develop alternative energy sources such as renewables. However, in recent years, research on the development and implication of renewable energy in the GCC countries is continuously growing (Alawaji 2001; Al-Karaghouli 2007; AER 2008; Bilen et al. 2008; Nalan et al. 2009; Chiu and Chang 2009; Ghorashi and Rahimi 2011; Al-mulali 2011; Anagreh and Bataineh 2011; Bataineh and Dalalah 2013; El Fadel et al. 2013). One of the key challenges, however, facing many of the regional countries is the lack of structured tool to aid a systemic account of energy policy and planning. The only recognised tools that have been attempted to aid energy planning in GCC countries are Long-range Energy Alternatives Planning (LEAP) system (El Fadel et al. 2013), Energy-Economy-Environment Modelling Laboratory (E3MLab) (Fragkos et al. 2013), panel data analysis model (Al-mulali 2011; Arouri et al. 2012) and techno-economic modelling of PV/battery systems (Al-Saqlawi 2017).

While some of these models are capable of giving valuable insights into analysis of energy demand and supply in an *economy*, they are, however, not able to account for the dynamics relating to connecting the power sector with *society* and the *environment*, since they are largely based on a static economic modelling approach. Indeed, Al-Saqlawi (2017) provided a systemic account of socio-economic and environmental implications of renewable energy development in Oman. However, the study was mainly focused on one technology type, i.e. solar photovoltaic (PV), focused on the residential sector only and evaluated the socio-economic and environmental implications against one point of time without extending to study the long-term implications. Thus, this chapter investigates the intersection between Oman's electric power sector and economic, social and environmental domains. By so doing, the chapter develops scenarios to assess the long-term implications of renewable energy integrity in Oman's future fuel mix particularly in the electric power sector. System dynamics methodology is employed to build the scenarios and to provide a systemic account for economic, social and environmental implications of renewable energy uptake in Oman.

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[1] Sustainable development in this chapter refers to the definition in the Brundtland Commission Report of 1987: development that meets the needs of the present without comprising the ability of future generations to meet their needs (Brundtland 1987).

2 Oman: Power Sector and Renewable Energy

2.1 Fossil Fuels and Oman's Electric Power Sector (1970s–2018)

The evolution of Oman's electric power system is highly correlated to the discoveries of oil and gas resources since the 1960s. The first power and desalination plant was established in 1975 in Al Ghubra, with an initial capacity of 25.5 MW of electricity and 6 million gallons of desalinated water. The plant was initially fired by diesel before its upgrade in 1980s. That upgrade converted the plant from diesel to natural gas and increased the capacity to 294 MW and 12 million gallons of water. In 1986, due to demand for water that outpaced supply, two new water units were constructed to double the production capacity to 24 million gallons. Initially, the Al Ghubra project principally supplied the capital city (Allen and Rigsbee 2000).

A new Ministry for Water and Electricity Regulation was established in 1978. The new ministry extended the construction of power stations to areas beyond the capital city, including some northern parts of Oman, building a 250 MW station to serve the Rusayl Industrial Estate, the 26.5 MW Wadi Al Jizzi station serving residential sector and a 53 MW station serving a copper refinery and Sohar. Another 22 locations outside the capital city were also supplied with about 27 MW by diesel-powered generation plants (Allen and Rigsbee 2000). The development of the national grid in the 1990s connected the capital city with other distributed generation plants and led to the establishment of new power projects to meet growing electricity and water demands.

In 2005, the Authority for Electricity Regulation was established to undertake the regulation of the newly restructured electricity sector. Likewise, the Public Authority for Electricity and Water was established to handle all of the sector's legal responsibilities, which were previously enacted by the Ministry for Water and Electricity Regulation. Up to 2018, the Authority for Electricity Regulation regulates the electricity sector under the new Sector Law, which was approved by the Council of Ministers in 2004 to oversee the development of regulation and progressive privatisation of the electricity and related water sectors (IBP Inc. 2015).

The new electricity sector consists of three markets: the Main Interconnected System (MIS), which serves the majority of customers residing in the northern part of the county; the rural areas market, which serves rural areas in Oman; and the Dhofar electricity market, which serves the southern part of Oman. Generation, transmission and distribution companies were unbundled under the new electricity market, except for those in the rural electricity market. Under the 2004 law, Oman Power and Water Procurement Company (OPWP) is the only entity that buys electricity from all licensed electricity generation companies under long-term contracts of power purchase, which span 15 years on average, and sells bulk electricity supplies to electricity distribution companies (AER 2008). The Oman electricity distribution market has been monopolised by four licensed, state-owned electricity distribution companies, i.e. Muscat, Majan, Mazoon and Dhofar, that have the right to buy the bulk supply of electricity from OPWP in order to distribute electricity

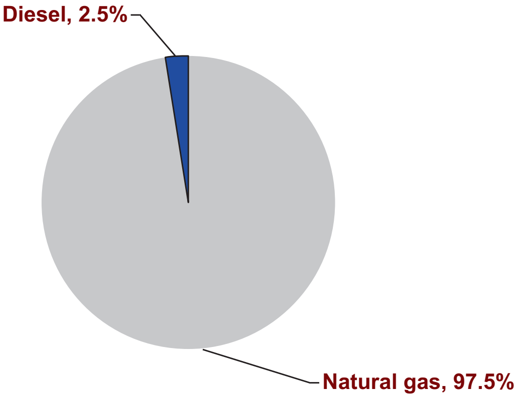

Fig. 2.1 Fuel mix for electric power generation in Oman in 2011. (Source: Author based on data from AER (2011))

within their authorised areas. The legislation stipulates that the electricity distribution companies can only purchase their electricity from the OPWP (Royal Decree 78/2004 2004).

Electricity generation is characterised by high reliance on hydrocarbon-based technologies such as open cycle gas turbine (OCGT) and closed cycle gas turbine (CCGT). The main national grid, i.e. MIS, consists of a total of 11 plants, which generate electricity from natural gas (OPWP 2015). Of those, five are operational OCGT plants with a total generation capacity of 1945 MW and six are CCGT plants with a total generation capacity of 5171 MW (OPWP 2015). The electricity generators purchase their gas requirements from the Ministry of Oil and Gas. The contribution of natural gas in the fuel mix for electricity generation accounted for more than 97% in 2011, while the diesel, which is used in off-grid plants to generate electricity for rural areas or as backup for grid-connected plants during peak periods, contributed just less than 3% (Fig. 2.1) (AER 2011).

2.2 *Rising Energy Challenges*

The high dependence on available natural gas and diesel resources to fire power plants along with highly subsidised fossil fuel-based energy services such as electricity has created new challenges for Oman's power sector. These include energy security, economic vulnerability to oil prices and increasing greenhouse gas emissions.

In a total area of 309,501 km^2, the population of Oman almost doubled from 2.34 million in 2003 to 4.24 million in 2013 (World Bank 2013a). Population growth, the semiarid environment of Oman, the need for air conditioning, the increase in the standard of living, expansion of energy-intensive industrialization, introduction of new households and infrastructure investments and highly subsidised electricity services have been driving the annual growth of power demand by double digits. Oman's annual growth of power demand was projected to be 10% between 2013 and 2020 (OPWP 2014). Meanwhile, the peak power demand is expected to increase at 11% annually in the same period. Since the 2005 market restructuring, the number of electricity accounts has increased by 116.6% (AER 2017), and electricity supply in 2017 reached 32.3 TWh, 240% higher than in 2005 (Fig. 2.2). Residential customers accounted for 46.0% of total supply in 2017, compared to a 55.2% share in 2005. In return, natural gas used for electricity generation has increased from 104.4 billion Scf in 2000 to 295 billion Scf in 2015 (AER 2011; NCSI 2015), and the domestic share of natural gas consumption by the power sector increased from 19.1% in 2000 to 21% in 2014 (NCSI 2015).

Due to the increasing demand on domestic natural gas supplies and because Oman has very small oil and gas reserves compared with other gulf countries along with the country's long-term contracts and commitments to export natural gas, Oman has already started to import natural gas from Qatar via the Dolphin pipeline system since 2008 (EIA, US 2013). Further, Oman has signed a memorandum of understanding with Iran to import gas. Oman's crude oil reserve to production ratio (R/P ratio) is equal to 14 years, and its natural gas R/P ratio is equal to 27 years (IRENA 2016).

Furthermore, the increasing demands on oil and gas for power generation divert the allocation of oil and gas commodity for local use rather than export. Giving Oman's narrow export profile characterised by high proportion of oil and gas, the allocation of oil and gas for domestic use directly impacts Oman's economy which is highly reliant on oil and gas export revenues. This challenge is in line with the economic vulnerability to oil price shocks. In other words, as oil prices rise, the economic revenues go up and so governmental spending on salaries and investments. When the prices decline, and giving Oman's narrow export profile, the state budget is directly impacted and so the governmental spending. Austerity measures to eliminate the negative effects of low oil prices, however, affect the employment

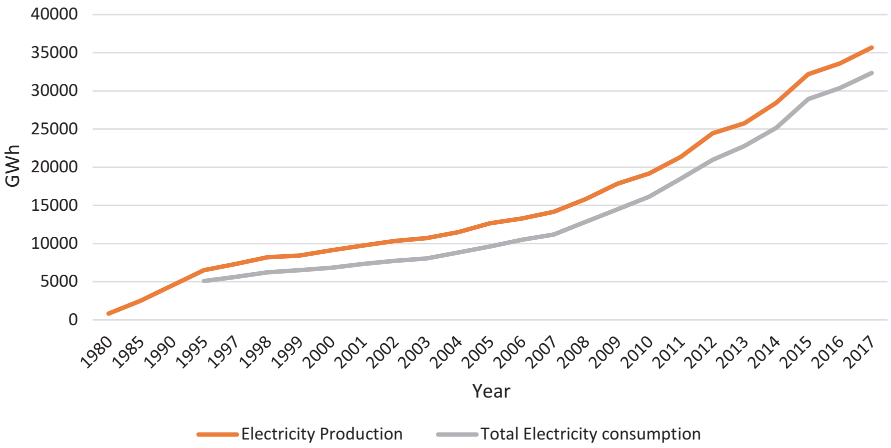

Fig. 2.2 Dynamics of electricity production and consumption in Oman (1980–2017). (Source: Author own with data from Statistical Year Book (NCSI 2012, 2015, 2018))

in both public and private sectors especially that the private sector in Oman is directly connected to the public sector.

Domestic consumption of hydrocarbon resources, mainly oil and gas, has also contributed to incremental increases in Oman's total carbon emissions due to 100% reliance on these resources to meet increasing domestic energy needs. Oman is not a major contributor to global total greenhouse gas (GHG) emissions, but it is ranked among the highest in the world in terms of per capita carbon emissions (World Bank 2013b). In 2013, Oman, for example, was ranked 13th globally in terms of per capita CO_2 emissions (World Bank 2013b). The total greenhouse gas emissions in Oman have increased by 452.28% between 1970 and 2012 and are projected to grow by an average of 5% per year (World Resources Institute 2014). The energy sector accounted for 90% of total GHG emissions in 2014 due to 100% reliance on hydrocarbons, followed by emissions sourced from bunker fuels, industrial activities, agriculture and waste (World Resources Institute 2014). Renewable energy, if managed properly, could provide solution to the aforementioned challenges, i.e. energy security, employment and increasing GHG emissions. Therefore, the purpose of this chapter is to assess the role of renewable energy to address these particular challenges.

2.3 The Current Status of Renewable Energy in Oman

Aware of the arising economic, social and environmental challenges associated with 100% reliance on hydrocarbons, the Omani government has started to pay attention towards developing alternative energy resources such as renewables. In 2008, Oman's Authority for Electricity Regulation launched a study to assess the potential renewable energy resources in Oman. The study indicates the existence of significant renewable energy resources in Oman, especially wind and solar. The AER (2008) study indicates that the solar energy density in Oman is among the highest in the world. The solar insolation varies from 4.5 to 6.1 kWh/m^2 on a daily basis, which corresponds to 1640–2200 kWh per year. The highest potential is concentrated in northern Oman and in desert areas, which cover 82% of the country, while the lowest is in the southern coastal area.

The AER (2008) study identified two solar technologies suited to the environmental conditions in Oman: photovoltaic (PV) systems and solar thermal plants or concentrated solar power (CSP). Under the assumption that 50% of the houses in Oman are suitable for PV installation and that an area of 20 m^2 is available at each house, the same study estimated that the total potential area would provide space for an installation capacity on the order of 420 MW and annual electricity production of 750 GWh (AER 2008). CSP systems, on the other hand, concentrate solar insolation in order to produce steam, converting kinetic power into electricity as in conventional power plants. The advantage of CSP systems is that they store heat recovered during the day for use at night, enabling continuous electricity production. The AER (2008) study indicated that 1 km^2 of land is required to install CSP power plant of 10 MW capacity. Accordingly, if ~280 km^2 of desert area (0.1% of the country's land area) are used to build CSP plants, around 13,900 GWh can be produced (AER 2008). Further, the AER (2008) study identified significant wind energy potential in coastal areas from Masirah to Salalah in Southern Oman and in the Dhofar mountain chain north of Salalah. Theoretically, it is estimated that the installation of 375 wind turbines with 2 MW capacity, 80 m hub height and 90 m rotor diameter in Oman would have a technical generation potential of at least 750 MW and require a wind farm land area of approximately 100 km^2, preferably installed in the available lands in the mountains north of Salalah or at Sur; this corresponds to 20% of the total electricity generation in Oman in 2005 and around 0.03% of the country's land area.

From the above discussion, it appears that if all available solar and wind resources have been harnessed, a total of 3970 MW electricity capacity can be generated from renewables, which corresponds to around 48.2% of total electricity installed capacity in 2018.

The release of a 2008 governmental study was followed by an introduction of two policy initiatives that aim to promote the uptake of renewable energy in Oman. On 16 March 2013, the Authority for Electricity Regulation (AER) announced the first policy to promote the integration of renewable energy in rural area energy systems. The goal of this first renewable energy policy was to promote the integration of renewable energy deployment into the current diesel-based energy system that provides electricity to remote and rural areas (AER 2013). The second policy initiative, locally called the 'Sahim' scheme, was established by Oman's AER in 2017 (Viswanathan 2017). It enables individuals, such as homeowners and institutions, to produce solar electricity for use and surplus sale to electricity distribution companies at the cost of electricity. The present share of renewable energy in total electricity installed capacity is less than 1% (author's calculations).

In addition, in 2017, the Omani government has established a national committee to develop a national energy strategy aiming to investigate the possible integrity of alternative energy sources and reduce the dependence on domestic supplies of oil and gas (Prabhu 2018). The new fuel diversification strategy envisions a 10% share of renewable energy in power generation capacity by 2025, which equals to 2600 MW, 3000 MW use of clean coal by 2030, as well as the use of petcoke and imported gas (Prabhu 2018). Although the strategy has been approved in 2018 (Prabhu 2018), the strategy could benefit from a systemic account of intersection between the power sector and economic, social and environmental domains, which is currently missing. This is important to evaluate the extent at which the integrity of alternative energy sources could address the arising energy issues in Oman (see Sect. 2.2), namely, shortages in natural gas supplies, employment and increasing CO_2 emissions (see Sect. 2.2). Therefore, this chapter positions itself to address this gap in Oman's fuel diversification strategy and aims to provide a systemic account for the intersection between Oman's electric power sector and economic, social and environmental domains. This is useful because it allows policymakers who represent different sectors to see a fuller picture in terms of the potential effects posed by the use of alternative energy sources.

3 Scenario Modelling Approaches

3.1 From Linear to System Thinking

Since the early 1970s, a wide variety of models became available for analysing energy systems or subsystems (such as power systems) due to the sudden oil price increases. The high price of oil emphasised the need for coordinated developments of the energy systems and led to a number of modelling efforts for strategic planning. Since then models have been developed for different purposes – they were concerned with better energy supply system design given a level of demand forecast and better understanding of the present and future demand-and-supply interactions and energy supply planning (Bhattacharyya 2011).

Moreover, the recent challenges of climate change, security of energy supply and economic recession have triggered efforts to investigate the potential role of renewable energy to combat these issues by converting energy systems from dependency on fossil fuels to renewable energy sources (Lund 2007). A crucial element in this transformation is often to show coherent technology analyses of how renewable energy can be implemented and what effects renewable energy has on other parts of the energy system (Connolly et al. 2010). Different computer tools were developed to analyse the integration of renewable energy into various energy systems under different objectives. There are a large number of models from which a selection of scenario modelling tool can be challenging in this research (e.g. see Connolly et al. 2010). To overcome this challenge, it is important to identify clear objectives of the model under question before selecting the relevant modelling tool. Therefore, the following paragraphs provide a discussion of the most relevant modelling tools that can be used to approach the specific objective of modelling exercise for energy policy as discussed in this chapter.

The Brookhaven Energy System Optimization Model (BESOM) is one of the early day applications that was developed at a country level for efficient resources allocation in the USA. The first version of the model was implemented at the national level for a snapshot analysis of a future point in time. Later on, the capability of the model was extended to include a macroeconomic linkage through an input-output table. Further, multiperiod or dynamic models have emerged. Market allocation (MARKAL) is a derivative of the BESOM model. In addition to country specific models, more generic models for wider applications, including MARKAL model, came into existence. The tradition of linking an econometric macroeconomic growth model with an interindustry energy model was pioneered by Hudson and Jorgenson (1974).

In the mid-1980s, the focus was shifted to energy-environment interactions. At this stage, the energy models incorporated environmental concerns more elaborately and the practice of long-term modelling (Bhattacharyya 2011). An example is Teri Energy Economy Environment Simulation Evaluation model (TEEESE) which was used in India for evaluating energy-environment interactions and producing a plan for greening the development process in India (Pachauri and Srivastava

1988). In the 1990s, the focus shifted towards energy-environment interactions and climate change-related issues. During this period, the effort for regional and global models increased significantly and a number of new models came into existence. These include Asian-Pacific Model (AIM), second-generation model (SGM), RAINS-Asia model, Global 2100, DICE, POLES, etc. Existing models like MARKAL saw a phenomenal growth in application worldwide. Similarly, the LEAP model became the de facto standard for use in national communications for the United Nations Framework Convention on Climate Change (UNFCCC) reporting (Bhattacharyya 2011).

These early forms of energy models, however, were mainly linear programming applications based on the optimisation of energy systems. A more comprehensive model that integrates a large number of economic components with respect to MARKAL is the General Equilibrium Model for Energy-Economy-Environment interactions (GEM-E3) (Musango 2012). The GEM-E3 model includes the economic frameworks used by the World Bank (national accounts and social accounting matrix) as well as projections of full input-output tables by country/region, employment, balance of payments, public finance and revenues, household consumption, energy use and supply and atmospheric emissions (Capros et al. 1997). The GEM-E3 model resembles the structure of Threshold 21 (Bassi 2009), a causal-descriptive model, where system dynamics is employed and where society, economy and environment are represented.

Threshold 21 and other system dynamics models are able to combine optimisation and market behaviour frameworks and the investigation of technology development into one integrated framework that represents the causal structure of the system (Bassi 2009; Musango 2012). System dynamics models offer a complementary approach that allows the assessment of renewable energy integration in an energy system while concurrently simulating the interaction of a large number of feedback loops with major factors in the economy, the society and the environment (Musango 2012; Musango et al. 2012). Both scenario analysis and system dynamics approaches consider a higher degree of complexity inherent in systems than the study of individual projects or technologies. They allow the endogenous complexity of energy systems and building future possible pathways into the future to be captured. This provides useful insights for policymaking to evaluate the impacts of alternative energy uptake scenarios. To this end, in this chapter, system dynamics modelling is used as a scenario-modelling tool. A detailed overview of the system dynamics modelling approach is provided in the following section.

3.2 System Dynamics Approach

System dynamics can be defined as a methodology used to understand how systems change over time. The way in which the elements or variables composing a system vary over time is referred to as the behaviour of the system. In the ecosystem example, the behaviour is described by the dynamics of population growth and decline.

The behaviour changes due to changes in food supply, predators and environment, which are all elements of the system (Martin 1997).

A common scientific tool used to investigate patterns and behavioural change over time is modelling. A *model* can be defined as a 'representation of selected aspects of a real system with respect to specific problems(s)' (Barlas 2007). According to this definition, we do not build models of systems, but we build models of specific aspects of systems to study specific problems.

Therefore, *system dynamics* modelling is an approach used to study the behaviour of complex systems. It aims to demonstrate how policies, decisions, structures and delays are interrelated and influence growth and stability. The interrelationships create structure, which in turn produces behaviour (Lee and von Tunzelmann 2005). Sterman (2000) suggests that dynamic complexity arises because systems are dynamic, non-linear, tightly coupled, governed by feedback, history dependent, self-organising, adaptive, counter-intuitive, policy-resistant and characterised by trade-offs, etc. Dynamic complexity arises from the interaction between agents over time. System dynamics is also a problem-solving approach that involves models and simulations that examine a variety of relationships between the components of any dynamic processes (Sterman 2000).

One major advantage of models is to try things out and analyse their consequences, including experiments that would be impossible, impractical or unethical with a real system or in system configurations that do not (yet) exist. For instance, studying energy systems often involves recommending alternative policy options that can steer the system towards more sustainable modes. Models can be used to experiment with the consequences associated with implementing alternative policy options. Such experimentation in the real world might involve time delays and/or great expense. Also, some alternative policy options may have unperceived negative social effects that can be avoided through modelling practices (Sterman 2000).

System thinking advocates stress that the world is a complex system, in which we understand that 'everything is connected with everything else' in such a way that 'you cannot just do one thing'. This implies that if people had a holistic view of the world, they would then act in consonance with the long-term best interests of the system as a whole (Sterman 1994). The feedback loop character of system dynamics accounts as a concept to aid decision-making processes. In reality, we make decisions to alter the real world; we receive information feedback about the real world, and, using the new information, we revise our understanding of the world and the decisions we make to bring the state of the system closer to our goal (Fig. 2.3).

System dynamics modelling approach offers a tool that can capture and address the short-term and long-term impacts of decision-makers on the real world. In general, the advantage of using system dynamics models is their ability to integrate systematically the knowledge about variables and processes of the analysed system and to let their interactions generate a phenomenon of interest. With explicit assumptions and clarity of causal factors, these models can generate an understanding of the operating mechanisms under question.

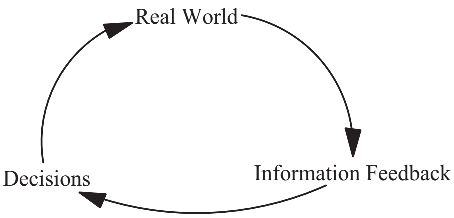

Fig. 2.3 Feedback process in decision-making. (Sterman 2000)

4 Methodology: Development of the Dynamic Model

System dynamics methodology was used to develop four scenarios of renewable energy share in Oman's future energy mix. System dynamics is a methodology, originally developed by Jay Forrester and his colleagues at Massachusetts Institute of Technology (MIT) in the 1950s. Computer simulation models are used to develop models that enable better understanding of complex systems and their dynamic behaviour under a given set of conditions or scenarios so that to avoid potential negative consequences or prepare for them (Sterman 2000; Ford 2009). In this methodology, the dynamic behaviour of the system is assumed to be a result of interconnected web of feedback loops. Feedback loops are illustration of connection between variables, which define a system under question, with causal links. They are of two types: positive (also known as reinforcing) and negative (also known as balancing). Positive feedback loops enhance or amplify the feedback of information. Negative feedback loops are goal seeking and tend to resist change in the system.

Vensim software was used to build the scenarios in this research. Vensim allows to explore the dynamical behaviour of the system once the variables are identified and connected, feedback loops are recognised and the model is ready for simulation. In this study, there are two subsequent steps that were used in order to develop the simulation models using Vensim software. These are causal loop diagrams and followed by stock-and-flow models based on the modelling process of Ford (2009) and Wolstenholme (1990). Once the stock-and-flow models were designed, the simulation equations were built in order to connect the variables that identify each model in concern.

4.1 Data Sources

Oman's high dependence on oil and gas over the last four decades has been associated with unprecedented challenges such as energy security, employment and increasing CO_2 emissions (see Sect. 2.2). In this study, these criteria formulate a foundation for the model structure.

Quantitative data were collected from different secondary sources including Omani governmental documents such as statistical yearbooks issued by the National

Center for Statistics and Information, Oman; annual transmission capability statement reports prepared by the Oman Electricity Transmission Company; the Oman Power and Water Procurement Company (OPWP) 7-year statement reports; annual reports issued by the Authority for Electricity Regulation; and other electronic database like World Bank, US Energy Information Administration (EIA), International Energy Agency (IEA), World Resources Institute (WRI), BP Statistical Review of World Energy and International Monetary Fund (IMF).

4.2 Setting the Scenarios

In order to enable estimating the future effects associated with the deployment of different renewable energy technologies in Oman's economic-environmental-social contexts, a starting point involved formulating four scenarios for future renewable energy deployment in Oman. Given that the maximum power that can be harnessed from solar and wind resources account potentially for 48.2% of total electricity installed capacity in 2018 (see Sect. 2.3), three renewable energy integrity scenarios are proposed along with a business-as-usual scenario. These scenarios assume different trajectories of solar PV, CSP and wind share in Oman's future total electricity installed capacities (Table 2.1), as follows:

- Business-as-usual scenario implies that there is no promotion for renewable energy policies or implementation of any renewable energy action plans.
- Moderate scenario implies 10% of electricity generation is sourced from renewable energy sources through 2040.
- Advanced scenario implies 30% of electricity generation is sourced from renewable energy sources through 2040.
- Ambitious scenario implies 50% of electricity generation is sourced from renewable energy sources through 2040.

A starting point to build the scenario models was to define a conceptual framework that informs the structure of the model under question. As discussed in Sect. 2.2, energy security, reduction of CO_2 emissions and job creation were defined as the most important factors to promote the uptake of renewable energy in Oman (Fig. 2.4). These factors formulated boundaries for this research's model and informed the build of an overall conceptual framework which was used to build an

Table 2.1 Scenarios for renewable energy deployment pathways through 2040

	Scenario assumptions				
Scenario name	Solar PV	Solar CSP	Wind	Total RE	FF
BAU	0%	0%	0%	0%	100%
Moderate	2%	3%	5%	10%	90%
Advanced	10%	10%	10%	30%	70%
Ambitious	10%	20%	20%	50%	50%

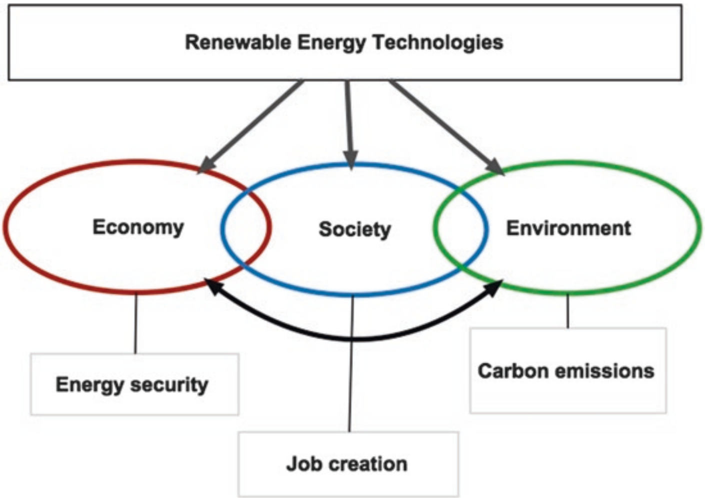

Fig. 2.4 A conceptual framework shows the potential contribution of renewable energy technologies to energy security, job creation and carbon emissions reduction which represent economic, social and environmental domains, respectively

aggregated model structure for scenario analysis for future uptake of renewable energy in Oman. In this conceptual framework, the identified policy indicators have been classified under three main domains: economic, environmental and social. Energy security, for example, is set under the economic domain. This, in turn, interacts with another two domains: social and environmental domains. Under the social domain, job creation is considered as the main criterion that represents this domain. The environmental domain considers carbon emissions for further assessment. Energy security, carbon emissions and job creation are selected as policy indicators against which the performance of scenarios will be evaluated.

4.3 Feedback Loops Representing Intersection Between Oman's Power Sector, Economic, Social and Environmental Domains

The use of system dynamics methodologies to build the scenario models comprises two main steps: (i) identifying the main feedback loops in the system and (ii) identifying the stock-and-flows in the system.

In this section, the main feedback loops that represent the intersect between Oman's power sector and economic, social and environmental domains are identified and presented in Fig. 2.5. The development of the main feedback loops was guided by the conceptual framework presented in Fig. 2.4.

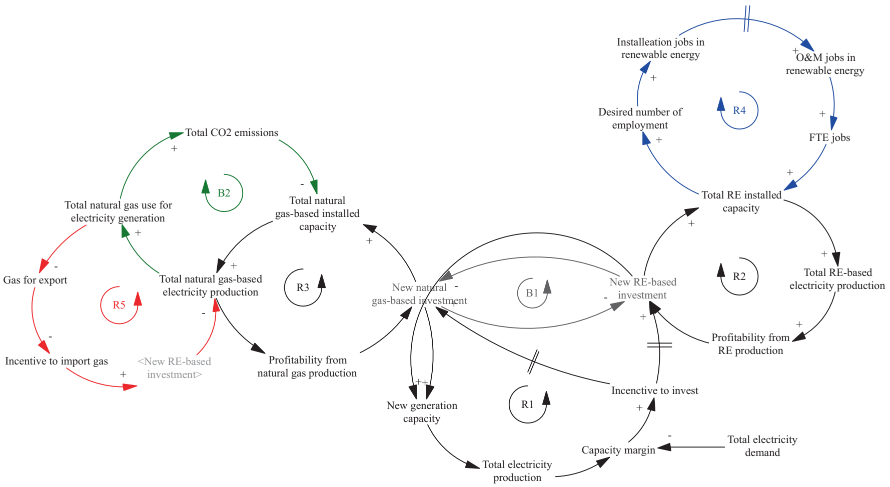

Fig. 2.5 Presentation of important feedback loops that represent the dynamic behaviour of Omani energy system

The main assumption of the overall causal loop diagram (Fig. 2.5) is that increasing share of renewable energy investments decreases the share of natural gas-based investments (B1), which represents a balancing relationship. Thus, the balancing causal loop (B1) represents the interaction between the new renewable energy investments and new natural gas-based investments. R2 causal loop indicates a reinforcement loop for total electricity production from renewables. That is, the larger the investments aimed to increase the renewable energy capacity, the larger electricity production from renewables and hence renewable energy profitability (R2). Similarly, R3 causal loop suggests that the larger the investments aimed to increase natural gas-based capacity, the larger electricity production from conventional sources and hence natural gas-based profitability.

The three modelled domains, i.e. economy, society and environment, with which renewable energy interacts are illustrated in red, blue and green, respectively (Fig. 2.5, also see Fig. 2.4). The economic domain (in red) is represented by one reinforcing loop, R5. As electricity generation from natural gas-based technologies increases, the demand for natural gas in power sector increases, leading to decline in commodity allocated for export, incentivising natural gas imports, which in return creates an incentive to invest in renewables to enhance energy security (Fig. 2.5, R5). The social domain (in blue) is represented by one reinforcing loop, R2. As total renewable energy installed capacity increases, the desired number of jobs in the new sector increases which in return leads to creation of job in both installation and operation and maintenances stages of project life cycle (Fig. 2.5, R2). The environmental domain (in green) is represented by one balancing loop, B2. As electricity generation from natural gas-based technologies increases, natural gas consumption by the power sector increases, leading to total increase in CO_2 emissions which in return disincentivises investments in natural gas-based technologies and hence incentivises the search for clean energy sources (Fig. 2.5, B2).

5 Components of the Dynamic Model: Stock-and-Flow Diagrams

This section presents the main stock-and-flow diagrams that informed the analysis of renewable energy impacts on social, economic and environment domains under different scenarios proposed in Sect. 4.2. A starting point for the model development was to simulate the supply and demand of Oman's main national grid power system. This is important to forecast the future energy demand as well as future desired installed capacity, through 2040 as per this chapter. Therefore, supply and demand sub-model were designed (Fig. 2.6).

The supply and demand sub-model consist of two stocks: annual electricity demand and total installed capacity. The annual electricity demand (ED) increases by changes in electricity demand, which is determined by the electricity demand growth rate. Total installed capacity (IC), on the other hand, is determined by the investments in the power sector. Investments in the power sector result from the desired capacity adjustment, which equals to capacity margin. Capacity margin (CM) is calculated, as follows:

$$\mathrm{CM} = \left(\mathrm{IC} - \mathrm{ED}\right) / \mathrm{ED} \tag{2.1}$$

The forecast of desired installed capacity is necessary because it enables to estimate the future share of renewable energy in total power generation capacity. In this way, it is possible to connect energy security, employment and CO_2 emission sub-models systematically. These sub-models are explained, as follows.

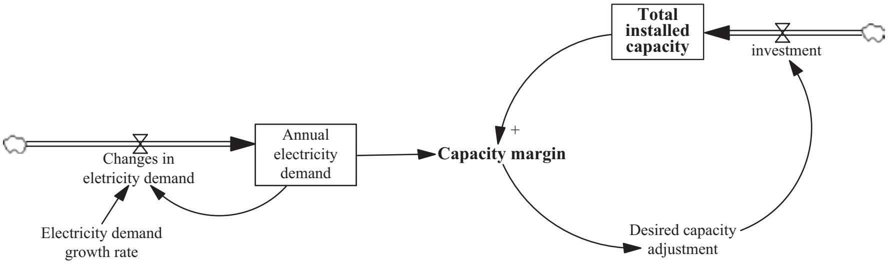

Fig. 2.6 Supply and demand sub-model

5.1 Energy Security Sub-model

Natural gas is the main fuel used to generate electricity for Oman's main national grid. For the main national grid, open cycle gas turbine or combined cycle gas turbine power technologies are the main two types of gas-fired power-generating technologies (see Sect. 2.1). The sub-model for natural gas use, therefore, calculates the total amount of natural gas used to generate electricity for the main national grid in Oman under different renewable energy integrity scenarios (Fig. 2.7). This sub-model evaluates the influence of renewable energy integrity on natural gas consumption.

The energy security sub-model consists of three stocks: FF installed capacity, total FF electricity production and total natural gas use in BTU.

FF installed capacity (FFIC, in MW) increases by FF investment growth (G_{FFI}, in MW/year) and decreases by depreciation rate (DR, in MW/year), as follows:

$$\mathrm{FFIC} = \mathrm{FFIC}\left(21354^{*}1e+06\right) + \int\left[G_{\mathrm{FFI}} - \mathrm{DR}\right]dt \tag{2.2}$$

FF investment growth (G_{FFI}, in MW/year) is calculated by multiplying FF investment growth rate ($\mathrm{GR}_{\mathrm{FFI}}$, in fraction/year) by total installed capacity (IC, in MW):

$$G_{\mathrm{FFI}} = \mathrm{GR}_{\mathrm{FFI}}{}^{*}\ \mathrm{IC} \tag{2.3}$$

Depreciation rate (DR, in MW/year), on the other hand, is calculated by dividing the FF installed capacity (FFIC, in MW) by average technology life (ATL, in years):

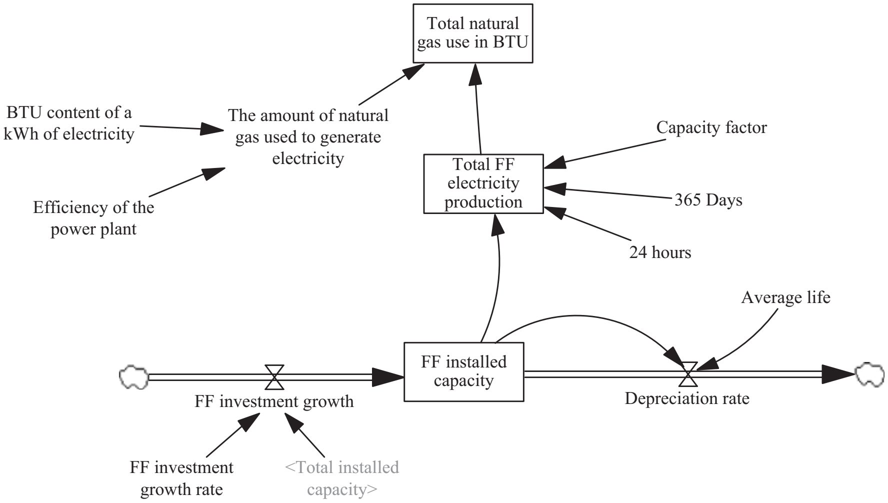

Fig. 2.7 Stock-and-flow diagram for energy security sub-model

$$\mathrm{DR} = \frac{\mathrm{FFIC}}{\mathrm{ATL}} \tag{2.4}$$

Total FF electricity production (FFEP, in kWh) is calculated from multiplying FF installed capacity (FFIC, in MW) by capacity factor (CF, in 0.48) by 356 days by 24 hours, as follows:

$$\mathrm{FFEP} = \mathrm{FFIC}^{*}\mathrm{CF}^{*}\,365\,\mathrm{Days}^{*}\,24\,\mathrm{Hours} \tag{2.5}$$

Therefore, the natural gas use in BTU is quantified from multiplying total FF electricity production (TFFEP, in MWh) by the amount of natural gas used by power plant to generate 1kWh of electricity ($\mathrm{NG}_{\mathrm{kWh}}$, in BTU/kWh), as follows:

$$\mathrm{NGU}_{\mathrm{BTU}} = \mathrm{TFFEP}^{*}\,\mathrm{NG}_{\mathrm{kWh}} \tag{2.6}$$

The amount of natural gas used by power plant to generate 1 kWh of electricity depends on the efficiency or heat rate of the power plant and the heat content of the fuel. The heat rate is a measure of the efficiency of a generator and is simply the amount of energy used by an electrical power plant to generate 1 kWh of electricity. The amount of natural gas used by power plant to generate 1 kWh of electricity is thus calculated by dividing the BTU content of a kWh of electricity ($\mathrm{BTU}_{\mathrm{kWh}}$, in BTU/kWh) by the efficiency of the power plant (E_{NG}, in %) as follows:

$$\mathrm{NG}_{\mathrm{kWh}} = \mathrm{BTU}_{\mathrm{kWh}} / E_{\mathrm{NG}} \tag{2.7}$$

The parameters and input variables for the energy security sub-model are presented in Table 2.2.

5.2 *Employment Sub-model*

Renewables contribute to the creation of direct, indirect and induced jobs. The term direct jobs refers to jobs related to core activities such as manufacturing, fabrication, construction, site development, installation and operation and maintenance (O&M) (Wei et al. 2010). On the other hand, indirect jobs refer to the jobs created within the supply chain supporting a specific renewable energy project such as

Table 2.2 Parameters used in energy security sub-model

Parameter	Type	Value	Unit	Notes/source
BTU content of a kWh of electricity	Constant	3412	BTU/kWh	US EIA website
Efficiency of power plant	Constant	52	%	American Electric Power
Power plant capacity factor	Constant	48	%	US EIA website
Average life of power plant	Constant	20	Year	Estimated

extraction and processing of raw materials and the administration at ministries. Induced employment commonly refers to jobs created as a result of economic activities of direct and indirect employees. The wages paid to direct and indirect employees are spent on goods and service, supporting further employment. In this study, however, only direct jobs are calculated. The calculation of indirect jobs is considered not applicable because renewable energy technologies are not created locally but imported. Likewise, given the fact that detailed knowledge of how industries link to one another is required and nascent development of renewable energy in Oman, the evaluation of induced jobs remains a difficult task.

In order to determine the number of direct jobs that can be created as a result of establishing different types of renewable energy power plants in Oman, the job creation sub-model was designed (Fig. 2.8).

The job creation sub-model consists of two stock variables: capacity under construction and operational generation capacity; and three flows: construction rate, completion rate and ageing rate. Thus, the stock of capacity under construction (CUC, in MW) increases by construction rate (CNR, in MW/Year) and depletes by completion rate (CMR, in MW/Year). Similarly, operational generation capacity (OGC, in MW) increases by completion rate (CR, in MW/Year) and decreases by ageing rate (AR, in MW/Year), as follows:

$$\mathrm{CUC} = \mathrm{CUC}(0) + \int [\mathrm{CNR} - \mathrm{CMR}]\,dt \tag{2.8}$$

$$\mathrm{OGC} = \mathrm{OGC}(0) + \int [\mathrm{CR} - \mathrm{AR}]\,dt \tag{2.9}$$

The creation of renewable energy installation jobs is associated with the project construction. Therefore, the number of renewable energy installation jobs is calculated by multiplying capacity under construction (CUC, in MW) by the installation employment factor (IEF), as follows:

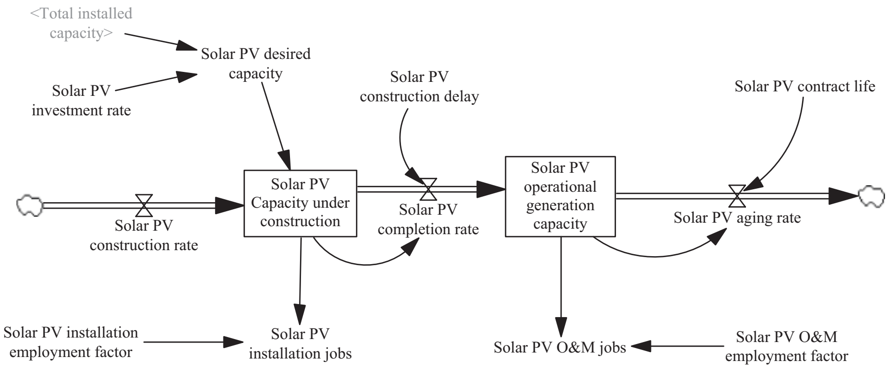

Fig. 2.8 The stock-and-flow diagram of job creation sub-model. Solar PV sub-model is shown for illustration

Table 2.3 Parameters used in job creation sub-models for three types of technologies: solar PV, CSP and wind technology

Parameter	Type	Value	Unit	Notes/Source
Solar PV O&M employment factor	Constant	0.3	Jobs/MW	(Blyth et al. 2014)
Solar PV installation employment factor	Constant	13.2	Jobs/MW	(Blyth et al. 2014)
Solar CSP O&M jobs/MW	Constant	0.5	Jobs/MW	(Blyth et al. 2014)
Solar CSP installation employment factor	Constant	10.2	Jobs/MW	(Blyth et al. 2014)
Wind O&M employment factor	Constant	0.2	Jobs/MW	(Blyth et al. 2014)
Wind installation employment factor	Constant	1.3	Jobs/MW	(Blyth et al. 2014)

$$\mathrm{IJ} = \mathrm{CUC} \times \mathrm{IEF} \tag{2.10}$$

Similarly, the creation of renewable energy operation and maintenance (O&M) jobs is associated with the project operational generation capacity. Therefore, the number of renewable energy O&M jobs is calculated by multiplying operational generation capacity (OGC, in MW) by the O&M employment factor (OMEF), as follows:

$$\mathrm{OMJ} = \mathrm{OGC} \times \mathrm{OMEF} \tag{2.11}$$

Based on the above stock-and-flow diagram structure, which represents the solar PV technology only, three job creation sub-models for three types of renewable energy technologies are explored and developed in this chapter (i.e. PV, CSP and wind technologies). The parameters that represent the values for each technology type are shown in Table 2.3. Given the fact that renewable energy development in Oman is relatively nascent, employment factors, which vary by technology as well as location, are not available for Oman. Therefore, employment factors identified in Blyth et al. (2014), which apply to European countries that have different macroeconomic conditions than Oman, are used for the purpose of exploring possibilities for Oman.

5.3 CO_2 Emission Sub-model

The reduction of natural gas consumption under different scenarios, as quantified in in the energy security sub-model, has environmental advantages in terms of reducing CO_2 emissions. The quantification of natural gas use under different scenarios enables the quantification of the amount of CO_2 emissions generated under different scenarios due to renewable energy integrity. The CO_2 emission sub-model, therefore, calculates the reduction of CO_2 emissions as a result of reducing natural gas used to generate electricity under different scenarios of renewable energy integrity (Fig. 2.9).

The CO_2 emission sub-model (Fig. 2.9) consists of two stocks: total natural gas use in mmBTU (NGU_{BTU}) and total CO_2 emissions ($\mathrm{Emissions}_{CO_2}$, in kg). The stock

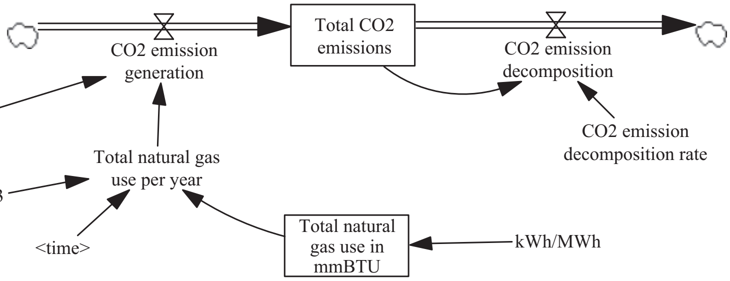

Fig. 2.9 The stock-and-flow diagram of the air emission sub-model

of total natural gas use in mmBTU (NGU_{mmBTU}) has been already identified and quantified in the energy security sub-model (see Sect. 5.1).

The stock of total CO_2 emissions (Emissions_{CO_2}, in kg) has two flows, inflow of CO_2 emission generation (Generation_{CO_2} in kg/year) and outflow of CO_2 emission decomposition ($\text{Decomposition}_{CO_2}$ in kg/year). Thus, the stock of total CO_2 emission is increased by CO_2 emission generation (Generation_{CO_2} in kg/Year) and decreased by CO_2 emission decomposition ($\text{Decomposition}_{CO_2}$ in kg/Year), as follows:

$$\begin{aligned} \text{Emissions}\,CO_2 &= \text{Emissions}\,CO_2\left(1.8652e+10\right) \\ &+ \int\left[\text{Generation}_{CO_2} - \text{Decomposition}_{CO_2}\right]dt \end{aligned} \tag{2.12}$$

CO_2 emission generation (Generation_{CO_2} in kg/year) is determined by multiplying CO_2 emission coefficient per fuel (in kg/MWh) by total natural gas use per year ($TNGU_{mmBTU}$, in mmBTU/year), by the factor 0.293, which converts the NGU_{mmBTU} value from mmBTU to MWh and is given as:

$$\text{Generation}_{CO_2} = CO_2\ \text{Emissions Coefficient} \times NGU_{mmBTU} \times 0.293 \tag{2.13}$$

The parameters and input variables for the CO_2 emission sub-model are presented in Table 2.4.

6 Socio-economic and Environmental Implications of Renewable Energy Integrity in Oman

The performance of renewable energy scenarios in relation to economy, environment and society are discussed as follows.

Table 2.4 Parameters used in CO_2 emission sub-model

Parameter	Type	Value	Unit	Notes/source
CO_2 emission coefficient	Constant	181.08	kg /MWh	US EIA website
Emission decomposition rate	Constant	0.1%	Fraction/ year	Assumed
Total CO_2 emission initial value	Constant	1.8652e+10	kg	World Resources Institute

6.1 Energy Security

A major concern in low-carbon energy transitions is their implication to energy security. In this study, the use of renewable energy, namely, solar and wind, proved to enhance energy security via replacing the use of natural gas to meet the increasing power demands.

In the business-as-usual scenario, wherein no renewable energy is integrated, the use of natural gas for electricity generation was expected to increase by 28% by 2050 compared with 2010. On the other hand, the use of natural gas declined in all other three scenarios compared with the business-as-usual scenario (Eqs. 2.6 and 2.7) due to increase of the share of renewable energy in power generation. Under the moderate scenario, natural gas use was reduced by almost 27% in 2040 compared to the business-as-usual scenario; the advanced scenario suggests a decline by almost 46% in 2040; and over 64% reduction is estimated by the ambitious scenario in 2040, compared to the business-as-usual scenario (Table 2.5 and Fig. 2.10).

6.2 Employment

The simulation output for the social indicator is presented in Fig. 2.11. Given the increase in the renewable energy share in the moderate, advanced and ambitious scenarios, the employment in installation and operation and maintenance of renewable energy technology increases correspondingly (Eqs. 2.10 and 2.11).

Solar CSP provides the largest number of jobs over time compared with other technologies, namely, solar PV and wind technologies. Since there is no installation of renewable energy technologies in Oman in 2018, the total number of jobs is proposed to steadily increase after 2018 through 2040 (Fig. 2.11). Since there is no deployment of renewable energy in the business-as-usual scenario, there are not any jobs associated with renewable energy technologies in this scenario. However, the deployment of renewable energy technologies may adversely impact the number of jobs provided by the fossil fuel sector. This calculation, however, is not included in our models since it goes beyond the aims of this chapter.

For all types of technologies, ambitious and advanced scenarios suggest more installation and O&M job creation compared to the moderate scenario due to the increasing share of renewable energy in the power generation. Yet, in all scenarios,

Table 2.5 Average reduction of natural gas use in power generation under different scenarios compared to business-as-usual scenario

Scenario	2020	2030	2040
Moderate	−10%	−24%	−27%
Advanced	−17%	−40%	−46%
Ambitious	−24%	−56%	−64%

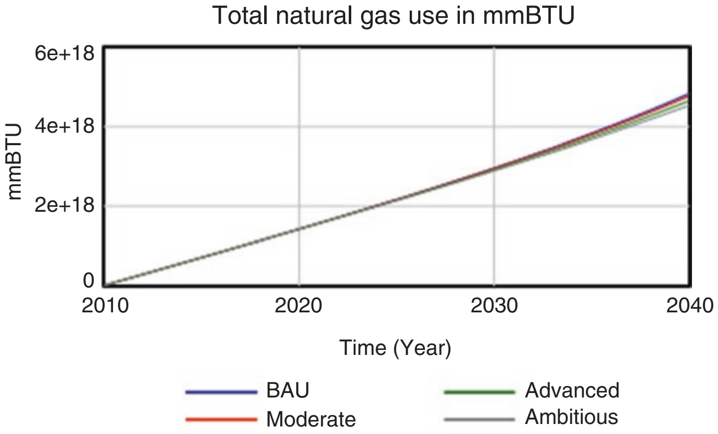

Fig. 2.10 Projection of natural gas use in power generation under four scenarios in 2010–2040

the installation jobs decline due to the end of the power plant construction period (Eqs. 2.8 and 2.10). Operation and maintenance jobs, on the other hand, start to increase by the completion of power plant construction but start to decline due to the ageing of the power plant (Eqs. 2.9 and 2.11) (Fig. 2.11).

6.3 CO_2 Emissions

All scenarios show a steady upwards trend in the total CO_2 emissions produced from electricity generation through 2040 (Eqs. 2.12 and 2.13). The reason is that, in all scenarios, natural gas continues to constitute a proportion of electricity generation mix.

The business-as-usual scenario, wherein no renewables are considered in electricity generation, shows the highest exponential growth in the total CO_2 emissions through 2040, compared with all other scenarios. In this scenario, under the current growth rate of natural gas consumption for power generation, the total CO_2 emissions are expected to rise by 400% in 2040 if no renewables are developed.

All other scenarios, on the other hand, contribute to a relative reduction in total CO_2 emissions sourced from power generation because of the integration of renew-

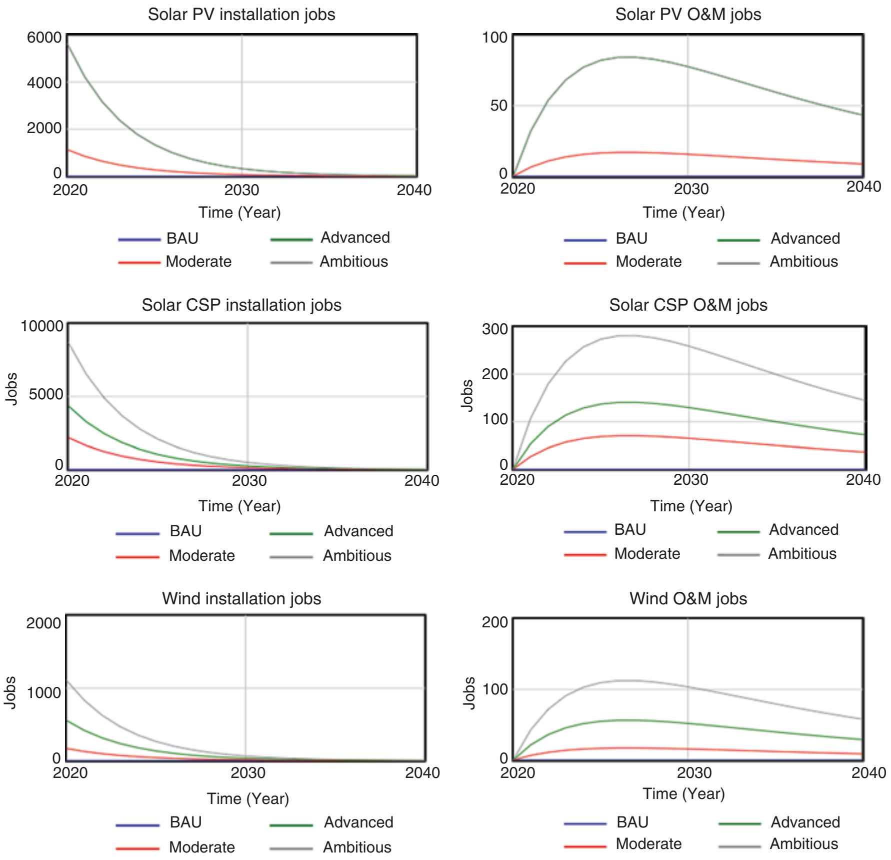

Fig. 2.11 Total number of installation and O&M jobs per year created by each type of renewable energy technology 2020–2040

able energy technologies (Table 2.6 and Fig. 2.12). In the moderate scenario, wherein the share of renewable energy accounts for 10% of total power generation, the total CO_2 emissions are reduced by more than 20% in 2040, compared to the business-as-usual scenario. The advanced scenario shows a reduction of the total CO_2 emissions by over than 40% in 2040, compared to the business-as-usual scenario.

The ambitious scenario, on the other hand, shows a major reduction in total CO_2 emissions compared with the other scenarios due to the dominance of renewable energy technologies in the power generation. About 58% of this reduction is achieved using 10% solar PV, 20% solar CSP and 20% of wind turbine technologies as well as reducing the natural gas use by more than 60% in 2040, compared to the business-as-usual scenario (Table 2.6 and Fig. 2.12).

Table 2.6 Percentage of CO_2 emission reduction by scenario compared to BAU scenario

Scenario	2020	2030	2040
Moderate	−12%	−23%	−25%
Advanced	−7%	−32%	−41%
Ambitious	−9%	−45%	−58%

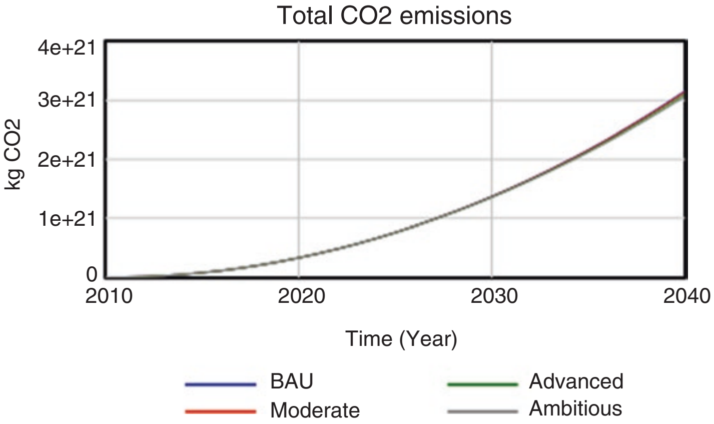

Fig. 2.12 Total CO_2 emissions (in kilogrammes) resulting from natural gas used for power generation in Oman through 2050 under four scenarios

7 Model Verification and Validation

System dynamics models need to be subjected to two types of tests: structural validity tests and behavioural validity tests (Barlas 1989). Structural validity tests aim to determine whether the structure of the model is an acceptable representation of the actual system structure. Behaviour validity tests aim to determine whether the model is able to produce an output behaviour that is close enough to the behaviour of the actual system.

7.1 *Structural Validity Tests*

Four tests were conducted to validate the structure of the model: boundary adequacy, structure verification, dimensional consistency and parameter verification (Qudrat-Ullah and Seong 2010). These are discussed in detail, as follows.

Boundary adequacy and structure verification tests were conducted during the initial stage of model development, i.e. the development of conceptual model. In terms of boundary adequacy, energy security, reduction of CO_2 emissions and job creation were defined as the most important variables which formulate the boundary of this chapter's model (see Sect. 2). Thus, all variables associated with energy security, reduction of CO_2 emissions and job creation were generated endogenously (see Fig. 2.5). Energy demand was the only exogenous variable (see Fig. 2.5).

For the structure verification of our model, country-specific data of Oman was utilised to construct the model (see Sects. 2, 4.1 and 4.2). The conceptual model is represented by a causal loop diagram, as depicted in Fig. 2.5. The causal relationships developed in the model were based on the available knowledge about the real system (see Sect. 4.3).

Furthermore, two tests were conducted during the stage of model's stock-and-flow development (see Sect. 5). These are dimensional consistency and parameter verification. Dimensional consistency test requires that each mathematical equation in the model be tested if the measurement units all the variables and constants involved are dimensionally consistent (Qudrat-Ullah and Seong 2010). Dimensional consistency of each of the mathematical equations used in the model was checked. For instance, Eq. 2.5 was used to calculate the annual electricity production, as follows:

$$\text{FFEP} = \text{FFIC}^{*}\text{CF}^{*}\,365\,\text{Days}^{*}\,24\,\text{Hours}$$

This equation suggests that annual fossil fuel-based electricity production (FFEP) is dependent on two factors: (i) FF installed capacity (FFIC) and (ii) capacity factor (CF). To ensure dimensional consistency, the value of FFIC was estimated based on the installed capacity of natural gas-based electricity in Oman (in MW) over a period of time equals to a year (in days/year multiplied by hours/days). The capacity factor of natural gas-based power plants in Oman was estimated at value of 0.48 (dimensionless). Thus the dimensional analysis of the equation above is:

$$\text{MWh / Year} = \text{MW}^{*}\left(\text{dimensionless}\right)*\left(\text{days / Year}\right)*\left(\text{hours / days}\right)$$

To ensure parameter verification, the values assigned to the model parameters were sourced from the existing knowledge and numerical data from Oman's case (see Sect. 4.1, Tables 2.2 and 2.4). In some cases, however, where Oman's specific data were not available, external sources of data were utilised to serve the quest of the model. Employment factor is one example of such external data (see Table 2.3).

Based on these tests, the structure of the model was deemed appropriate.

7.2 Behavioural Validity Tests

To ensure behavioural validity and to build on the confidence gained from the validity of the model structure, two transient behaviour tests were carried out to measure how accurately major behavioural patterns in the real world can be reproduced by the model. According to Barlas (1996), the use of graphical or visual measures of typical behaviour features is adequate to validating a model in terms of behaviour.

Firstly, since the modelling was carried out using the Vensim software, the extreme condition testing provided by its ‘reality check’ feature was used. In this process all ‘if/then’ statements according to the relationships between variables are compared with the model simulations, and their conformance with the anticipated behaviour based on the model is checked (Gallati 2008), and this shows a conformance with the conceptual model.

Secondly, in the scenario description, we demonstrated that the trajectories for the base scenario remains essentially unchanged under different iterations, for example, in the employment sub-model (see Sect. 6.2) where there are substantial changes to the social indicators under different scenarios, the base scenario remains the same. This sensitivity analysis shows that the typical behaviour features of the model are valid enough for results to be communicated based on the model simulation. Therefore, once the model was operational, validity tests were conducted to compare the model-generated behaviour to the observed behaviour of the real system. Comparing the output data from a system dynamics-based simulation model with corresponding data from the real world can be done in different ways (Barlas 1989; Qudrat-Ullah 2008). In this chapter, the mean square error (MSE) analysis and the root mean squared percent error (RMSPE) were used to evaluate the behaviour of the model. The MSE provides a measure of the total error, and the RMSPE provides a normalised measure of the magnitude of the error. The simulation of the model started from 2010, providing 8 years of simulated data to compare to the actual behaviour of the electricity demand in Oman (Fig. 2.13). The error analyses in terms of the MSE and the RMSPE were 0.00039561 and 3%, respectively. The RMS percent error of 3% means that the variable replicates the behaviour accurately, an indication of high confidence in the model.

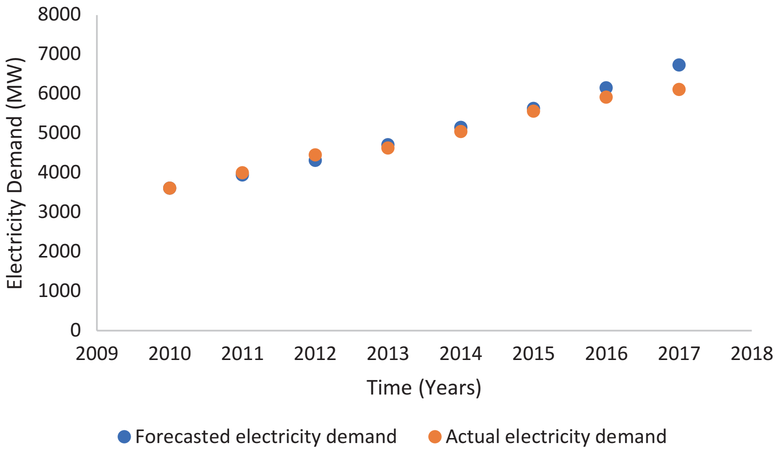

Fig. 2.13 Forecasted and historic electricity demand, Oman

8 Conclusions

This chapter provided a specific focus on building a methodological basis for environmental and macroeconomic impacts of renewable energy deployment in Oman. The developed scenarios are promising to inform the future impacts of renewable energy deployment in Oman as well as supporting renewable energy policymaking in Oman.

The assessment of prospective long-term impacts of renewable energy uptake in Oman in relation to the domains of environment, economy and society has been achieved by developing four scenarios in order to bring about different insights into the possible transition pathways for renewable energy uptake in Oman to 2040. The first scenario, business-as-usual, was used as a reference scenario in which no renewables are considered. The second scenario, the moderate scenario, considers a 30% share of renewable energy in electricity generation by 2040. The third and fourth scenarios consider 50% and 70% shares of renewable energy in electricity generation by 2040, respectively.

The scenarios were developed through two steps: causal loop diagrams, followed by stock-and-flow sub-models. Causal loop diagrams revealed the interlinkage between renewable energy technology deployment and environmental, economic and social domains which represented the carbon emissions, energy security and job creation policy indicators, respectively. In order to enable the simulation of causal loop diagrams, three stock-and-flow sub-models have been developed – air emissions, natural gas saving and job creation – against which the performance of the scenarios was measured.

Based on the simulation results for long-term energy scenarios, the following conclusions can be drawn:

- It was determined that the dominant factors affecting the promotion of renewable energy in Oman are the economic indicators of gas savings, an environmental indicator of total CO_2 emissions and a social indicator of job creation. These factors influence the government's desire to invest in renewable electricity generation.
- The economic indicator analysis ascertained that Oman's reliance on fossil fuel-based electricity may bring future challenges in the event of substantial increases in electricity demand, the limited availability of domestic fossil fuel resources and substantial energy import price increases. Instead, renewable energy deployment can enhance the economy, either through the security of energy supply by saving fossil fuel resources for future use or through freeing natural gas resources used in power generation for export sales or other uses like industrialisation.
- The simulation analysis of environmental indicators suggests that policymakers should consider future mitigation of adverse environmental consequences that might emerge from continuous use of fossil fuel resources in power generation, as illustrated in the CO_2 emission scenarios.

- The simulation analysis of social indicators suggests that there is a need to consider the deployment of alternative energy sources like renewables due to the potential number of green jobs that can be created throughout the renewable energy life cycle.

Acknowledgements Special thanks to all people who spared the time to discuss the work on the model. Thanks are due to my colleagues at Imperial College London: Dr. Judith A. Cherni, Dr. Marcello Contestabile, Dr. Adam Hawkes and two other anonymous colleagues.

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Chapter 3
Energy and Emission Modelling for Climate Change Mitigation from Road Transportation in the Middle East: A Case Study from Lebanon

Marc Haddad and Charbel Mansour

Abstract Road transportation worldwide is undergoing a rapid transition to more sustainable alternative fuel vehicle technologies as an effective means of dealing with climate change and related challenges. This chapter provides an assessment framework and a case study of the potential savings in energy use and CO_2 emissions from alternative fuel vehicle technologies compared to existing conventional vehicles, including the dynamic modelling of different mitigation strategies at the fleet level. The case study is done in an urban area of Lebanon's Greater Beirut Area which has one of the most unsustainable road transport systems in the region. The framework highlights the need to account for real-world driving and weather conditions since poor roads, congested traffic, and extreme weather conditions common in the developing countries of the Middle East can reduce the benefits of these vehicles. Results show that introducing micro-hybrid vehicles to make up 35% of the fleet in 2040 reduces energy use and emissions by 19% compared to the business-as-usual scenario, thereby stabilizing growth trends in 2040 as compared to 2010 figures. The addition of 10% hybrid electric vehicles by 2040 to the first strategy leads to 11% additional savings compared to 2010. This shows the need to incentivize cleaner fuel vehicles and to systematically explore additional strategies for reducing energy consumption and emissions in road transportation.

Keywords Real driving conditions · Alternative fuel vehicles · Energy consumption · GHG emissions · Cost analysis · Developing countries · Road passenger transport · System dynamics · Mitigation strategies

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H. Qudrat-Ullah, A. A. Kayal (eds.), *Climate Change and Energy Dynamics in the Middle East*, Understanding Complex Systems,
https://doi.org/10.1007/978-3-030-11202-8_3

1 Introduction

The adverse environmental, health, and economic impacts of transportation activity worldwide are on a continuously rising path, with the road transportation sector being one of the highest contributors of greenhouse gas (GHG) and air pollutant emissions globally. This is caused in part by the growing number of cars on the road, the longer commute distances, and the corresponding increase in fossil fuel consumption in road transport. These problems are especially acute in the most rapidly growing economies of the developing world, including a number of countries of the Middle East where nonrenewable petroleum resources account for almost 95% of the energy used in transport (Kahn Ribeiro et al. 2007). In fact, the consumption of oil in transport in the Middle East region has almost doubled from 67.1 million tons in the year 2000 to 124.6 million in 2014 (OECD/IEA 2016), with annual growth forecasts of 1.9% on average until 2040 (U.S. EIA 2016), almost double the rate of increase for Europe. This is due to a significant increase in transport activity in the region at the rate of about 2% per year, driven by higher than world average growth in population (67%) and real GDP (22%) until 2035 (WEC 2011). This comes amidst the almost exclusive reliance on passenger cars as the principal mode of mobility across the region. As a result, transport was responsible for over 20% of energy-related GHG emissions in the majority of Middle Eastern countries, with over 15% coming from road vehicles (UITP 2016).

It is in this context that investigating climate change mitigation strategies for the transport sector in this part of the world becomes important. Therefore, this chapter provides a comprehensive framework for performing a systematic assessment to identify feasible mitigation strategies in the context of developing countries of the Middle East where data is scarce and studies are lacking. A country of great interest in this region is Lebanon which stands as having one of the most unsustainable road transportation systems in the region (Haddad et al. 2015) and which will be used as a case study to illustrate the impacts of introducing alternative fuel vehicles as mitigation options in the Middle East region. The case study will be based on real driving conditions in Lebanon's Greater Beirut Area (GBA) and can serve to inform researchers and decision-makers in the region of the real-world potential of these vehicles for reducing energy use and GHG emissions from the road transport sector.

The proposed framework follows a bottom-up approach, starting with a preliminary understanding of existing conditions in order to develop a baseline scenario for energy consumption in transport. This is followed by identifying mitigation technologies that are feasible in the local context and modelling their energy savings and emission reduction potential in real-world conditions. Finally, system dynamics modelling at the fleet level is used to assess the long-term impact of deploying different mitigation technologies over future planning horizons while accounting for changes in socioeconomic conditions and transport-related policy measures.

The chapter is structured as follows: Sect. 2 provides a detailed description of the current state of road passenger transport in the GBA, which is essential for understanding real driving conditions in this context. Section 3 presents the methodological framework used in the case study. Sections 4, 5, 6, and 7 illustrate the use of the framework for the case of the GBA, including an overview of the modelling tools used, the selected mitigation strategies, and the local data and assumptions considered in the modelling, as well as the modelling results in terms of future trends for vehicle stock, vehicle-kilometers travelled, fuel use, and CO_2 emissions. Concluding remarks are given in Sect. 8.

2 Overview of the Current State of the Transport Sector in the Greater Beirut Area

The road transport system in Lebanon, a developing country on the eastern Mediterranean, is one of the most unsustainable in the Middle East region. This is due to an underdeveloped roadway infrastructure, an almost exclusive reliance on fossil fuels, and the absence of an effective mass transit system, leading to heavy congestion and high levels of air pollution and GHG emissions (Haddad et al. 2015). This is especially true in the Greater Beirut Area (GBA), the country's capital and major economic hub where more than 40% of the Lebanese population resides, making it a suitable context for assessing the environmental impacts from energy consumption in urban transportation in the Middle East.

2.1 Characteristics of the Road Transport System in the GBA

The road transport sector in Lebanon has seen a large and rapid increase in demand for mobility in recent years, and the upward trend is projected to continue for decades to come (MOE/UNDP/GEF 2016). Over the past two decades, Lebanon's passenger vehicle fleet has been growing rapidly from 450,000 vehicles in 1994 to 1,490,000 in 2015. In the GBA, privately owned passenger cars constitute over 90% of the fleet, with an equivalent of around 434 passenger vehicles per 1000 people, more than triple the Middle East regional average of 134.8 (USDOE 2014). This trend is to increase over the next decade at an annual rate of 1.5%, especially in the absence of an effective public transportation system or any alternative mass transit modes such as marine ferry or rail service. In fact, the public transport system in Lebanon consists mostly of minivans and taxis operating without any proper scheduling or coordination, and lacking basic infrastructure such as stations and dedicated stops, leading to poor network coverage and low utilization.

The age distribution of the passenger vehicle fleet in Lebanon reflects its old nature with 71% of vehicles older than 10 years. The fleet is dominated by gasoline internal combustion engine vehicles (ICEV), with over 60% of the cars having engine displacements exceeding 2.0 liters, while only 8% have engines less than 1.4 liters (MOE/URC/GEF 2012). This translates to very high energy demand in road transport, as described in the next subsection.

Traffic conditions in the GBA are characterized by a high rate of congestion for the majority of the day, way beyond typical morning and evening peak periods (Omran et al. 2015). The expected demographic growth will double the total number of motorized trips, estimated in 2013 at 1.5 million daily passenger trips in GBA, with vehicle occupancy of approximately 1.7 passengers per vehicle, very low compared to world standards (CDR 2017).

Poor roadway conditions severely restrict traffic flow speeds in GBA, with a low average speed of around 18 km/h., decreasing to less than 10 km/h in peak traffic conditions. The efficiency of conventional vehicles at these low speeds drops by 10% (Mansour et al. 2011). The inadequate state of the road network in the GBA is compounded by a chronic failure in traffic law enforcement across the country. As a result, driving patterns in and around the GBA are highly chaotic, and driver behavior is correspondingly aggressive.

In summary, the increase in the number of vehicles on the road, the inadequate roadway infrastructure, and the lack of proper enforcement of traffic laws all contribute to excessively congested traffic, aggressive driving behaviors, and chaotic driving conditions in the GBA. The resulting low speeds, high accelerations and decelerations, trip times, and distances all impact fuel consumption and emissions of passenger vehicles in GBA conditions.

2.2 Energy Consumption and Emissions in Road Transportation in the GBA

As a result of the growing number of passenger vehicles and the dominance of old model gasoline cars with large engine displacements, the energy intensity of the road transport sector in Lebanon is higher than the world average and 1.6 times the Middle East average, estimated at 3.08 MJ/pass.km (or the equivalent of 15.06 GJ/capita) (Haddad et al. 2015). In fact, the road transport sector in Lebanon has seen a substantial increase in automotive gasoline consumption of approximately 25% since 2006, accounting for 40% of total national oil consumption in 2012 (MOE/UNDP/GEF 2015).

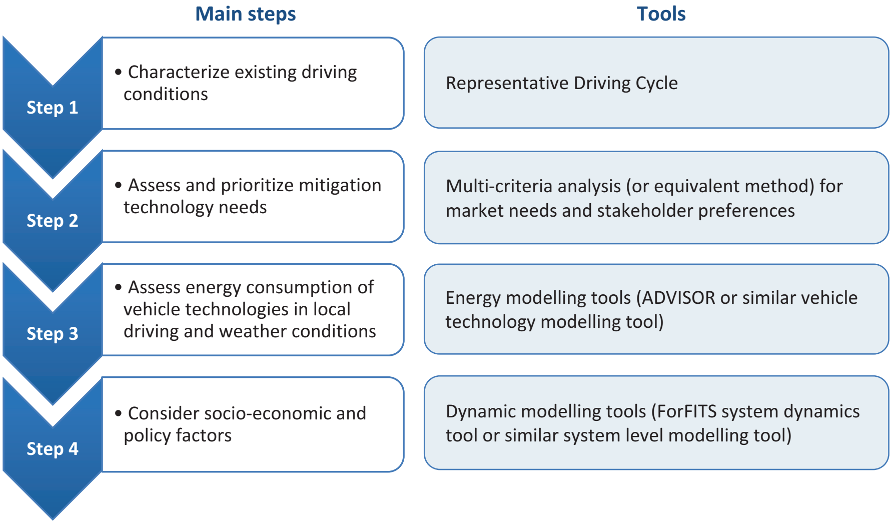
This makes road transportation in Lebanon the second biggest emitter of national GHG emissions responsible for climate change, accounting for over 23% of total annual emissions in 2012 (MOE/UNDP/GEF 2016). Passenger cars contribute the largest share of these emissions, nearly 76% of total road CO_2 emissions in 2010. Overall, GHG emissions from Lebanon's transport sector have been on a continuously rising trend, by an average annual increase rate of 8% for CO_2, 6% for CH4, and 15% for N2O (CDR 2017).

Besides GHG emissions, the transport sector is the main source of air pollution in the country (MOE/UNDP/ECODIT 2011, Chap. 4), contributing 99% of the total CO emissions, 62% of NOx, 4.8% of SOx, and 63% of NMVOCs (CDR 2017). This is because vehicle performance drops on poor roads and in traffic congestion conditions as engine combustion efficiency is reduced, resulting in higher pollutant emissions, with some pollutants serving as indirect GHGs and contributing to the global warming effect.

3 Methodological Framework

In developing countries, the extensive data required for modelling and assessment of complex socio-technical systems such as the national road passenger transport system are typically lacking. Therefore, standard approaches need to be adapted for such contexts. The following framework, illustrated in Fig. 3.1, proposes a systematic approach for assessing energy use and climate change impacts for road passenger transport systems in developing countries, from assessment of existing conditions to modelling the impact of appropriate mitigation strategies based on national goals and international commitments.

The first step of the assessment framework is to understand existing driving conditions in the area of study, such as average speeds and accelerations during peak and off-peak periods, in order to construct representative speed profiles known as driving cycles. Second step involves the identification and prioritization of feasible mitigation technologies, such as specific alternative fuel vehicle types, based on local market needs and capabilities. Third step consists of a technical assessment of the energy and environmental performance of the identified mitigation technologies in local driving and weather conditions. This is because local roadway and traffic conditions impact the fuel and environmental performance of vehicle technologies



	Main steps	Tools
Step 1	• Characterize existing driving conditions	Representative Driving Cycle
Step 2	• Assess and prioritize mitigation technology needs	Multi-criteria analysis (or equivalent method) for market needs and stakeholder preferences
Step 3	• Assess energy consumption of vehicle technologies in local driving and weather conditions	Energy modelling tools (ADVISOR or similar vehicle technology modelling tool)
Step 4	• Consider socio-economic and policy factors	Dynamic modelling tools (ForFITS system dynamics tool or similar system level modelling tool)

Fig. 3.1 Framework for assessing mitigation strategies for energy use and GHG emissions in road transport

and weather conditions require the use of heating or cooling auxiliaries which consume additional energy that should be accounted for in the modelling. Finally, the last step of the framework involves a fleet-level assessment of the performance of the considered mitigation technologies in the local context, accounting for socio-economic factors such as the cost of new technologies and their rate of adoption by local users, while considering appropriate policies that govern the entire road transport system.

The main steps of the proposed framework are detailed in Sects. 4, 5, 6, and 7 and illustrated for the case of the GBA in Lebanon. The results from the combined assessment steps provide a comprehensive picture of the real state of energy use and GHG emissions in the road passenger transport system in Lebanon and serve as a road map for adopting mitigation measures for sustainability in similar transport systems of the developing countries of the Middle East.

4 Construction of Real-World Driving Cycles

Driving patterns are represented by a driving cycle which captures the variation of speed for a vehicle over time. Original equipment manufacturers (OEMs) use regulatory driving cycles to measure fuel consumption and emissions on a chassis dynamometer test bench. This type of driving cycle lacks the ability to capture vehicle performance under real-world driving conditions which are unique for every geographical area because of the variation of the road network topography, roadway conditions, traffic congestion, and driving behavior (André 1998). This is why a representative driving cycle is necessary when realistically assessing consumption and emissions in a particular area of study. For example, most major cities of the Middle East region are known for heavily congested and poorly regulated traffic conditions, which require the construction of specific driving cycles different than those available for European or North American cities. Real world variations are usually accounted for by considering factors such as road gradient, vehicle stop duration, driver behavior, trip length, trip composition, and weather conditions, among other roadway and trip parameters (Fontaras et al. 2017). In particular, auxiliaries such as air conditioning and heating, which are not accounted for in regulatory cycles, are significant contributors to energy consumption. This is especially relevant for electrified vehicles where the additional consumption can significantly affect the electric driving range (Raykin et al. 2012). The Middle East region is known for its hot climate which requires the use of air conditioning in vehicles, but some Middle Eastern countries on the eastern Mediterranean, such as Lebanon, also experience significant temperature differences between summer and winter times, requiring the use of heating and cooling auxiliaries for several months out of the year. This means the additional fuel consumption and emissions from the use of auxiliaries can be significant in this context.

Figure 3.2 illustrates a relatively straightforward approach for developing a representative driving cycle without having to acquire data from external sources, which is useful in the context of developing countries where data is usually scarce.

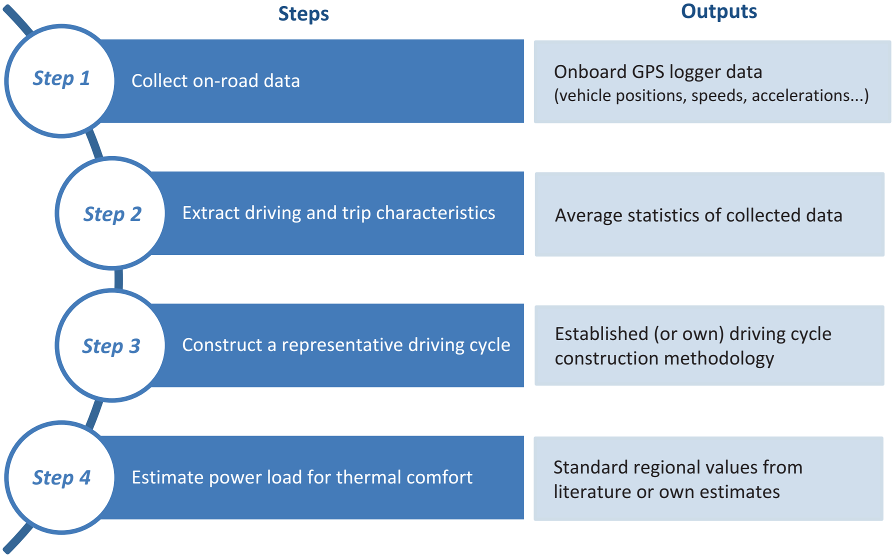


Fig. 3.2 Approach for developing a real-world driving cycle for local driving and weather conditions

The approach consists of first collecting driving and trip data which are used to construct driving cycles representing average speed profiles over time, and from which one or more representative driving cycles are extracted using statistical screening techniques known as driving cycle construction methods. This allows for the estimation of the power loads required by the particular powertrain to operate heating and cooling auxiliaries on the representative driving cycle in local weather conditions.

Accordingly, a specific driving cycle emulating the Lebanese driving conditions in GBA was built for the purpose of this case study based on on-road measurements from a travel survey using GPS data loggers. The GPS devices log the vehicle's on-road position data, recording the latitude, longitude, altitude, and velocity of the vehicle, every 1-second time interval. In this case, on-road measurements were done by several drivers using different midsize class conventional engine vehicles in an attempt to cover all GBA road types (urban, highway), traffic conditions (peak, off-peak), and trip compositions (e.g., congested urban driving followed by free-flow highway driving). Travel and vehicle data were collected over a period of 4 months, covering a total distance of 10,834 km from 1501 trips in the GBA at different times of the day on working days. Figure 3.3 illustrates the combination of some of the typical routes recorded in GBA, representing the most frequented main roads serving key entry points into the central business district.

Summary driving characteristics extracted from the travel survey are listed in Table 3.1, which represent average values of the collected data for average vehicle speed (V_{avg}); average running speed (without stops) (VR_{avg}); average acceleration

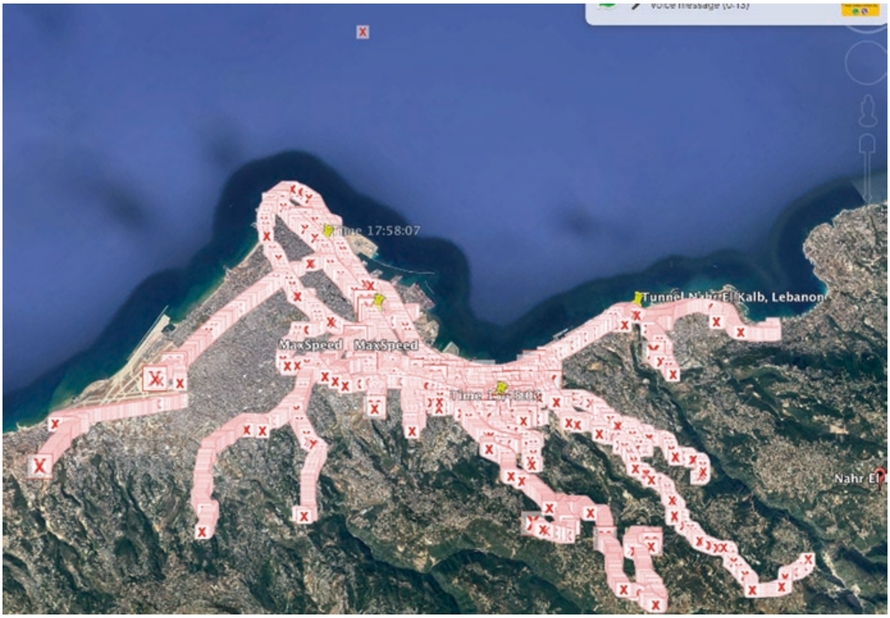


Fig. 3.3 Typical routes from the total sample of surveyed routes in GBA

Table 3.1 Driving characteristics for the GBA

V_{avg} (km/h)	VR_{avg} (km/h)	A_{avg} (m/s^2)	D_{avg} (m/s^2)	%I	%C	%A	%D	Stops/km	PKE, (m/s^2)
19.07	28.35	1.20	−1.21	31.52	16.17	26.19	26.12	12.19	0.46

(A_{avg}) and deceleration (D_{avg}); time spent in acceleration (%A), in deceleration (%D), at cruising speed (%C), and at idle (%I); number of stops per kilometer of travel (stops/km); and positive kinetic energy (PKE). These are the parameters that are typically needed for the development of representative driving cycles.

The data in Table 3.1 shows relatively low average speeds with frequent stops and high acceleration and deceleration rates, which reflects the heavy traffic congestion conditions and aggressive driver behaviors in GBA. In these conditions, the energy consumption of conventional vehicles increases significantly, especially when using the air conditioning system.

Using the above driving characteristics, driving cycles are developed for the GBA by using any of the available construction methods in the literature (Kamble et al. 2009; Kent et al. 1978; Kruse and Huls 1973; Schifter et al. 2005; Shi et al. 2011; Tong and Hung 2010; Watson et al. 1982) or by developing a new method that can generate a representative speed profile that closely emulates the collected data.

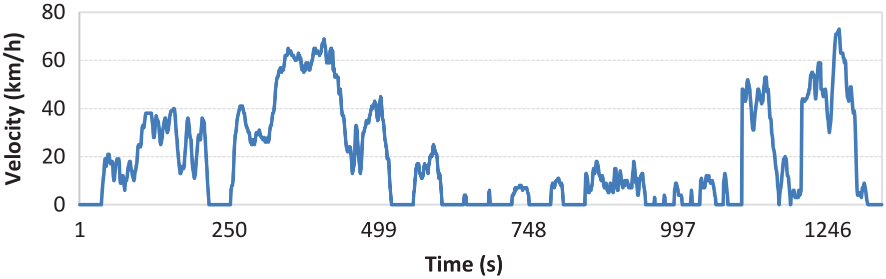


Fig. 3.4 Representative driving cycle in the GBA

The methods differ by the types of statistics considered and the screening approach chosen to compare them against the real driving data. In this case study, the authors use the method by Tamsanya et al. (2009) to generate a representative driving cycle for the GBA, shown in Fig. 3.4.

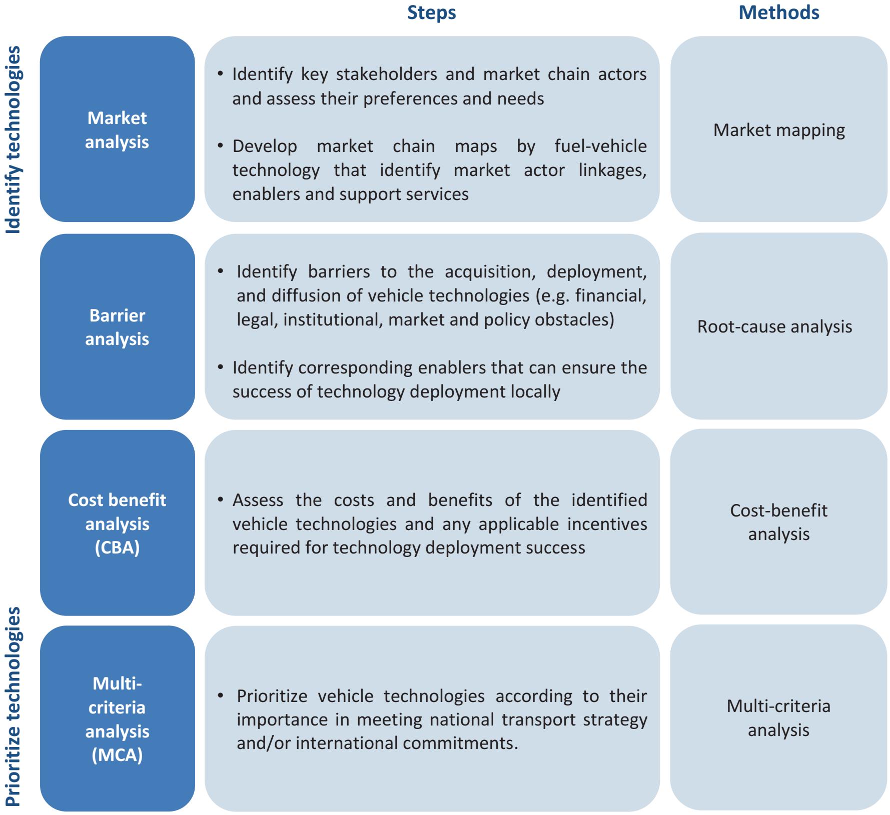
Note that it is also useful to generate representative driving cycles for peak and off-peak traffic conditions since vehicle performance and energy consumption are much higher in peak conditions, especially in GBA where the peak period extends over several hours of the day. A detailed description of driving cycle development for the GBA is given in Mansour et al. (2018b).

5 Technology Needs Assessment for Road Transport

A technology needs assessment is needed to identify and prioritize feasible new vehicle technologies that can effectively mitigate energy use, especially fossil fuel consumption, and GHG emissions in road transport. In the case of Middle Eastern countries, this assessment is critical since old vehicle technologies are dominant and the vast majority of alternative fuel vehicle technologies have yet to be introduced. Such an assessment should typically consider meeting the goals of a national transportation strategy, or the country's international commitments, such as Lebanon's Intended Nationally Determined Contribution (INDC) commitments under the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) (MOE 2015), as considered in this assessment.

The main approach for conducting a technology needs assessment is shown in Fig. 3.5:

An illustration of the use of the above approach for the present case study is presented in the following subsections. For a detailed discussion of this approach, see (MOE/URC/GEF 2012).



		Steps	Methods
Identify technologies	Market analysis	• Identify key stakeholders and market chain actors and assess their preferences and needs • Develop market chain maps by fuel-vehicle technology that identify market actor linkages, enablers and support services	Market mapping
	Barrier analysis	• Identify barriers to the acquisition, deployment, and diffusion of vehicle technologies (e.g. financial, legal, institutional, market and policy obstacles) • Identify corresponding enablers that can ensure the success of technology deployment locally	Root-cause analysis
	Cost benefit analysis (CBA)	• Assess the costs and benefits of the identified vehicle technologies and any applicable incentives required for technology deployment success	Cost-benefit analysis
Prioritize technologies	Multi-criteria analysis (MCA)	• Prioritize vehicle technologies according to their importance in meeting national transport strategy and/or international commitments.	Multi-criteria analysis

Fig. 3.5 Approach for identifying and prioritizing feasible vehicle technologies for the local context

5.1 Market Analysis

The first step in the identification of feasible vehicle technologies for the local context is carrying out a market chain analysis to accomplish two main objectives: first, to identify the key stakeholders, including government authorities and car market actors responsible for vehicle acquisition, deployment, and diffusion processes in the local market; and, second, to assess the existing market linkages between the various actors, the policy environment, and support services that can enable the transition to cleaner fuel vehicle technologies, taking into account the local user's preferences and purchasing power.

The market chain analysis in this case involved a brainstorming exercise with the key stakeholders, assisted by transport experts, to assess all applicable fuel-efficient and alternative fuel vehicle technologies, such as micro-hybrid electric vehicles (mHEV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), and battery electric vehicles (BEV). The outcome of the market analysis is in the form of market maps by fuel vehicle technology, as shown in Fig. 3.6 for the case of HEV technology in Lebanon.

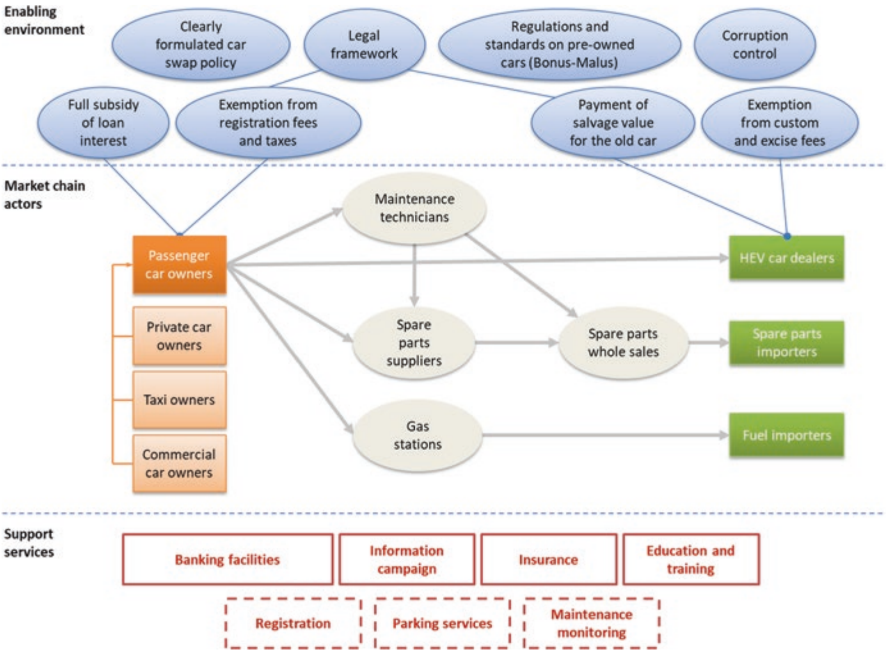


Fig. 3.6 Market map for HEV deployment in Lebanon

As can be seen in Fig. 3.6, the market chain is illustrated from the perspective of the car users (shown on the left-hand side of the figure) and their interactions with maintenance and spare part providers (shown in the center) and car dealers (shown on the right-hand side). Also shown is the influence of policies and regulations (the enabling environment at the top) and a listing of enabling mechanisms (the support services at the bottom) that must be considered for their potential to enable the creation of a market for new vehicles. The market chain analysis for HEV determined that it is essential to incentivize the car users, due to generally low environmental awareness in the country, through such mechanisms as loan subsidies, as well as incentivizing car dealers through the reduction of customs and excise taxes in order to improve the sales competitiveness of these vehicles in the market.

Once all market chain maps for all applicable fuel vehicle technologies are developed, a barrier analysis exercise is conducted to identify potential barriers and the corresponding enablers for the deployment of each technology, as discussed in the following subsection.

5.2 Barrier Analysis

Barrier analysis is a group exercise typically conducted in two steps: first, identifying and classifying existing and potential barriers hindering the deployment of the identified vehicle technologies, in consultation with local stakeholders. This includes the classification of the identified barriers under broad but comprehensive categories including economic, financial, market, legal, policy, regulatory, and social barriers, among others. The second step is conducting a root cause analysis to determine the proper enabling measures to overcome the identified barriers, including validation of the identified enablers in meetings with local stakeholders and experts.

An example of the use of the barrier analysis methodology is shown in the following example list of identified barriers facing HEV deployment and the primary root causes behind them for the case of Lebanon:

- The starter problem identified is the current absence of a market for hybrid vehicles due to several identified socio-economic barriers.
- The main barriers are:
  - The low demand for hybrid vehicles due to the high purchase cost of these cars and the low environmental awareness of users
  - The lack of consumer or market incentives and the wrong perception of consumers regarding hybrid cars' performance
  - The high demand for pre-owned inefficient gasoline vehicles due to the low cost of these cars and the wide availability of bank loan facilities
  - The inappropriately allocated road usage fees
- The primary root causes behind the identified barriers are:
  - The currently inadequate transport policies and the lack of national strategy for transport demand management
  - This in turn is due to having a government clash of interests and therefore limited willingness to invest

Based on the analysis of existing barriers facing HEV deployment in Lebanon, several financial and nonfinancial enablers are identified. An example list of financial enablers includes:

- Government incentives to reduce vehicle purchase and ownership costs
  - Market incentives such as exemption from customs and excise fees on HEV vehicles and spare parts
  - Consumer incentives such as exemption from registration fees, road usage fees, reduction of loan interest rates, and extension of loan period
  - Technician incentives such as bank loan facilities and customs fees exemption on maintenance and repair equipment for domestic technicians

A detailed barrier analysis for the case of Lebanon is provided in (MOE/URC/GEF 2012, Sect. 5.5)

5.3 Cost Benefit Analysis

The objective of a cost-benefit analysis (CBA) as part of the technology needs assessment is to identify the cost value of the identified vehicle technologies and their potential contribution to energy use and GHG reductions, where lower-cost,

Table 3.2 Transport costs considered in the assessment for the case of Lebanon

Cost component	Description
Ownership costs (Fixed: USD)	Vehicle purchase cost estimated from local market survey and from international prices for vehicles not yet available locally Vehicle salvage value at 20% for the first year and 12% for the following years over a vehicle service life of 10 years Value-added tax at 10% of the vehicle purchase cost Customs fees at 5% of the vehicle purchase cost Excise fees at 15% on the first 13,333 USD of the vehicle purchase cost, plus 45% of the vehicle's value above the initial value Car registration fees 4% of the vehicle purchase cost
Infrastructure costs (Fixed: USD)	Charging station cost estimated at 1000 USD for a slow charger
Annual operating costs (Variable: USD/km)	Fuel cost at a fuel price of 1.0 USD/liter for gasoline and 0.13 USD/kWh for electricity for an estimated annual mileage of 15,000 km Insurance fees of 14.5% of the vehicle purchase cost over the first 5 years of ownership, plus an average of 150 USD/year for the remaining 5 years of vehicle service life Road usage fees estimated at 159 USD/year for the midsize 11–20 horsepower vehicle category
Maintenance and repair costs (Variable: USD/km)	Maintenance and repair costs estimated at 0.033 USD/km for gasoline ICEV, 0.0317 USD/km for HEV, 0.0298 USD/km for PHEV, and 0.0276 USD/km for EV Battery cost for a single replacement over the 10-year service life of the vehicle estimated from 2015 industry data at 450 USD/kWh every 8 years or 240,000 km, with one battery replacement considered

more efficient and cleaner technologies are favored over higher-cost and less beneficial technologies.

A detailed CBA for the case of Lebanon is provided in Mansour and Haddad (2017), with the main steps and results discussed in this section.

Fixed and variable vehicle costs are first estimated for the local context, with values for the case of Lebanon presented in Table 3.2. Note that cost externalities such as accident and travel time costs are not considered in the analysis since they are assumed to be equivalent among the different vehicle technologies.

The total cost per vehicle-kilometer (veh.km) for each vehicle technology is computed by using Eqs. 3.1 and 3.2.

$$\text{Total Ownership Cost} = \frac{\sum \text{all ownership cost components} - \text{salvage value}}{\text{Annual travel distrance} \times \text{Vehicle service life}} \tag{3.1}$$

$$\begin{aligned}\text{Total Operating Cost} = {} & \left(\text{Average gasoline consumption} \times \text{Cost of fuel}\right) \\ & + \left(\text{Average electricity consumption} \times \text{Electricity tariff}\right) \\ & + \sum \text{remaining operating cost components}\end{aligned} \tag{3.2}$$

Example costs per veh.km for conventional and electrified vehicles in Lebanon are shown in Table 3.3. Also listed are government subsidy figures for the clean vehicle technologies if exempted from customs and excise fees. Note that the exemption

Table 3.3 Estimated vehicle costs, government subsidy, and potential energy and CO_2 benefits for Lebanon

Vehicle Technology	Ownership cost (USD/km)	Operating cost (USD/km)	Subsidy (USD/km)	Total cost (USD/km)	Potential energy savings (%)	Potential CO_2 benefits
ICEV	0.338	0.142	–	0.480	–	–
HEV	0.449	0.102	0.151	0.400	15–25	Medium
PHEV	0.580	0.039	0.202	0.417	45–65	High
BEV	0.543	0.029	0.187	0.385	100[a]	Very high[a]

[a] Energy and emission savings for BEV are estimated on a tank-to-wheel basis only

option was determined to be feasible by the concerned stakeholders during the barrier analysis exercise. The total cost is therefore the sum of the ownership and operating costs minus the government subsidy and is borne by the user. Finally, potential energy savings and GHG reduction benefits for the new vehicle technologies are assessed qualitatively based on industry data and listed in the right-hand column of Table 3.3, to be included in the CBA as nonfinancial benefits, as in a cost-effectiveness analysis.

From the results of Table 3.3, it is apparent that HEV has good mitigation potential for the context of Lebanon and similar developing countries, since the vehicle ownership and operating costs (0.4 USD/pass.km) are 17% lower than for a comparable ICEV (due to lower vehicle operating costs of the more efficient hybrid powertrain) while providing up to 25% savings in energy use and moderate CO_2 reduction benefits compared to ICEV.

5.4 *Multi-Criteria Analysis*

The technology prioritization for the identified vehicle technologies is done through a multi-criteria analysis (MCA) or equivalent decision analysis exercise, where transport experts and stakeholders assess and prioritize the technologies using weighted criteria according to their importance in meeting the national transport mitigation goals. The criteria are set according to expert and stakeholder judgment, relying on two main objectives: minimizing the GHG and pollutant emissions for the transport sector and maximizing the environmental, social, and economic development benefits. Each of the main criteria is attributed specific sub-criteria and assigned a weight based on its significance in meeting the main objectives.

The main steps and results of the MCA exercise for Lebanon are summarized below. The prioritization of new vehicle technologies for the case of Lebanon was based on the following selection criteria:

- GHG reduction potential
- Availability of technologies
- Potential in attracting investment

- Potential of market penetration
- Cost-effectiveness of mitigation measures

Table 3.4 presents the criteria and weights used in the prioritization process for this case study. The rating values attributed to each criterion range from 0 (no relevance/ no impact) to 5 (high relevance/ high impact).

For each identified technology, factsheets were elaborated and disseminated to a wide spectrum of researchers and technicians from national and international institutions for review and feedback. These factsheets contain detailed information on technology characteristics, institutional and organizational requirements, adequacy of use, capital and operational costs, advantages, as well as barriers and challenges. This was followed by a consultation meeting with a pool of experts and key stakeholders, ensuring that the opinions and judgments of concerned institutions, decision-makers, experts, and the public were taken into consideration. The modality of the MCA exercise was also presented in addition to the selection criteria, the ranking method, as well as the respective weights for each criterion. During the working group session, the proposed weights were validated, and the ranking was done in an open discussion exercise among the experts, with scores being attributed based on general consensus.

Table 3.5 presents the final scores that were attributed to proposed technologies of the transport sector. The resulting scores were derived based on the needs and challenges raised by the experts and stakeholders during the working group session and the individual meetings, mainly that:

- In 2016, Lebanon signed the Paris Agreement of the UNFCCC and committed to INDC mitigation measures for reducing national GHG emissions starting in 2020, by a minimum of 15% in 2030 compared to 2010 or by 30% if international financial support is provided (MOE 2015). As a result, it was decided to use a higher weight factor for the criterion of reducing GHG emissions.
- Lebanon enacted a strategy for the transport sector to meet INDC commitments by renewing the vehicle fleet with newer model fuel-efficient vehicles and alternative fuel vehicles. As a result, it was decided to use higher weight factors for the criteria of feasibility potential and applicability timeframe.
- Lebanon needs short timeframe solutions to improve its air quality as air pollution has daily direct impacts on people's health. As a result, it was decided to use a higher weight factor for the criteria of the near-term feasibility and improving air quality.
- Though electric mobility has proven itself as the future of transport, thanks to superior energy and emission performance, the deployment of electrified vehicles that need to be plugged into the grid is difficult to achieve on the short and medium terms, as Lebanon is in deficit in terms of electricity supply and clean electricity resource mix and due to the high costs of the vehicle and new charging infrastructure. As a result, it was decided to use a higher weight factor for the criteria of affordable technology and low infrastructure investment.
- While OEM gas vehicles are safe to use, namely, OEM compressed natural gas vehicles (CNGV) and liquid petroleum gas vehicles (LPGV), uncertified and

Table 3.4 Criteria and weights for the prioritization process

Criteria	Weights	Comments
Consistency with national policy and local context		
Relevant to existing national plans and needs	4	The technology supports national transportation needs (e.g., reducing traffic and pollutant emissions in GBA) and international commitments for reducing GHG emissions (e.g., meeting Lebanon's INDC commitments) and is aligned with national energy supply security plans
High feasibility potential	4	The technology does not have barriers with high risks hindering its deployment
Technology effectiveness		
Efficient technology	5	The technology ensures a low consumption of fossil fuel per passenger-kilometer
Safe technology	2	The technology ensures safety to passengers as well as to maintenance technicians. The risk of accidents must be considered in the safety assessment of the technology
Reliable technology	2	The technology is reliable and mature and can be implemented without high risks
Technology cost-effectiveness		
Low infrastructure investment costs	4	The technology does not require high investment costs for the infrastructure indispensable for its operation, such as recharging stations for plug-in and electric vehicles, pipelines and compressed gas stations for natural gas vehicles, and land use for bus corridors
Operating and maintenance cost savings	2	The technology presents significant annual operating and maintenance cost savings comparing to conventional gasoline-powered vehicles
Affordable technology	3	The purchase cost of the technology is affordable for passengers, if accompanied with taxes and legislative reforms
Environmental effectiveness		
GHG emission reduction	5	The technology reduces substantially the GHG emissions during vehicle operation. Note that well-to-wheel emission reductions must be considered
Improvement of air quality	5	The technology reduces significantly the pollutant emissions during vehicle operation. Note that well-to-wheel emission reductions must be considered
Reduce hazard waste	2	The technology does not involve hazardous waste
Social benefits		
Socio-economic benefits	1	The technology presents good impact for socio-economic development and creates job opportunities
Short timeframe for applicability	3	The technology does not require too much time for bringing it to a commercially operable status

Table 3.5 Technology prioritization results

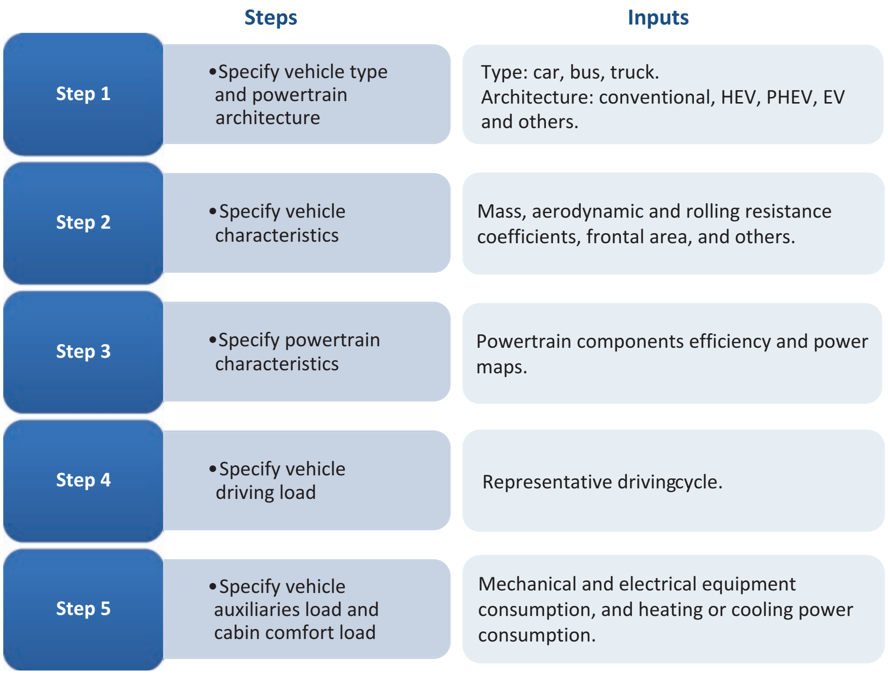
Priority	Criteria	mHEV	HEV	PHEV	BEV	CNGV	LPGV
Consistency with national plans	Relevant to national strategy and international commitments	3.7	3.7	3.2	3.2	3.7	2.5
	High feasibility potential	4.0	4.0	1.7	1.7	3.0	4.1
Technology effectiveness	Efficient technology	2.7	3.3	4.3	4.5	2.7	3.0
	Safe technology	4.0	3.0	3.0	3.0	3.1	2.1
	Reliable technology	4.7	4.0	3.7	3.7	4.0	3.3
Technology cost-effectiveness	Low infrastructure investment costs	4.3	4.3	1.7	1.7	3.0	3.7
	Operating cost savings	3.0	3.3	4.0	4.0	2.7	3.5
	Affordable technology	4.3	3.7	2.7	1.7	4.0	4.2
Environmental effectiveness	GHG emission reduction	3.0	3.3	4.3	4.3	3.7	1.7
	Improvement of air quality	3.0	3.7	4.0	4.7	2.2	1.3
	Reduce hazard waste	3.0	2.7	2.3	2.3	3.0	3.7
Social benefits	Socio-economic benefits	2.3	2.7	3.5	3.5	3.3	3.1
	Feasibility in the near-term	4.0	4.0	2.0	2.0	3.0	4.4
	Total/100	**69.3**	**71.3**	**63.9**	**64.8**	**60.7**	**59.5**

self-retrofitted gas vehicles present significant safety concerns. Therefore, in a developing country such as Lebanon where appropriate safety regulations are lacking, using natural gas for electricity generation to power electrified vehicles is a preferred alternative to the mass deployment of gas vehicles.

The MCA exercise enabled the selection of priority technologies for the transport sector in Lebanon. As a result, the top-ranked technologies for the case of Lebanon are, by order of preference, (1) HEV, (2) mHEV, (3) PHEV, (4) BEV, (5) CNGV, and (6) LPGV. Due to their low ranking, gas vehicles (CNGV and LPGV) were no longer considered in the assessment for the case of Lebanon, especially that these vehicles require a separate and equally costly distribution and recharging infrastructure as for electric vehicles, while providing fewer savings in energy consumption and emissions. A detailed energy, emissions, and cost assessment of gas compared to electrified vehicles in Lebanon can be found in Mansour and Haddad (2017).

6 Energy Modelling for the Prioritized Vehicle Technologies

In order to assess the environmental impacts of the prioritized vehicle technologies, a modelling of energy consumption in real-world driving conditions is conducted. This consists of evaluating the energy consumed for operating the vehicle powertrain and auxiliaries, such as cabin cooling and heating equipment, under specific



	Steps	Inputs
Step 1	• Specify vehicle type and powertrain architecture	Type: car, bus, truck. Architecture: conventional, HEV, PHEV, EV and others.
Step 2	• Specify vehicle characteristics	Mass, aerodynamic and rolling resistance coefficients, frontal area, and others.
Step 3	• Specify powertrain characteristics	Powertrain components efficiency and power maps.
Step 4	• Specify vehicle driving load	Representative drivingcycle.
Step 5	• Specify vehicle auxiliaries load and cabin comfort load	Mechanical and electrical equipment consumption, and heating or cooling power consumption.

Fig. 3.7 Approach for energy modelling of vehicle technologies in real driving conditions

driving and weather conditions. The steps and the required data for conducting a comprehensive assessment of the energy and environmental performance of a particular vehicle technology are illustrated in Fig. 3.7.

Using the above approach, the prioritized vehicle types and architectures for Lebanon were modelled in the software tool ADVISOR (advanced vehicle simulator) developed by Argonne National Laboratory (Markel et al. 2002), and their energy consumption and GHG emissions were simulated on the representative driving cycle developed in Sect. 4 under GBA driving conditions. The modelling steps and simulation results for this case study are summarized in the following subsections for the down-selected HEV, mHEV, PHEV, and BEV midsize passenger cars. For complete modelling details, refer to Mansour et al. (2018b).

6.1 *Vehicle and Powertrain Characteristics of the Modelled Technologies*

A reference midsize conventional gasoline ICEV is first chosen, and its energy consumption and GHG emissions are simulated in ADVISOR to serve as the baseline in comparison with other technologies. The other vehicles are then modelled using the same glider mass (the mass of the vehicle without the powertrain components)

Table 3.6 Vehicle configuration characteristics

Vehicle type	Curb Mass (kg)	Battery Capacity (kWh)	Total Power (kW)
ICEV	1315	–	81
mHEV	1315	–	81
HEV	1325	1.3	81
PHEV	1395	5.5	100
BEV	1305	30	80

as the reference ICEV but accounting for additional weight from the battery pack and electric motor and any other differences in powertrain components and engine power and efficiency maps but maintaining the same driving performance. This results in different curb mass values for the different vehicles. Table 3.6 shows example vehicle and powertrain characteristics used in the modelling.

6.2 Simulated Vehicle Loads in Real Driving Conditions

The vehicle driving load and the auxiliaries load required for the vehicle to run on the specified driving cycle for the GBA are simulated in ADVISOR. The model calculates both mechanical and electrical power loads needed to operate the vehicle and the auxiliaries at each instant and deduces the resulting energy consumption in these conditions.

Specifically, the vehicle driving load is first modelled by calculating the power load required to overcome the aerodynamic, friction, and grading resistive forces in addition to inertial forces at each instant over the specified driving cycle. Vehicle driving loads required for city driving are therefore lower than those for highway driving due to the lower vehicle speed inside the city. For example, the vehicle driving load for the HEV on the GBA driving cycle varied around an average of 3000 W, reflecting the mostly congested urban driving conditions.

Second, the auxiliary systems' load is estimated, including mechanical (pumps, fans, and other mechanical equipment powered by the engine) and electrical (radio, display, lights, and other electrical equipment powered by the battery) power loads. Typical values for midsize vehicles range between 300 W and 600 W. These loads are assumed constant throughout the modelling as a representative average.

In the Middle East and other regions with extreme hot or cold temperatures, it is very important to account for cabin comfort loads for heating or cooling. The impact of these loads is particularly significant in electrified vehicles, namely, in terms of increased fuel consumption in the HEV and decreased electric range autonomy in the PHEV and BEV. In the case of the HEV, an electric heat pump system with a constant coefficient of performance that is powered by the battery was considered in the modelling. The power load of the heat pump is dependent on ambient temperature and is assumed constant throughout the modelling. Typical average summer and winter conditions for the GBA are considered, and the corresponding power

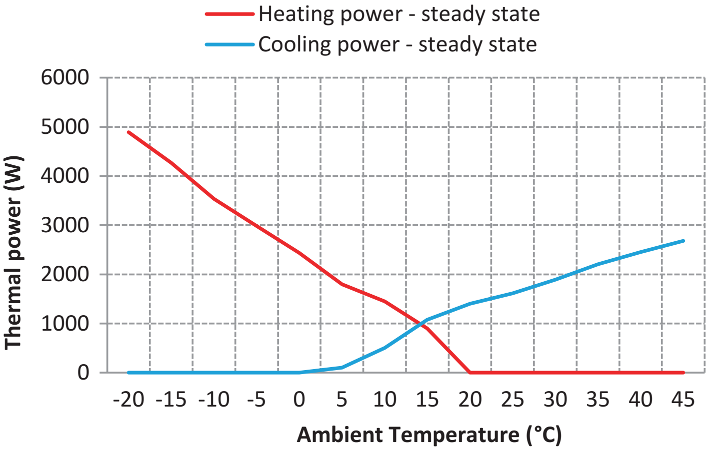


Fig. 3.8 Cabin heating or cooling power load as a function of external temperature

load for heating or cooling is obtained from Fig. 3.8 as developed in Mansour et al. (2018a) based on a dynamic cabin thermal model under steady-state operation.

For the case of Lebanon, 2000 W of cooling energy is required for the use of air conditioning in 30 °C average temperature, as a conservative estimate for spring and summer conditions over approximately 6 months out of the year in Lebanon. In winter conditions, an estimate of 1000 W for heating is required at an average temperature of 15 °C in PHEV and BEV vehicles only, as ICEV, mHEV, and HEV use the waste heat from engine coolant to heat the cabin.

Finally, to determine the actual electric consumption required from the battery for heating or cooling the cabin, the required energy estimated above is multiplied by the heat pump's coefficient of performance (COP), with typical COP values ranging between 1.2 and 1.5. Therefore, for the modelled HEV in Lebanon's weather conditions, the total additional electric consumption to power the air conditioning in summer conditions is an average of 2600 W, which is a significant load compared to the vehicle average driving load in GBA conditions.

6.3 Energy Consumption Results in GBA Driving Conditions

The engine fuel consumption FC_{avg} (*L*/100km) and battery electric energy consumption EC_{avg} (Wh/100km) of the considered alternative fuel vehicle technologies are computed in ADVISOR over the specified driving cycle for the GBA and are compared relative to the reference ICEV.

Figures 3.9 and 3.10 illustrate the maximum, minimum, and average gasoline fuel and electric consumptions, respectively, estimated for each vehicle type. This includes additional energy consumption due to the use of air conditioning. Note that PHEV consumes both fuel types since it is capable of both gasoline and electric drive modes.

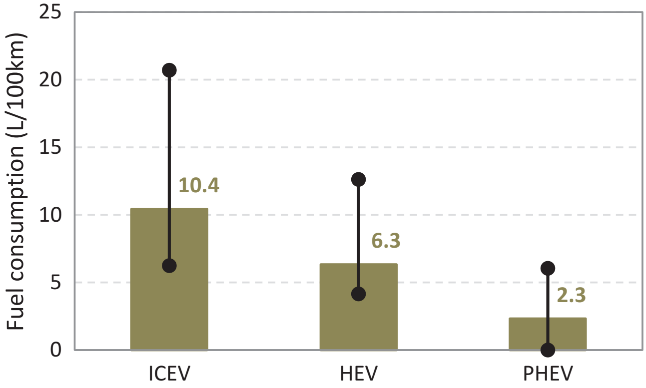


Fig. 3.9 Average, minimum, and maximum gasoline fuel consumption by vehicle type in GBA

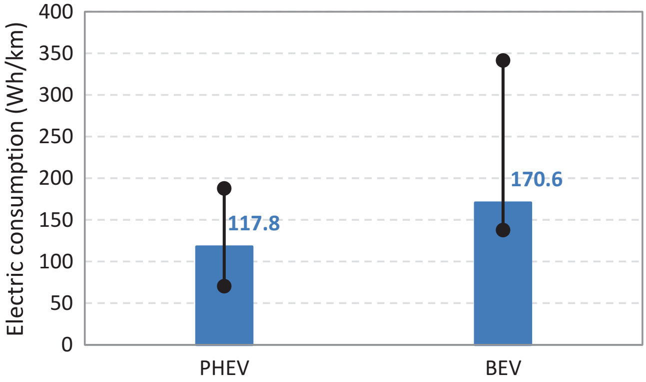


Fig. 3.10 Average, minimum, and maximum electric consumption by electrified vehicle type in GBA

As shown in the figures, the HEV and PHEV provide substantial fuel savings relative to ICEV of 39.4% and 77.9% on average, respectively, with PHEV consuming the least gasoline fuel and relying more on electric autonomy, which is especially efficient in congested city driving. Also, the more the vehicle is electrified, the less it is sensitive to variations in traffic conditions, as shown in the narrower range between minimum and maximum gasoline fuel consumption results for HEV and PHEV. Note that while BEV has high variability in their electric consumption, this however does not affect vehicle efficiency since the electric motor operates at high efficiency over a wide range of torques and speeds.

Note also that the additional consumption from the use of cooling auxiliaries compared to the baseline constitutes 16% additional gasoline consumption for the ICEV, 13.5% for the HEV, and 84.6% for the PHEV. This shows that the impact of air conditioning in warm regions such as the Middle East is significant, especially for electrified vehicles. In fact, the fuel efficiency in PHEV is drastically reduced, with additional consumption nearly equivalent to energy consumed for vehicle traction. PHEV also incurs additional electric consumption of 2.6%, and BEV incurs total additional electric consumption of 20.6%. This can have consequences on the electric driving range of these vehicles and becomes a concern in cities where charging infrastructure is poorly developed, as is the case in Middle Eastern countries.

Similar levels of additional seasonal consumption were calculated due to the use of heating auxiliaries in GBA winter weather conditions of 15C average temperature, with 6.8% increase in gasoline consumption for HEV and 53.8% for PHEV and 13.8% additional electric consumption for BEV. No additional gasoline consumption is incurred by ICEV for cabin heating since the heat used is recovered from waste engine coolant.

7 Dynamic Modelling of Mitigation Strategies at the National Fleet Level

In order to assess the energy savings and environmental mitigation potential of the prioritized passenger vehicle technologies at the level of the entire fleet in a particular country, comprehensive modelling tools are needed to capture the dynamics of the system over time. Such tools allow the consideration of socio-economic factors and government policies and their impact on the transport system, such as financial subsidies of alternative fuels, or strategies for expanding the reach of the mass transit system, among others. System dynamics modelling is a particularly useful and holistic approach for this purpose (Abbas and Bell 1994; Qudrat-Ullah 2016) as it allows the inclusion of socio-economic factors and external policies in the modelling, leading to more reliable results, with an increasing number of transport mitigation studies using this approach in recent years (Feng et al. 2013; Fong et al. 2009; Haddad et al. 2017; Liu et al. 2015).

In this study, the United Nations Development Agency's (UNDA) system dynamics model ForFITS (For Future Inland Transport Systems) designed to assess mitigation strategies at a national level is adopted. ForFITS is a comprehensive model built with the commonly used software tool "Vensim" (Ventana Systems Inc. 2013) and uses demographic and socio-economic data and assumptions, including policy inputs, as well as characteristics of the transport system, vehicles and fuels to model vehicle stock and transport activity over time. The model then converts the vehicle and transport activity dynamics into fleet-wide annual estimates of energy consumption, CO_2 emissions, transport activity by mode, and modal share characteristics over time, as shown in Fig. 3.11 (UNECE 2013). Note that the ForFITS model has been extensively validated through regional case studies in several pilot countries to ensure the accuracy of results under different socio-economic dynamics and a variety of hypotheses (UNECE 2017).

The annual estimation of energy use and GHG emissions in ForFITS is based on the ASIF decomposition framework which relies on four vehicle and fuel related components: travel *A*ctivity (passenger and/or freight), modal *S*tructure (including vehicle class and powertrain type), energy *I*ntensity (vehicle efficiency, characteristics and load factor), and *F*uel carbon content (Millard-Ball and Schipper 2011).

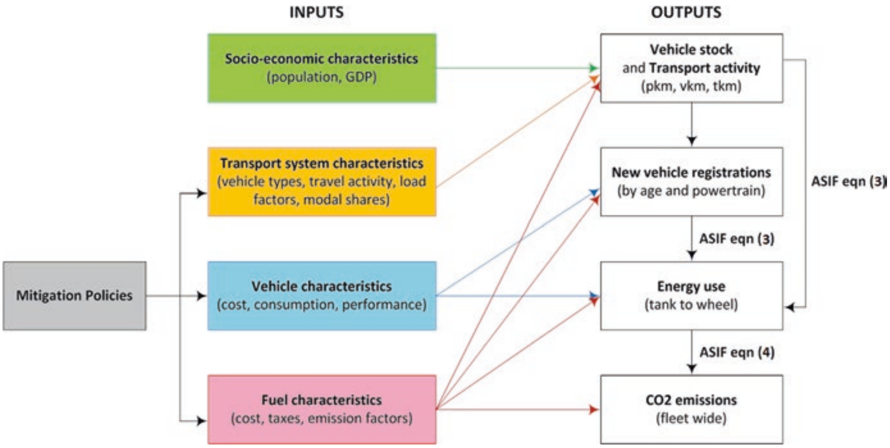


Fig. 3.11 ForFITS simplified model structure. (Adapted from (UNECE 2013))

The calculations are shown in the ASIF equations for total fuel use F (3.3) and total emissions E (3.4):

$$F = \sum_i F_i = A \sum_i \left(\frac{A_i}{A}\right)\left(\frac{F_i}{A_i}\right) = A \sum_i S_i I_i \tag{3.3}$$

$$E = \sum_i E_i = A \sum_i \left(\frac{A_i}{A}\right)\left(\frac{F_i}{A_i}\right)\left(\frac{F_{ij}}{F_i}\right)\left(\frac{E_{ij}}{F_{ij}}\right) = A \sum_i S_i.I_i.EF_{ij} \tag{3.4}$$

where *Fi* and *Ei* are the tank-to-wheel amounts of fuel used (as calculated in ADVISOR) and the corresponding emissions generated, respectively, by vehicle (*i*) with a defined set of characteristics (by service, mode, vehicle class, and powertrain); *Fij* is the fuel (*j*) used in vehicle (*i*) and *EFij* is the corresponding emission factor; *Ai* is the activity of vehicle (*i*) and *A* is the overall vehicle activity (in vehicle-kilometers, vkm); *Si* is the sectoral structure (expressed as shares of vkm by service, mode, vehicle class, and powertrain); and *Ii* is the energy intensity (the average fuel consumption per vkm by service, mode, vehicle class, and powertrain).

Like all models based on the system dynamics approach, ForFITS consists of a stock-and-flow model structure. Stocks capture the accumulation of quantities in the system, such as the emissions generated by vehicle activity in any given period, and flows capture the rates of change of these quantities over time, such as the influx of new passenger cars into the total vehicle stock every year. The model consists of an external input sheet linked to 38 views to represent the various technological, environmental, and socio-economic aspects of the transportation system, in addition to eight output views for presenting the results. Figure 3.12 illustrates part of a ForFITS view for estimating the travel demand growth for road passenger vehicles as modelled in Vensim.

The view shows auxiliary variables, linked by information feedbacks, with the underlying equations describing the relationships stored behind each variable and

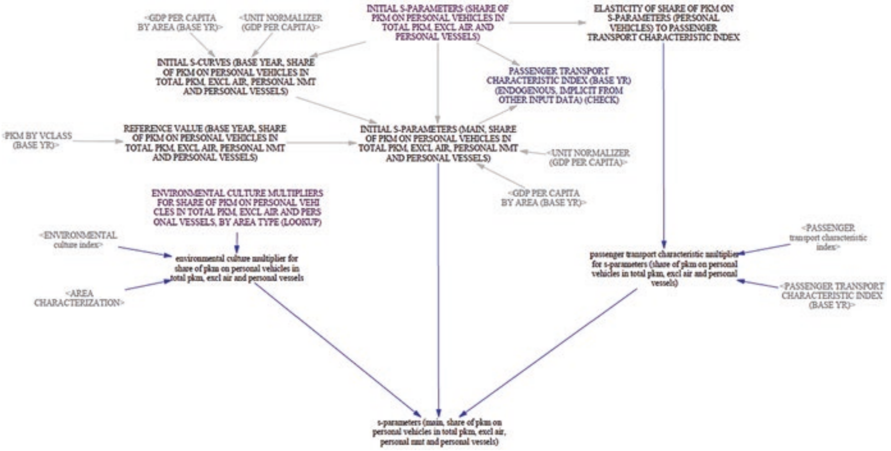


Fig. 3.12 ForFITS Vensim view for estimating road passenger travel growth

therefore not shown on the model view. In this view, the shape of growth for road passenger-kilometers over time, defined as an S-curve due to the feedback nature of that type of growth, is estimated using historical data and characteristics of economic, vehicle, and environmental aspects of the road transportation system. Thus, information characterizing the transport system in the base year (chosen as the year 2010 in this case study) is combined with the evolution of population and GDP in order to forecast annual trends in transport activity, vehicle stock, fuel consumption, and CO_2 emissions for future years.

The data required to model the baseline scenario for the Lebanese road passenger transport system, such as historical data about vehicle numbers, occupancy rates, travel distances, and fuel consumption were obtained from the concerned Lebanese government ministries and authorities, as well as from meetings with local stakeholders. Socio-economic data, such as population and GDP trends until the year 2040, were developed considering average growth rates. The main modelling assumptions for the baseline scenario are shown in Table 3.7.

The main data used to describe the detailed characteristics of the transport system in the base year are summarized in Table 3.8.

Two mitigation strategies were considered: the first strategy is to increase the share of mHEV to about a third of the total vehicle fleet in 2040, thereby replacing the larger fuel-inefficient vehicles, combined with a progressive increase in gasoline prices up to 150% of the 2010 base year levels by 2040. The second strategy includes the same assumptions as the first strategy in addition to the introduction of HEV to the market. Since hybrid technology has yet to be adopted in the Lebanese market, it is assumed that the annual share of HEV sales out of all newly registered vehicles can increase to a relatively conservative figure of 10% by 2040. This assumption was further validated with the local stakeholder community as a realistic target given the current and projected market conditions. Table 3.9 provides details on the appropriate data and modelling assumptions for the two considered mitigation strategies.

Table 3.7 Main modelling assumptions for the baseline scenario in 2010 with future projections

System	Parameter	Value	No action projection
Transport	Passenger transport system index (PTSI) *0 = total dependence on personal vehicles* *1 = full reliance on public transport*	0.1 *(calculated based on the share of distance travelled by public transport out of total passenger-kilometers in the same year)*	Maintained constant
Socio-economic	Environmental culture index (ECI) *0 = absence of environmental awareness* *1 = environmentally focused culture*	0.2 *(estimated based on stakeholder feedback about environmental awareness in Lebanon and benchmarked against published values for developed countries)*	Maintained constant
	Population *(actual 2010 value)*	4,341,000	Growth by 22% until 2040
	Gross domestic product (GDP) *(actual 2010 value in billion USD)*	60.223	Growth by a factor of 4
Vehicle	Powertrain technology share*(actual 2010 figures in %)*	11.8% for small vehicles 55% for midsize vehicles 33.2% for large vehicles	Maintained constant but with improving powertrain technology efficiencies over time
Fuel (gasoline and diesel)	CO_2 emission factors (kg CO_2/liter gasoline equivalent, lge)	Gasoline: 2.3207 Diesel: 2.4803	Maintained constant
	Fuel price including tax (USD/lge)	Gasoline: 1.093 Diesel: 0.624	Growth to 150% by 2040 *(due to declining oil resources and increasing fuel taxes over time)*

Table 3.8 Characteristics of the road transport sector in 2010

Vehicle Type	Vehicle Stock	New vehicle registrations	Annual distance travelled *(vkm)*	Vehicle load *(pass/veh)*	Vehicle fuel consumption *(lge/100 km)*
2–3 Wheelers	60,588	13,416	5000	1	3–6.5
Passenger LDV					
Small vehicles	139,503	11,258	10,000	1.18	8
Midsize vehicles	649,044	52,423	10,000	1.18	12
Large vehicles	393,682	31,798	10,000	1.18	16
Taxi	50,000	1785	25,000	1.18	15
Buses	12,388	1188	50,000	11.2	25

Table 3.9 Assumptions for modelling the mitigation strategies

Mitigation strategies	Fuel price (including tax)	Transport system and environmental indices	Passenger LDV powertrain shares in 2040	
			Conventional	Hybrid
Introduce mHEV	Growth to 150% by 2040	Transport: 0.15 in 2040 *(reflects Lebanon's INDC commitment to increase the share of travel kilometers by public transport)* Environmental: 0.7 in 2040 *(derived from interviews with local stakeholders about the rising trend of environmental awareness in Lebanon)*	35% small vehicles 55% midsize vehicles 10% large vehicles	0%
Introduce mHEV and HEV	Same as the first mitigation strategy			10% of new vehicle registrations

The baseline scenario is simulated first to estimate the reference energy use and CO_2 emissions in future years under no-action baseline conditions. The results for energy use are presented in Fig. 3.13, along with the baseline projections for total passenger vehicle stock and passenger activity.

The results show that the passenger vehicle stock and the total distance travelled are projected to increase substantially compared to the base year, with a similar growth trend in total vehicle-kilometer activity. These growth trends are a consequence of the population and economic growth and lead to a corresponding increase in CO_2 emissions since these are directly related to the amount of fuel consumed, as shown in Fig. 3.14.

The modelling results for the baseline scenario illustrate the potential severity of mobility and environmental challenges in future years if no mitigation actions are taken, as CO_2 emissions from the passenger road transport system are expected to increase by 27% in 2040, which works against Lebanon's INDC commitment to reduce overall emissions by 15–30% in 2030. The results also show that midsize and large vehicles are responsible for the majority of CO_2 emissions, as the current absence of any policies in Lebanon to discourage the purchase of larger fuel-inefficient vehicles results in an 88% future share for midsize and large vehicles out of the total passenger vehicle fleet. This demonstrates the need for environmental policies to promote the purchase of smaller vehicles, as in the two proposed mitigation strategies.

Figures 3.15 and 3.16 present the modelling results for energy use and distance travelled in terms of percent reductions in the two mitigation strategies relative to the baseline scenario. Note that CO_2 emission savings follow a similar trend to the reduction in energy use shown in Fig. 3.15 since the level of CO_2 emissions is proportional to the vehicle fuel consumption.

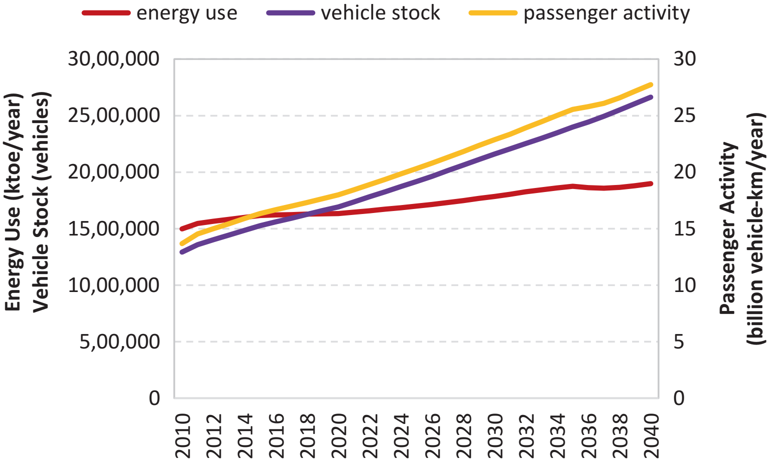


Fig. 3.13 Baseline projection of passenger vehicle stock, passenger activity and energy use

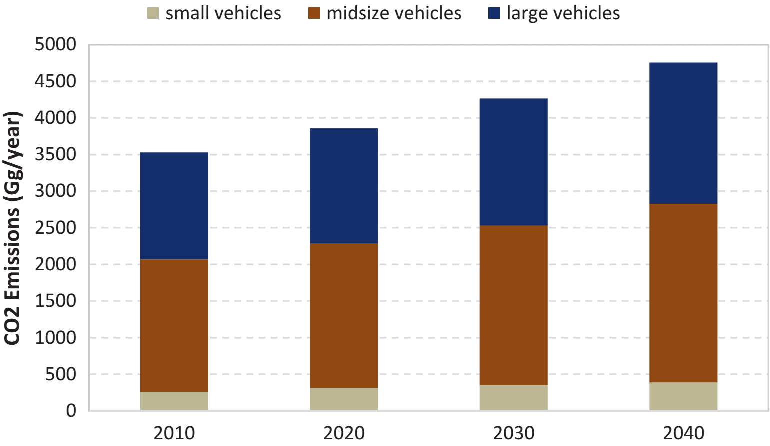


Fig. 3.14 Baseline projection of passenger vehicle CO_2 emissions per vehicle class

As can be seen from the figures above, introducing mHEV alone reduces energy use and CO_2 emissions in 2040 by 19% compared to the baseline scenario. This is due to the fuel efficiency of these vehicles and, in parallel, the corresponding decrease in the share of the larger fuel-inefficient vehicles. In addition, the assumed fuel price increase by 50% over the 2020–2040 planning horizon naturally impacts the number of trips compared to the baseline scenario, thereby reducing the total distance travelled illustrated in Fig. 3.16, and with it the corresponding energy consumed and the emissions generated from these trips, as shown in Fig. 3.15. Therefore, the contribution of mHEV to mitigating the impacts of climate change in transport, coupled with the relatively low cost of these vehicles, makes them a desirable option for developing countries of the Middle East where GDP per capita is low.

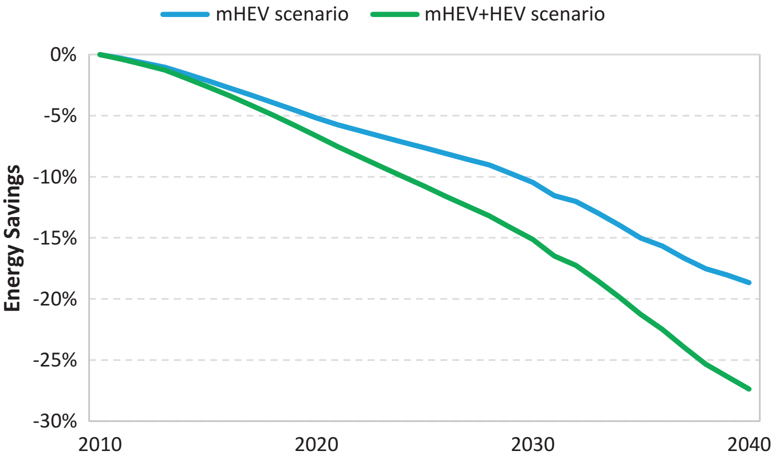


Fig. 3.15 Change in energy use under the two mitigation strategies relative to the baseline scenario

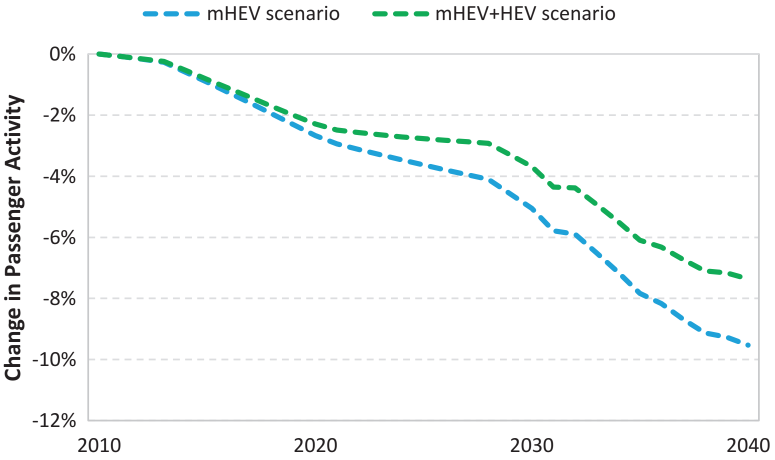


Fig. 3.16 Change in passenger activity under the two mitigation strategies relative to the baseline scenario

Since the second proposed mitigation strategy includes the first strategy in addition to the deployment of the more fuel-efficient HEV, more savings are expected compared to the first strategy, as demonstrated in Fig. 3.15. These savings are substantial compared to the first strategy and the baseline scenario, with a total reduction of 27% compared to the baseline by 2040 and 11% additional reductions in energy use and CO_2 emissions in 2040 compared to 2010 figures. These improvements are achieved despite the slight increase in vehicle-kilometer activity in this strategy compared to the introduction of mHEV alone, as shown in Fig. 3.16. This is explained by the fact that the highly fuel-efficient HEV are able to counter the increasing fuel prices in future years, allowing more passenger trips to be made than under the first mitigation strategy without HEV.

More importantly, this strategy sees a first decrease in 2040 below the 2010 base year levels, instead of only controlling the rising trend over time. This is important to note since it is achieved with only a conservative HEV share of 10% and no new infrastructure construction or any additional investments needed, making this technology easily deployable in the near term. This shows how beneficial hybrid technologies can be in the long term in cities of the Middle East where no electric charging infrastructure is available for more advanced electrified vehicles.

But while these results are promising, the modelling shows that mitigation strategies involving vehicle technologies alone are not sufficient to reverse the current unsustainable conditions captured in the 2010 baseline scenario for Lebanon. To that end, a more holistic approach involving mitigation strategies beyond the road vehicle passenger transport system is needed, such as expanding the reach of the public bus transport system or accounting for emissions from non-passenger (freight) transport. A detailed discussion of such a holistic assessment for the case of Lebanon is provided in (Haddad et al. 2017), where it is shown that synergy between complementary mitigation strategies can lead to new benefits which exceed the cumulative total from each mitigation strategy alone. In systems thinking, this is known as “the whole is greater than the sum of the parts” and is seen, for example, when combining the introduction of alternative fuel vehicles with the revitalization of mass transport. These combined strategies can increase overall environmental awareness and reduce people’s reliance on motorized transport, leading to even higher levels of emission savings than the sum of the individual contributions from each mitigation strategy alone. This highlights the importance of dynamic modelling in the development of a holistic mitigation portfolio, especially when appropriate policy incentives and disincentives are also included in the modelling to test their impact on the overall success of the mitigation effort over the long term.

8 Concluding Remarks

This chapter provided an assessment framework of the energy and environmental performance of alternative fuel vehicle technologies for mitigating climate change impacts from road passenger transport. The use of the framework was illustrated in the Middle Eastern context for the case of Lebanon’s GBA using real driving and weather conditions. Energy modelling results showed that tank-to-wheel fuel consumption is reduced by 39.4% for HEV and 77.9% for PHEV compared to ICEV, which means that electrified vehicles are fuel-efficient regardless of the aggressive and congested driving patterns in GBA. However, it is found that the use of heating and cooling auxiliaries in congested traffic increases consumption of these vehicles, by 13.5% for HEV and 84.6% for PHEV when using air conditioning. This shows that the impact of air conditioning use in warm regions such as the Middle East is significant, especially for electrified vehicles.

A system dynamics modelling of the road transport system also showed that renewing the fleet with mHEV and HEV leads to significant reductions of national energy use and CO_2 emissions by a total of 27% in 2040 compared to the business-as-usual scenario, despite the increasing demand for mobility. This serves to inform policymakers of the real-world performance of new technologies in order to properly plan future strategies. Therefore, this case study demonstrates that a systematic and comprehensive approach for modelling the energy use and emissions of mitigation technologies is needed to properly assess their benefits in the local context, especially in regions such as the Middle East where challenging weather, roadway, and traffic conditions are present.

The case study also shows that electrified vehicles powered by clean electricity are needed to face the serious sustainability challenges facing the road transport sector in congested cities with underdeveloped road infrastructure such as the GBA. Consequently, governments in the region should incentivize these technologies in order to make them competitive in the market and to embark on developing the electricity infrastructure in order to meet future requirements for clean mobility.

Finally, the assessment methodology and the results presented in this chapter can be extended by considering the socio-economic and infrastructure development dynamics required to encourage user adoption of new technologies in developing countries of the Middle East region. Several system dynamics studies have developed technology diffusion and user adoption models (see, e.g., Pasaoglu et al. (2016) and Struben and Sterman (2008)). However, the majority of studies are based on industrialized contexts where the backbone infrastructure for alternative fuels, such as natural gas pipelines and clean electricity mix, is readily available. This is not the case in developing countries where transition to alternative fuel vehicles is highly dependent on the availability of backbone infrastructure, the very limited purchasing power of consumers, and the lack of environmental awareness, among other limiting factors. Therefore, future work can be to capture additional key factors and relationships specific to the context of developing countries, such as government investment in backbone and refueling infrastructure, policy enablers for incentivizing the most beneficial technologies, and the preferences of end users for new technologies. User adoption models include several attributes such as vehicle costs, driving range, environmental awareness, word of mouth, and refueling infrastructure availability, all of which are context-specific and require local data and assumptions. The results of this modelling can serve to inform local authorities and stakeholders on how to accelerate the adoption of beneficial technologies for the lowest infrastructure costs.

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Chapter 4
Climate Change and Energy Decision Aid Systems for the Case of Egypt

Aya Sedky Adly

Abstract Energy is always conserved, and it cannot be destroyed nor created; it can only be transformed from one form to another. Determining which forms are more useful is strongly influenced by climate change. Moreover, the growth of energy production and consumption is strongly affecting and being affected by the climate change in many aspects. In warmer countries, such as Egypt, climate change is expected to have an even larger impact on different energy forms demand. However, since economic, technical, and environmental energy concerns change from country to another, addressing the impact of both current climate and future climate changes on demand should be worked out by decision-makers in accordance with the country policies and geographical conditions. This work is concerned with how experts should best characterize such uncertainties for decision-makers of climate change scenarios including changes in mean climate characteristics as well as changes in the frequency and duration of weather events in Egypt. It also provides decision aid in developing climate action plans and selecting the most suitable mechanisms in correspondence to energy demands.

Keywords Egypt · Climate change · Energy · Decision-making

1 Introduction

Climate change is a global issue that has significant impact all over the world. It poses a major threat to all dimensions of sustainable development and has widespread impacts across various sectors and ecosystems such as food, water, and energy; forests and biodiversity; coastal and marine environment; as well as on the occurrence and intensity of climate-related hazards such as floods and drought. It also carries potential for internal and external conflicts.

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H. Qudrat-Ullah, A. A. Kayal (eds.), *Climate Change and Energy Dynamics in the Middle East*, Understanding Complex Systems,
https://doi.org/10.1007/978-3-030-11202-8_4

Developing nations are believed to be particularly susceptible to the impacts of climate change (Field et al. 2014; Patt et al. 2009; Nakicenovic 2010). This derives from the dependence of livelihoods on climate-sensitive sectors such as agriculture, tourism, fisheries, and forestry; climate-sensitive infrastructures such as houses, buildings, municipal services, and transportation networks; and limited adaptive capacity to cope with impacts. Not all developing nations are equally vulnerable to climate change; however, a function of exposure to projected changes and socioeconomic factors determine sensitivity and adaptive capacity (Field et al. 2014).

Egypt, a developing country, is generally one of the warm countries that is considered one of the most vulnerable countries to stress under climate change with associated risks that are expected to affect adversely all sectors in Egypt (Smith et al. 2013). In Egypt, climate change is considered one of the most factors that can have a significant effect in many aspects due to several reasons. Some of the reasons are geographic exposure, low income, and limited capability to adapt to climate change. Another reason is the fact that Egypt relies on the Nile River as its main and almost exclusive source of fresh water. As Nile provides the majority of Egypt's water that feeds the country's fields, cities, and industries, which put Egypt at a disadvantage, as any further warming would seriously affect productivity (Mendelsohn 2008), agriculture, forestry, tourism, and energy.

Climate change phenomenon has been one of the global level concerns as its consequences can result in serious changes intimidating the future of the land. According to the World Meteorological Organization (WMO) published study and the Third Assessment Report (TAR) of the latest Intergovernmental Panel on Climate Change (IPCC) (Pachauri and Reisinger 2007), there was much made of twenty-first century temperature projections. The projections rely on "story lines" that report self-consistent social development possibilities for the next 100 years. These are processed into scenarios known as "Special Report on Emissions" scenarios and published in an IPCC document (IPCC 2000) (Nakicenovic et al. 2000b). The "story lines" vary from high population growth/high emission assumptions to low population growth with substitution of low greenhouse gas technologies such as solar, wind, and nuclear.

Egypt is one of the countries in which it is expected that climate change will bring increases in average temperatures (1–3 °C) where the magnitude and direction of these changes will vary regionally. This rapid rise will threaten the stability of the country through the disruption of supplies of food and water in many regions, particularly in the desert regions.

In summer times with hot dry climates, approximately half of the urban peak load of energy consumption is utilized in cooling demands for air-conditioning satisfaction. As a consequence of increasing the urbanization rate in developing countries like the case in Egypt, the pressure placed on energy resources to provide indoor inhabitants satisfaction is accentuating too.

Although the rise in temperature is not the only manifestation of climate change, the IPCC work reported that with regard to man's impact on the climate, it was found that the increase in greenhouse gas concentrations over the last 50 years is likely the cause of warming over.

In addition, the IPCC stated that it has more confidence in projecting future climatic trends by the capacity of models (Rahmstorf et al. 2007).

Since the industrial revolution carbon dioxide (CO_2), which is an inevitable waste product from fossil fuel combustion, has been released into the atmosphere in large amounts increasing the natural greenhouse effect, this causes a rise in the average temperature and changes the climate. Every year, about 30 billion tons of CO_2 are released into the atmosphere that is an average of 5 tons per person. The concentration of CO_2 has risen by 30% in some 250 years. The IPCC projections reported increased precipitation, with observable variability according to the region and season (Bates 2009).

Another consequence is a rise in the level of the seas (Egypt touches both the Mediterranean and Red Seas), following the thermal expansion of water bodies.

It was found that 33 cities in the world are having risk of sea-level rise. These cities have about 8 million people. Alexandria in Egypt is one of the most threatened cities because of the rising sea level.

Regretfully, the issue of climate change was not taken seriously in Egypt (Gregory, n.d.; Nicholls et al. 2011) in spite of being one of the five countries in the world vulnerable to the negative effects of climate change, such as rising sea level or sinking parts of Delta, reflected in all social and economic harm.

It is expected that the average sea level will increase by up to 8 meters over the next 1000 years in an "average" scenario. This can be clarified by warming and melting of continental ice sheets. The increased amounts of CO_2 released in the atmosphere will remain for prolonged time, and the warming of water masses will take a very long time. Thus it is important to notice that even if the concentration of CO_2 is stabilized – which requires a considerable reduction of emissions – the temperature will continue to rise slowly with a strong chance of this leading to the melting of a significant fraction of the ice caps (Rahmstorf 2010).

Climate change in the Nile Basin was found to have its impact on Nile discharge (Gleick 1991; Conway and Hulme 1993; Conway 1996). The effect of doubling of carbon dioxide concentrations on Nile flows has been examined by early equilibrium experiments. The results were spanning from the positive to the negative (Conway et al. 1996; Strzepek 1996; Yates and Strzepek 1998). Researchers have worked with more recent general circulation models (GCMs) and employed statistical and dynamic downscaling techniques to form finer scaled climate projections for the Nile Basin. These data are then input into conceptual- or physical-based hydrological models (Di Baldassarre et al. 2011; Taye et al. 2015) to simulate future Nile flows.

Egypt is a large country with area of about 1,000,000 km^2 that has a disparity of climate conditions ranging from extremely hot conditions in the desert regions such as the Western Desert to cold conditions in Mountain St. Catherine in Sinai Peninsula (Mahmoud 2011). But in general, it is considered a hot-arid climate country with very high solar radiation intensity for most of the years (SODA 2013; Griffiths 2013); thus, finding techniques and choosing suitable decisions can play a major role in harvesting the solar radiation which is having direct impact on decreasing CO_2 release and energy consumption of other nonrenewable resources.

Climate change is expected to greatly undermine the socioeconomic progress made in developing nations, in the absence of targeted action. And the most affected nations are the poorest that compound ongoing developmental challenges (Costello et al. 2009; Nakicenovic 2010). The requirement for adaptation has been largely observed among developing countries since UNFCCC negotiations began in the early 1990s and has received renewed impetus in light of recognition of the now inevitable changes in climate. Advances in adaptation have been made over the last decade, covering the establishment and disbursement of adaptation funds through the UNFCCC, initiation of National Adaptation Plans (NAPs), completion of National Adaptation Programs of Action (NAPAs), mainstreaming of adaptation into development projects, and the emergence of a large body of scholarship investigating vulnerability to assist direct adaptation efforts (Berrang-Ford et al. 2011; Biagini et al. 2014; Fankhauser and Burton 2011; Mannke 2011; Sovacool 2012; Sovacool et al. 2012).

With economic growth and poverty reduction prospects of developing countries, such as Egypt, even under optimistic assumptions about the level and success of future global efforts, it is necessary to integrate adaptation plans into national development strategies to continue with the likely consequences of already unavoidable climate change. Egypt is one of the developing countries with highest exposure to biophysical impacts and limited adaptive capacity. To enable comparisons of the prospective benefits of conceivable adaptation measures, rational adaptation planning needs a forward-looking quantitative assessment of climate change effects on economic performance at wide level. To simplify these assessments of alternative adaptation strategies and to assess effects in the absence of policy-led adaptation action, a number of strategies for a range of developing countries have been made and applied in recent years. Examples include Arndt et al. (2011) and Robinson et al. (2012) for Ethiopia, Arndt et al. (2012) and Arndt and Thurlow (2015) for Mozambique, Thurlow et al. (2012) for Bangladesh, and Laube et al. (2012) and Strzepek and Yates 2000) for Egypt. However, all of these models aim economic aspects. For Egypt in specific, the majority of strategies aim buildings energy consumption (Fahmy et al. 2014).

Researchers affiliated to Egyptian universities and various research institutions to study climate change-associated risks and their implications (Hassaan and Abdrabo 2014) and the significance of climate change effects. The Climate Change Action Plan of Egypt needs to be provided by key elements, and this can be done by investigating the present and potential impact of climate change on energy, identifying existing gaps and sustaining research development in this aspect.

2 Current State of Energy and Climate Change in Egypt

Due to energy demand complexity, it would be hard to predict with confidence what will happen in the future as a result of climate change (Edenhofer et al. 2011).

However, there are some promising indicators as awareness of climate change, and its severe consequences among decision-makers in Egypt are still growing, which is probably a result of global growth of awareness specifically leaders who have more knowledge in the country. Additionally, this increase in awareness may be also duo to fear of water scarcity and droughts especially on lands formerly irrigated by the river Nile (Campbell-Lendrum and Corvalán 2007; Brown et al. 2007; Agrawala et al. 2004).

Energy has become the bloodline of most economies as it drives every sector of the economy. Energy is also considered as a major driver of growth, industrialization, and urbanization (Esso 2010). Many aspects depend mainly on energy as goods and services distribution, production, and consumption. As energy can cause significant impact on economic activities, it is also influenced by these activities. Thus, energy is not entirely an exogenous phenomenon in any economic system. As a result of this, it is necessary not to consider only the effects of energy on economic activities but also the reverse impacts or feedback loops as well (Salim et al. 2014).

The planet as a whole is gaining energy as the ocean heat content is increasing, and the atmosphere becomes warmer, mid-latitude glaciers are melting, sea levels are rising, and the Arctic Ocean ice cover is melting. All of these observations are based on facts (Hansen et al. 2016).

The imbalance in the energy of the planet can be explained by increases in the concentrations of greenhouse gases, notably carbon dioxide, methane, and nitrous oxide. Also combustion of natural gas, oil, and coal leads to increase in these gas concentrations. The concentration of these gases is found to be higher now than at any time over at least the past 800,000 years (Ramanathan and Feng 2009).

Broken down by years, Table 4.1 illustrates the significant increase in Egypt energy consumption over the past 38 years as reported by the BP Statistical Review of World Energy June 2018. According to Table 4.1, it can be seen that the energy consumption is accentuating rapidly in Egypt and alternative energy resources should be considered. Given that Egypt is in the Middle East and industrial growth is mainly responsible for the increase of energy consumption, if the country neglects the energy landscape for utilization of natural resources and new energy production techniques according to the conditions and costs, it will certainly confront a major energy crisis in the future.

As it is also noticeable from Table 4.1 the extraordinary increase in energy consumption since 1980, at first dominated by the industrialized countries, energy consumption in Egypt as a developing country has been generally low. Along with the increase in energy consumption, giving way more recently to industrial growth, most striking is the recent explosive growth of oil use there, along with the rising use of natural gas.

Egypt has consistently ranked 20th among the world's top 20 gas-flaring countries starting from the period 2007, where aggregate quantities of flared gas production were estimated at 53 billion cubic meters, which represents annual gain revenues of approximately 16 billion cubic meters. However, starting from 2015, consumption exceeded production by over 3 billion cubic meters for the first year ever, and stocks started to run down (Abdulrahman et al. 2015).

Table 4.1 Nonrenewable energy in Egypt since 1980

Type	Primary energy	Oil			Natural Gas			Coal
Year	Million tons oil equivalent	Thousand million barrels	Thousand barrels daily		Trillion cubic meters	Billion cubic meters		Million tons oil equivalent
	Consumption	Proved reserves	Production	Consumption	Proved reserves	Production	Consumption	Consumption
1980	18.0	2.9	580	257	0.1	2.1	2.1	0.6
1981	20.4	3.5	628	296	0.1	2.3	2.3	0.7
1982	22.8	3.7	651	336	0.2	2.6	2.6	0.7
1983	24.8	4.0	712	370	0.2	3.0	3.0	0.7
1984	27.0	4.0	816	398	0.2	3.9	3.9	0.7
1985	28.0	3.8	882	406	0.2	4.7	4.7	0.7
1986	28.7	4.5	806	409	0.3	5.5	5.5	0.7
1987	30.1	4.7	907	425	0.3	6.0	6.0	0.8
1988	31.0	4.3	869	431	0.3	6.7	6.7	0.9
1989	32.7	4.3	878	450	0.3	7.4	7.4	0.9
1990	33.8	3.5	897	465	0.4	7.8	7.8	0.8
1991	34.3	3.5	896	457	0.4	8.7	8.7	0.8
1992	34.2	3.4	906	445	0.4	9.5	9.5	0.8
1993	34.6	3.4	941	427	0.6	10.9	10.9	1.0
1994	35.2	3.9	921	427	0.6	11.6	11.6	1.0
1995	37.3	3.8	924	463	0.6	12.0	12.1	0.7
1996	39.3	3.8	894	488	0.8	12.8	12.5	1.0
1997	41.0	3.7	873	518	0.9	13.1	12.9	0.8
1998	42.7	3.8	857	545	1.0	13.5	13.2	0.8
1999	45.7	3.8	827	560	1.2	16.2	15.8	0.7
2000	48.4	3.6	779	552	1.4	20.2	19.3	0.9
2001	51.1	3.7	758	537	1.5	24.3	23.6	0.8
2002	51.9	3.5	751	524	1.6	26.3	25.5	0.8

2003	55.0	3.5	750	540	1.7	29.0	28.6	0.9
2004	57.6	3.6	701	556	1.8	31.8	30.5	0.9
2005	60.5	3.7	672	617	1.8	40.9	30.4	0.9
2006	63.5	3.7	679	601	2.0	52.6	35.1	0.9
2007	67.3	4.1	698	642	2.0	53.6	36.9	0.8
2008	71.7	4.2	715	686	2.1	56.8	39.3	0.7
2009	74.6	4.4	730	725	2.1	60.3	40.9	0.6
2010	78.4	4.5	725	766	2.1	59.0	43.4	0.5
2011	79.7	4.3	714	720	2.1	59.1	47.8	0.4
2012	83.8	4.2	715	747	2.0	58.6	50.6	0.4
2013	83.2	3.9	710	756	1.8	54.0	49.5	0.4
2014	82.9	3.7	714	806	1.8	47.0	46.2	0.4
2015	84.4	3.5	726	833	1.8	42.6	46.0	0.4
2016	88.2	3.4	691	854	1.8	40.3	49.4	0.2
2017	91.6	3.3	660	816	1.8	49.0	56.0	0.2

Natural gas is considered the least polluting of the fossil fuels. The gaseous by-products should be captured by some refineries and utilized for their energy content. However, viability of flare gas recovery projects is restricted in Egypt by high project development costs, lack of funding, and energy subsidies. Overcoming barriers facing flare gas recovery projects in developing countries like Egypt can be done by the Clean Development Mechanism (CDM) which can play a pivotal role especially in view of the low energy prices due to energy subsidies provided by the government (Dincer 2000).

The Clean Development Mechanism (CDM) is one of the flexible mechanisms defined in the Kyoto Protocol (Meehl et al. 2007; Bernstein et al. 2008; Solomon et al. 2007) that provides for emission reduction projects which generate Certified Emission Reductions (CERs) units which may be traded in emissions trading schemes. The CDM addresses the second objective by allowing the Annex I countries to meet part of their emission reduction commitments under the Kyoto Protocol by buying Certified Emission Reduction units from CDM emission reduction projects in developing countries (Grubb et al. 2009).

Since the Industrial Revolution, energy-driven consumption of fossil fuels in Egypt has led to a rapid increase in CO_2 emissions, disrupting the carbon cycle. Table 4.2 as reported by BP Statistical Review of World Energy June 2018 shows carbon dioxide emissions (million tons of carbon dioxide) from the consumption of energy during the period from 1980 to 2017. There is a noticeable rise in carbon dioxide emissions since the 2008 recession although the values moved toward stabilization of CO_2 emissions over the last few years; however, to begin to stabilize or even reduce atmospheric CO_2 concentrations, emissions need to not only stabilize but also decrease significantly (Abdallah et al. 1999).

The relationship that exists between energy consumption, growth of output, and carbon dioxide emissions is considered the main linkage between energy and economic system. The relation between these three variables is often complicated due to the dynamics of the feedback impacts existing between them. Four main hypoth-

Table 4.2 Carbon dioxide emissions in Egypt since 1980

Carbon dioxide emissions (million tons of carbon dioxide)										
Year	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
	45.7	52.5	59.1	64.9	70.4	73.1	74.8	78.6	81.0	85.5
Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
	87.9	88.6	88.0	87.5	88.4	93.5	99.5	103.9	108.1	113.6
Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
	118.7	126.3	121.9	131.3	136.6	147.1	151.3	160.2	170.5	177.2
Year	2010	2011	2012	2013	2014	2015	2016	2017		
	188.8	189.5	200.4	198.1	201.6	204.5	212.1	217.3		

eses have been reported on the linkage between energy consumption and economic growth. These four hypotheses are energy-led growth, growth-led energy consumption, neutrality, and feedback (Esso 2010; Apergis and Payne 2009).

The energy-led growth hypothesis implies that conservation policies are inimical to growth. On the other hand, growth-led energy consumption hypothesis confirms that energy savings does not necessarily implicit stunting growth since the direction of causality runs from growth to energy consumption. The neutrality hypothesis views energy demand and output growth as two exogenous forces (Esso 2010). It does not accept any form of relation between them. However, the feedback hypothesis considers energy and growth as complementary factors exerting significant effects on each other.

It is not enough to concentrate on the relation between energy consumption and growth in understanding aspects of global warming with its effects on climate change. But it is important to take into consideration the influence of this relationship on the environment as it induces atmospheric emissions, especially carbon dioxide. Burning of fossil fuels to produce energy has direct influence on emissions. In addition, increased emission levels with its associated climate change have impact on energy consumption and economic activity. Thus management of any of these factors must be inclusive to involve all the dynamics rather than treating them in isolation (Davis and Caldeira 2010; Holdren et al. 2000).

Since energy is an essential part in the production and consumption process, reducing energy consumption to reduce emissions from fossil fuels may lead to a significant negative impact on economic growth. Countries may seek different strategies and choices for reducing emission levels to enhance environmental quality, so it is important that examination studies for the links between these factors be disassembled at the country levels instead of global or regional levels (Enkvist et al. 2007; Gustavsson et al. 1995).

Rapid economic growth in emerging economies especially in Egypt has different impacts on energy consumption and accordingly environmental quality. Experts examined the causal dynamics among economic growth, energy use, and carbon dioxide emissions, specifically in emerging economies. It was found that the growth of these economies is due to the myriad of structural reforms executed over the years. These reforms have major effects on the whole structure of the economies, in terms of energy consumption, environmental policy, and economic activity. The dynamics of energy consumption, economic fundamentals (gross domestic product (GDP)), and carbon dioxide emissions can be affected by the exposure of economies to economic crises and adjustment policies. Literature (Esso 2010) has examined the impact of structural reforms on the relationships neglecting the effect of regime shifts on them (Schmalensee et al. 1998).

In general, if we are to arrest the current trend, we need to switch to an alternate energy economy. The challenge to respond is immediate. The impacts of a changing climate are already apparent and can only increase in disruptive potential in the future.

3 Possible Energy Resources for the Future

Egypt is a country with plenty of land, sunny weather, and high wind speeds; this makes it excellent place for renewable energy sources.

It even has a natural potential for becoming the world's biggest energy harvesting place as it has the main renewable natural elements to generate numerous energy of wind, sunlight, and hydro-energy. However, currently, Egypt depends heavily on oil and gas as its main energy supply (Salameh 2003; El-Katiri 2014).

Since the fossil fuel consumption has led to global warming, environmental pollution, harm local communities, and more other disasters in the world, replacing it with clean renewable energy has become a significant matter all over the world (Wang et al. 2016; Hoffert et al. 2002; Hansen et al. 2000). Currently, renewable energy development is considered a vital measure in climate change mitigation and greenhouse gas emission. All countries in the world are now focusing on reduction of the anthropogenic impact on climate change and increasing generation of renewable energy by producing more sources (Lombardi et al. 2016; Panwar et al. 2011). However, most of the total energy consumption in Egypt and in the world as well is mainly based on fossil fuels, despite their side effects on the communities and environment. Moreover, both production and consumption of these fuels are growing with time since they are currently a necessary for countries' economy and development (Cancino-Solórzano et al. 2010; Gualberti et al. 2013; Cancino-Solórzano et al. 2016). The renewable energy policy is not only a main purpose of sustainability but also energy efficiency and sufficiency (Hastik et al. 2015; Boyle 2004; Dincer 2000). Although there are anonymous amounts of conventional energy reserves that are buried either deep in the ground or under the ocean, countries tend to avoid discovering or seeking them since not only it is an extremely difficult task but also due to high costs, dangerous risk, and uncertainty. Even in the process of refining gas from oil sands, a great amount of the natural gas should be burned during the refinement (Pacesila et al. 2016).

IPCC 2014 (Team et al. 2014) reported that to avoid serious disasters, the world's electricity should be produced from zero-carbon sources by 2050; otherwise, the earth will suffer greatly from irreversible damage. They also reported that renewable energies should grow from 30% share of power sector to at least 80% while phasing out all fossil fuel generated without carbon capture and storage (CCS) by 2100 (Romm 2006). Table 4.3 illustrates electricity generation in Egypt during the period from 1985 to 2017 as reported by BP Statistical Review of World Energy June 2018, where the majority is produced from oil and gas despite having limited reserves. Therefore, renewable energy resources must be developed in Egypt to prevent these sources from having negative effects on the environment and to avoid running out of these limited sources. The government is currently finding renewable energy resources with technologies that are more efficient and new to be used for producing energy in the natural environment.

The use of wind energy technology is progressing rapidly during the past years. Since the wind power is a local clean resource that doesn't cause any pollution to

Table 4.3 Electricity generation in Egypt since 1985

Electricity			
	Terawatt-hours		
Year	Generation	Generation from oil	Generation from gas
1985	30.3	11.9	9.2
1986	32.5	13.2	10.3
1987	35.7	15.0	11.7
1988	38.7	16.7	13.2
1989	40.6	17.4	13.7
1990	42.0	15.6	16.4
1991	43.3	13.0	20.4
1992	45.0	12.2	22.9
1993	46.7	10.5	26.2
1994	48.6	8.5	29.3
1995	50.7	9.0	30.5
1996	53.6	10.6	31.5
1997	56.8	12.3	32.7
1998	60.7	16.1	32.5
1999	65.7	15.1	37.2
2000	73.3	16.9	42.2
2001	80.7	17.6	48.5
2002	86.2	14.6	57.5
2003	92.2	14.9	64.0
2004	98.3	13.5	71.5
2005	104.9	14.0	77.8
2006	111.7	15.3	82.9
2007	119.9	15.8	89.2
2008	128.8	17.9	94.9
2009	134.3	20.7	98.8
2010	144.4	21.0	109.1
2011	149.6	18.2	116.6
2012	162.8	21.4	126.6
2013	165.1	27.0	123.2
2014	171.2	31.9	124.6
2015	181.8	36.8	129.4
2016	188.2	34.8	137.5
2017	193.2	27.2	149.9

the environment, it is essential to encourage researches in order to overcome the current energy crises (Ackermann and Söder 2002).

Wind has even more merits such as being abundant, cheap, and inexhaustible. For all these reasons, wind turbine technology has increased over the past few decades in Egypt as reported by the BP Statistical Review of World Energy June 2018 as shown in Table 4.4, and governments have decided to enhance the knowledge about wind turbine technologies for electricity generation (Lewis and Wiser

Table 4.4 Cumulative installed wind turbine capacity in Egypt

Cumulative installed wind turbine capacity (megawatts)											
Year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
	6	6	36	69	69	69	69	145	145	230	310
Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	
	390	435	550	550	550	550	550	750	750	750	

2007; Redlinger et al. 2016; Pérez-Collazo et al. 2015; Ellabban et al. 2014). Among different sources of renewable energies, wind turbines are considered to be the most economical way. However, in terms of effectiveness, hydrogen is considered more effective due to instability caused by wind turbines that cause problems to the power grid (Agbossou et al. 2004; Jain 2011; Patel 2005; Bianchi et al. 2007).

Although plenty of wind energy is widely generated in many countries such as the USA, Germany, Spain, China, India, the UK, Denmark, and Canada, Egypt did not generate or consume that much. While the cumulative global wind energy generating capacity reached approximately 1122 terawatt-hours in 2017, Egypt generating capacity was only 2.5 terawatt-hours. According to preliminary estimates by the BP Statistical Review of World Energy 2018, the American Wind Energy Association (AWEA), and the European Wind Energy Association (EWEA), global wind power-generating capacity has been duplicated more than eight times from approximately 133 terawatt-hours in 2006 to reach over than 1122 terawatt-hours at the end of 2017 (Council 2017; Lewis and Wiser 2007).

Although Egypt enjoys an excellent wind regime, particularly in the Suez Gulf, where average wind speeds reach over 10 m/second, however as shown in Table 4.5, the Egyptian wind energy market only increased from just 0.1 terawatt-hours in 2000 to 2.5 terawatt-hours at the end of 2017. On the other hand, there are even more wind power developments in the near future on the Gulf of Suez coast.

So many studies were conducted to determine wind characteristics and feasibility in the whole world; examples include Gökçek et al. (2007), Genç and Gökçek (2009), Celik (2007), Gölçek et al. (2007), and Ucar and Balo (2009) for Turkey; Rehman et al. (2007) for Saudi Arabia; Acker et al. (2007) for the USA; Shata and Hanitsch (2006) for Egypt; and Luickx et al. (2008).

Recently, inauguration of one of the largest wind farms in Egypt took place on June 2018 as part of a wider drive to expand renewable energy capabilities in the country. The wind farm, which is located in the Gabal el-Zeit area of the Red Sea governorate, will be inaugurated by the Ministry of Electricity and Renewable Energy. With an overall capacity of 580 megawatts (MW) and a total of 300 wind turbines, the wind farm contains three projects. The new project is part of a number of new investments the Egyptian government has made to diversify into renewables energies such as recent plans to build the world's largest solar farm near the southern city of Aswan.

In addition, to wind, the potential source of power from the sun is significant even for sun-deprived countries such as Germany. Solar energy reaching the Earth's surface averages about 200 W m^2. If this power source could be converted to

Table 4.5 Renewable energy in Egypt since 1980

	Hydroelectricity		Renewables		Solar		Wind	
	Terawatt-hours	Million tons oil equivalent	Terawatt-hours	Million tons oil equivalent	Terawatt-hours	Million tons oil equivalent	Terawatt-hours	Million tons oil equivalent
	Generation	Consumption	Generation	Consumption	Generation	Consumption	Generation	Consumption
1980	9.8	2.2	–	–	–	–	–	–
1981	10.2	2.3	–	–	–	–	–	–
1982	10.5	2.4	–	–	–	–	–	–
1983	9.8	2.2	–	–	–	–	–	–
1984	9.6	2.2	–	–	–	–	–	–
1985	9.1	2.1	–	–	–	–	–	–
1986	9.0	2.0	–	–	–	–	–	–
1987	9.0	2.0	–	–	–	–	–	–
1988	8.8	2.0	–	–	–	–	–	–
1989	9.5	2.1	–	–	–	–	–	–
1990	10.0	2.3	–	–	–	–	–	–
1991	9.9	2.2	–	–	–	–	–	–
1992	9.8	2.2	–	–	–	–	–	–
1993	10.1	2.3	–	–	–	–	–	–
1994	10.7	2.4	–	–	–	–	–	–
1995	11.2	2.5	–	–	–	–	–	–
1996	11.5	2.6	–	–	–	–	–	–
1997	11.8	2.7	–	–	–	–	–	–
1998	12.1	2.7	–	–	–	–	–	–
1999	13.4	3.0	0.012	0.003	–	–	0.012	0.003
2000	14.2	3.2	0.1	0.018	0.0002	0.0001	0.1	0.02
2001	14.4	3.3	0.2	0.04	0.0009	0.0002	0.2	0.04

(continued)

Table 4.5 (continued)

	Hydroelectricity		Renewables		Solar		Wind	
	Terawatt-hours	Million tons oil equivalent	Terawatt-hours	Million tons oil equivalent	Terawatt-hours	Million tons oil equivalent	Terawatt-hours	Million tons oil equivalent
	Generation	Consumption	Generation	Consumption	Generation	Consumption	Generation	Consumption
2002	14.0	3.2	0.2	0.048	0.001	0.0002	0.2	0.05
2003	12.9	2.9	0.3	0.1	0.001	0.0002	0.3	0.1
2004	12.8	2.9	0.5	0.1	0.001	0.0002	0.5	0.1
2005	12.6	2.9	0.5	0.1	0.001	0.0002	0.5	0.1
2006	12.8	2.9	0.6	0.1	0.001	0.0002	0.6	0.1
2007	14.2	3.2	0.7	0.2	0.0012	0.0003	0.7	0.1
2008	15.1	3.4	0.9	0.2	0.0015	0.0003	0.9	0.2
2009	13.8	3.1	1.0	0.2	0.0022	0.0005	1.0	0.2
2010	13.0	2.9	1.4	0.3	0.0256	0.006	1.4	0.3
2011	13.0	2.9	1.7	0.4	0.1	0.02	1.6	0.4
2012	13.0	2.9	1.8	0.4	0.1	0.013	1.8	0.4
2013	13.2	3.0	1.6	0.4	0.1	0.014	1.5	0.3
2014	13.6	3.1	1.2	0.3	0.042	0.01	1.1	0.3
2015	13.7	3.1	1.9	0.4	0.1	0.015	1.9	0.4
2016	13.3	3.0	2.6	0.6	0.1	0.023	2.5	0.6
2017	13.4	3.0	2.7	0.6	0.2	0.04	2.5	0.6

electricity with an efficiency of 20%, it could supply Egypt demands for electricity (Jacobsson et al. 2004; Frondel et al. 2010).

Strategies to harvest electricity from abundant solar sources are suited to Egypt, as it is situated in the desert Sun Belt as stated by Egypt's Solar Atlas with 2000–3000 kWh/m^2/year of direct solar radiation. The sun shines 9–11 hours a day from North to South in Egypt, with few cloudy days (Ibrahim 1985; El-Metwally 2005).

Two approaches are usually followed to harvest sun energy and convert it to electricity. The first can be achieved using devices that absorb radiation and directly generate electricity which called photovoltaic (PV) cells. The second approach captures and deploys solar energy in order to generate heat. This heat is then used to generate steam which is applied to drive a turbine. The sunlight is usually concentrated for efficiency enhancement using a technology called concentrated solar power (CSP). This approach can achieve the same level as using limited resources such as oil and natural gas (McElroy 2016; Garces et al. 2007).

As presented in Table 4.5, solar energy was first generated in 2000. Since then, specifically after 2010, it was rapidly growing and estimated to grow even more in the future.

Recently, Egypt inaugurated the first solar power plant on March 2018 at a remote desert complex. The Benban Solar Park near the southern city of Aswan promises to transform Egypt into a major solar energy player in the world. The ambitious project, set to be the largest solar park in the world, aspires to provide somewhere between 1.6 and 2 gigawatt-hours of solar power by mid-2019. Egyptian officials believe the project will produce 20% of Egypt's power through renewable energy by 2020, which will serve 350,000 Egyptians and provide eco-friendly and cost-efficient power. The Benban complex aims to include 32 solar plants on a 37.2 square kilometer area and will churn out 1650 megawatts of electricity, according to the World Bank's International Finance Corporation (IFC).

By producing a huge power plant, Egypt is set to reduce the costs of costly power lines, power substations, and expensive hardware, which, in turn, is set to lower the cost of electricity.

In general, it was estimated that about 50% of the Earth's intercepted solar energy is absorbed at the surface, where a large portion of this energy consumed in evaporating water, oceans in particular. However, since the atmosphere has a limited ability to retain moisture, the water condenses to form clouds and falls back to Earth in the form of rain and snow (together these are called precipitation). Precipitation that falls on land can land on higher places with respect to sea level such as mountains. In this case, it can be granted in the form of potential energy. This potential energy can be stored (in lakes or dams, for instance), or it can be released and converted to kinetic energy (directed motion) as the water flows downhill on its return to the ocean. And along the way, energy can be captured and channeled to perform useful work. Generation of electricity is considered the most important application of water energy which is achieved by harvesting the potential energy stored in high-altitude dams or from kinetic energy produced from flowing water streams (McElroy 2016; Barbour et al. 2016; Garces et al. 2007).

Table 4.5 presents the growing hydroelectricity generation in Egypt during the period 1980–2017 as reported by the BP Statistical Review of World Energy June 2018. It also shows that consumption is considerably low in comparison to generation.

In furthering its move toward more sustainable and renewable energy sources, the Electricity Ministry of Egypt since February 2018 is planning to build the first hydropower plant in the Middle East at a capacity of 2400 megawatt using the pumped-storage hydropower (PSH) technology at Ataqa Mountain, Red Sea, to utilize renewable energy resources.

With the current status and future prospects of Egypt energy from wind, solar, and hydro, Egypt, a fast-growing country of more than 90 million, can be provided with the clean energy it needs to drive growth and fight poverty.

4 Characterizing Energy and Climate Change Uncertainties

Energy represents one of the essential pillars for the economic development of countries. Countries try to increase their energy resources and import energy from other countries in order to fulfill their needs, maximize their production capacity, and enhance their quality of life. Electricity is the second most widely consumed form of secondary energy all over the world after oil with a total final consumption value of 18% (Fischer 2008; Ghosh 2002).

Production of electricity requires a combination of primary energy resources. Regarding the Egyptian energy sector, electricity blackouts are frequent for more than 4 years due to increased energy demands, shortages of natural gas supply which is a major resource for electricity systems in Egypt, inadequate generation and transmission capacity, and aging infrastructure. This caused negative impact on vital demand areas and the country's economic development.

The government issued the feed-in tariff law for renewable energy projects in 2014 to decrease the use of natural gas and secure energy supply for the citizens. This law is considered an initial step of liberalization of the electricity market and including the private sector (Couture and Gagnon 2010; Mendonça 2009).

Part of the "Energy Technology Systems Analysis Program" (ETSAP) implemented by the International Energy Agency (IEA) was a project to expect the most economic energy mix for Egypt till the year 2035 using the TIMES energy model generator, and this project was called "Technical Assistance to support the reform of the Energy Sector" (TARES). This project uses long-term energy scenarios to conduct detailed analyses of energy systems. It combines two complementary approaches for modeling energy: a technical engineering approach and an economic approach (Loulou et al. 2004; Wamukonya 2003). The drawback in this project is not involving the environmental and social aspects of energy; thus, the consequences of climate change are not taken into consideration although they are important link to the development of energy.

In an attempt to involve the economic, environmental, and social dimensions and also the technical or institutional aspects of a product or a geographical region, the concept of sustainable development (SD) has been developed. This concept was introduced for their continuous developmental maintenance. In general, the energy market in Egypt shows an urgent need for applying this concept to flourish (Hopwood et al. 2005; Smit and Pilifosova 2003; Giddings et al. 2002).

Model imperfection is concerned with the uncertainty and inadequacy resulting from limited understanding of the Earth's climate and the restricted ability to simulate it.

Anything outside the climate framework and can affect it in the future is captured by forcing uncertainty. Initial condition uncertainty captures uncertainty for forward integration in time. It must be taken into consideration at least five distinct sources of uncertainty when analyzing climate models. Model uncertainty determines parameter values that are likely to provide the most informative results. The problem that confronts climate modeling is choices which are not only between the values of each model parameter but also between parameterizations themselves (Moore and Semmens 2008; Garlappi et al. 2006).

On the other hand, inadequacy captures deductive facts without combination of parameterizations and parameter values which would closely imitate all climate framework relevant aspects.

The design and analysis of experiments in the face of uncertainties are among the grand challenges of climate science today as computational constraints prevent models from any claim of near isomorphism with reality (Smith 2001; Cairns 2000; Draper 1995).

Climate can be a reflection of initial condition uncertainties (ICUs). Thus ruling the twenty-first century climate is conditioned on a particular model, determining ICU is essential for analysis and interpretations of climate forecasts (Grimm et al. 2006; Kay et al. 2009). The ICUs and model imperfections together are an intrinsic part of a climate forecast which should be taken into consideration (Stainforth et al. 2005; Wu et al. 2005).

Interpretation is an intricate process due to the extrapolating nature of the five distinct sources of uncertainty. Greenhouse gas scenario simulations related to CO_2 levels have no precise observations. Thus, forecasting is closer to interpolation because there is no corresponding archive for climate although there is an archive of forecasts and corresponding observations which assist to determine systematic inadequacies and to move back and forth between the state of the atmosphere and model states (Solomon et al. 2009; Davis et al. 2010; Schlesinger and Mitchell 1987).

5 Evolution of Energy Decision Systems

Future climate predictions are reliable for forecast periods up to a week. They are anticipated by using a variety of sources of data measurements as ground-based stations, ships, ocean buoys, aircraft, balloons, and satellites which are all based on complex computer models (Palmer et al. 2008; Kharin and Zwiers 2002; Hartmann et al. 2002; Räisänen and Palmer 2001).

The reanalysis approach utilizes computer models. It has the distinctive feature of anticipating the answer based on the historical record. It also refines the data input to the simulation procedure. The reanalysis simulation integrates the historical data by being updated every 6 hours. The reanalysis approach then introduces the best possible record of past changes in the feature of the atmosphere (Edwards 2001; Gibelin and Déqué 2003).

The capacity factor (CF) is a measure of the fraction of the rated potential of a specific power-generating facility that the facility is able to realize over a representative operational year (Lu et al. 2009).

In environments where wind conditions are not adequate to meet the limit, restricting the analysis to CF values in excess of 20% deduces that locating expensive wind turbines would make little economic sense (Shata and Hanitsch 2008).

Mostafaeipour and Mostafaeipour (2009) demonstrated the presence of different sources of renewable energies in the Middle East as well as in Iran as they analyzed the renewable energy issues and electricity production in the Middle East compared with Iran. It can be stated that developing a more sustainable energy sector in the Middle East is likely to be propitious for the near future. Sadorsky (2011) reported a number of important relationships between income, energy, and trade as he studied the dynamic relationship between energy and trade openness for a panel of eight Middle Eastern countries. The panel data set was worth studying as countries in the Middle East are considered among the most rapid growing consumers of energy.

Regarding Iraq, Kazem (Kazem and Chaichan 2012) reported that Iraq has good potential for developing renewable energy. He assessed the status and future of renewable energy in Iraq. He recommended utilization of renewable energy sources, such as solar, wind, and biomass. Alamdari et al. (2012) assess the wind energy in Iran by studying many sites. This work was an initial assessment for installing the wind farms. In addition, they utilized data from 63 stations across Iran to investigate the potential sites for exploiting solar energy. For each station, the values for maximum, minimum, and average annual horizontal radiation were obtained. They concluded that the recorded annual average values of horizontal radiation at some stations were higher than 500 W/m^2, showing their ability for photovoltaic applications which suggests for further study (Alamdari et al. 2013). Van der Zwaan et al. (2013) assessed potential for renewable energy jobs in the Middle East. He estimated renewable diffusion scenario for the Middle East jobs. He postulated a total required local work force of ultimately about 155,000 direct and 115,000 indirect jobs. This was based on assumptions regarding which components of the respective wind and solar energy technologies can be manufactured in the region itself. All jobs generated are assumed to be domestic. Shawon et al. (2013) found that the energetic and economic evaluation of different locations in the Middle East region can be illustrated as prospective areas for regions 1 and 2 and below marginal areas for region 3 in terms of both wind potential and economy. They assessed harnessing the available wind in Middle East region with a detailed analysis on the economics behind extending wind energy conversion technologies. The assessment was done by using wind energy potential and existing wind energy conversion technology.

Generally speaking, understanding how individuals make decisions is important for researchers and intervention designers concerned with the impact of human behavior on energy use and the environment.

6 Assessment of Energy Decision Systems

The greenhouse gas emissions' geophysical consequences such as global warming and global hydrological cycle attendant changes in addition to climate change socioeconomic dimensions such as policy assumptions' consequences on economic and energy systems are largely addressed by global climate and integrated assessment models (Lashof and Ahuja 1990) (Meinshausen et al. 2009; Shine et al. 2005).

Limited numbers of experiments have been made at regional scales for combination of different human and natural systems in a single integrated modeling framework. Thus, the models are limited in their ability to resolve some of regional feedbacks and interactions (Eckaus 1992).

Hibbard and Janetos (2013) described a general framework for integrated regional modeling involving a suite of component models that represent multiple human and natural systems, guide model improvement, and ensure relevant regional decisions results. This framework can overcome the problem that understanding and evaluating multiple human and natural systems at regional scales requires more integrated approach with the ability to capture the complex dynamics and feedbacks among regional systems and also retaining consistency of global processes and conditions. Thus, this framework allows better robust assessments of regional vulnerabilities and climate mitigation and accommodation options in particular those that include energy, land, and water systems, because they have complicated and unpredicted interaction ways as a response to climate change (Skaggs and Rice 2012; Skaggs et al. 2012).

Generating and linking open-source models of human and natural systems at scales relevant to regional decision-making was the aim of the Platform for Regional Integrated Modeling and Analysis (PRIMA) at Pacific Northwest National Laboratory (PNNL). PRIMA is an exclusive and powerful framework assigned to evaluate the responses to climate change and its effects at regional scales. The development of new models was needed in a number of cases, while in other cases it was enough to build on existing community models (Kraucunas et al. 2015).

Making of choices is often based on conflicted criteria in the decisional process. The aims of multi-criteria decision-making methods (MDMM) are headed for utilizing indicative data and evaluation procedures, assisting decision-makers to be compatible with fixed objectives and achieving decisional processes. Many external factors should be involved in the decision process. Some of these factors can be assessed by numerical models, while other factors are evaluated only with subjective judgment or in a qualitative way (Eom 1989; Beinat 1997).

Locals have control on elements and energy systems to provide comfort to the users by a minimum amount of energy demand. This was based on the philosophy of reaching efficient energy and natural spaces by passive ways with low cost and using the possible resources. Using passive, low-energy strategies to provide for users' comfort is challenging (Soares et al. 2013; Chu and Majumdar 2012).

Sustainable strategy must begin with perceiving of vernacular timeless trial and error, in spite of the fact of the possibilities introduced by the simulation tools in energy area (Dincer 2000).

7 Modeling, Analysis, and Discussion

Decision-making for climate change policy has been considered as a major debate within the Intergovernmental Panel on Climate Change (IPCC). It faces a significant range of scientific and socioeconomic uncertainties. Experts characterized accurately such uncertainties and developed 40 scenarios of the twenty-first century anthropogenic greenhouse gas emissions for the IPCC's Third Assessment Report (Houghton et al. 2001). These scenarios were generated by the Special Report on Emissions Scenarios (SRES) (Nakicenovic et al. 2000a) by inducing many assumptions on the key driving force values and by utilizing variable computer models (Change 1995; Change 2015).

The SRES utilized the full range of scenarios to ideally characterize the associated uncertainties as they found that it is not applicable to confirm likelihood to any of the emissions scenarios. On the other hand, the IPCC contributors generated a process to characterize uncertainties with probability distributions that represent the consensus of the scientific community (Giles 2002) and guide the Fourth Assessment Report. Well-defined probabilities are contingent to good decisions under uncertainty; thus, decision-makers will create their own politically motivated estimates of likelihood.

Probability-based estimates can have major constrictions when applied to a problem as climate change although they are considered powerful risk management tool. Thus, to avoid this problem, the IPCC should take into consideration variable decision-making approaches when there are uncertainty conditions that don't depend on probability expert consensus (Nakicenovic et al. 2000c; Moss et al. 2010).

Reducing vulnerabilities across a wide range of scenarios was done by developing quantitative methods that assess robust strategies (Metz et al. 2001). A quantitative representation of structural uncertainty has been developed by Ben-Haim (2001). This representation can be utilized to characterize the extent of model uncertainty against which a proposed strategy is robust. Scenario-based modeling was utilized by Rotmans and van Asselt (Van Asselt 2000) to characterize the futures in which alternative management styles will implement incompetently.

New ways to characterize scientific and socioeconomic uncertainties for climate change decision-makers have been offered. This was done by introducing advances in computer capabilities and achieving understanding of decision-making processes that enabled generation of frameworks. Implementation of these novel approaches may need some changes in the process (Lempert et al. 2004; Shackley and Wynne 1996; Creutzig et al. 2018).

It is important when addressing environmental issues, where different national and local interests are affected, to make the decision support frameworks flexible enough to adapt variability in institutional settings, culturally motivated, decision-making styles, and indigenous capabilities.

8 Conclusion

The energy development is a measure of power and development level in the future. Since fossil fuels are running out, countries bring renewable energies into dominant act by using the remaining fossil fuel infrastructure development. In general, the energy resources in the world are divided into renewable and nonrenewable energy resources, while nonrenewable energy is not infinite.

Egypt geographical location in the Middle East is close to the equator, and Nord Stream provides it with a distinctive feature for using new and renewable energy sources such as solar and wind power. Independence of oil in economics of countries is very essential in the approach of the development of renewable energy. Thus, the developing countries in this region have the ability to develop renewable energy infrastructure for future self-independency on energy demand.

Given the combination of an uncertain outlook, negative environmental effects, and the potential for a significant drop in nonrenewable energy sources reserves, climate change has become an evident concern in discussions among experts and decision-makers working in Egypt.

Yet climate change is not the only factor that will shape energy availability in Egypt in the coming years.

Influence of anthropogenic climate change drives us to think about the interactions of natural and human agency in forging environmental outcomes. Not only anthropogenic climate change can comprise physical dynamics of atmosphere interaction but also societal drivers of atmospheric composition.

Considering how a range of actors, including scientists, government officials, and international experts, understand the future of a climate-linked resources and that there is no single solution to adapt and mitigate climate to solve energy problems due to different geographical conditions, characteristics, etc., each country has to consider its own climate and resources to specify what is most suitable to accomplish the best results.

Such solutions should portray past and current state of research as well as highlight existing gaps in the literature and consequently identify those areas of research that need to be considered in the future by policy-makers in order to create their own motivated estimates of likelihood.

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Chapter 5
Control Strategy and Impact of Meshed DC Micro-grid in the Middle East

Mohamed Barara, Hervé Morel, Guy Clerc, Mustapha Jamma, Pascal Bevilacqua, and Abderrahime Zaoui

Abstract Installation of micro-grid provides as viable solution to the problem of energy efficiency and environmental in the world; this is especially true for countries in the Middle East which have an abundance of natural sunlight. Recently, DC micro-grids have been a focus of numerous researches, and some industrial deployments are starting (Shenai et al. IEEE Power Electron. Mag. 3:42–48, 2016). The interest is due to several advantages in comparison to AC micro-grids in terms of efficiency, minimum number of devices, no need for frequency/phase control, modularity, and reliability. Moreover, it enables an easy integration of renewable energy resources, particularly photovoltaic ones. This study targets meshed DC micro-grid while most of literature papers concern radial DC micro-grids. It will bring several remarkable benefits: redundancy, better utilization of installed converters, flexible configuration, enhanced system reliability, and availability especially in case of line faults (Chen et al. IEEE Trans. Power Deliv. 31:1719-1727, 2016). In meshed DC grids, the control strategy of current or power becomes a critical issue particularly if a modular and generic solution is researched. The study focuses on the use of smart nodes controlling the power flow in the grid. The proposed control strategy is modeled and the simulation results are presented. A reduce scale tests based on DSPACE DS1103 have been provided to validate experimentally the proposed control scheme.

Keywords DC Micro-grids · Smart nodes · Renewable energy sources · Middle East · split-PI converter · DSPACE DS1103

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H. Qudrat-Ullah, A. A. Kayal (eds.), *Climate Change and Energy Dynamics in the Middle East*, Understanding Complex Systems,
https://doi.org/10.1007/978-3-030-11202-8_5

1 Introduction

Natural energy flows (sun or heat,…) represent a large potential of renewable energy sources in the Middle East, in particular solar power. According to report by the electrical department at King Saud University, the Middle East receives 3000–3500 hours of sunshine per year, with more 5 KW/m of solar energy per day that are expected to play a considerable role of source of DC micro-grid.

Micro-grids are defined as small-scale grids that generate and deliver electricity to a defined geographic area, such as a building, a district, or an isolated location. They can be operated in islanded or grid-connected mode. Micro-grid architectures can be classified into AC or DC bus interconnections, as shown in Fig. 5.1, that is a kind of power grid area which is a combination of different kinds of power units which are usually based on renewable energy sources (Lu et al. 2011).

In an AC micro-grid, synchronization of all AC generators and output of the power converters of the DC sources and energy stores is necessary. Furthermore, due to the nonlinear characteristics of power electronics converters, power factor correction and topologies with sophisticated control strategy for harmonic distortion reduction are needed to improve the power quality of the AC bus (Oday 2011). The DC micro-grids have advantages over conventional AC micro-grids in the utilization of green power sources, since they can interface with DC systems more easily than AC systems, using simple power electronics. DC micro-grids present various advantages such as a better efficiency, no need for frequency/phase control, and higher reliability (Rey-López et al. 2015). Moreover most of the modern loads like computers, LED lighting, and electric vehicles work on DC power.

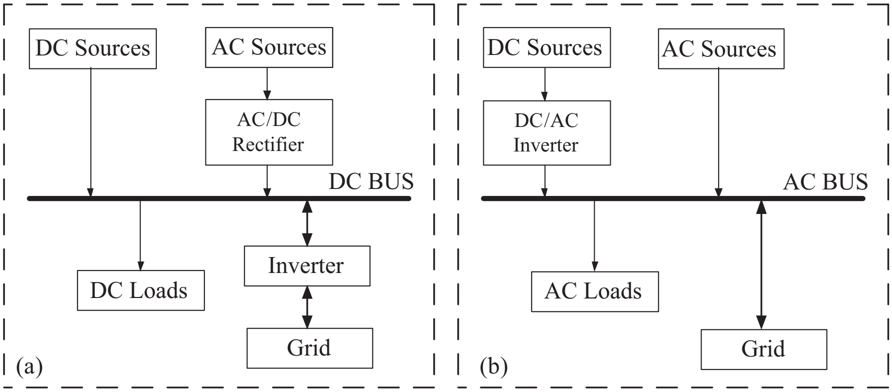


Fig. 5.1 Micro-grid topology. (**a**) Basic structure of DC micro-grid, (**b**) basic structure of AC micro-grid

1.1 DC Micro-grid System Configuration

A home power system can be divided into three parts: sources, distribution, and loads. Various power converters are usually required to adjust generator and load voltages to the DC bus voltage.

The radial structure of DC micro-grid is shown in Fig. 5.2. Renewable energy module is firstly used to provide the energy to the grid for the energy storage module or for the load module (Liu et al. 2010). Then, if the demand energy is not enough from the renewable energy module, the AC power supply will distribute the energy to the DC micro-grid by the bidirectional AC/DC converter. In addition, if the AC power supply is absent due to any unexpected case, the DC diesel generation system will serve as the standby energy module to offer the energy for the grid. Finally, the DC power will flow to the output load module, which includes three types of loads.

1.2 Standards and Research

Global architecture standards required for widespread implementation of 400 V DC are well under way. Micro-grids are being studied by a number of instances, as part of the smart grid research programs. DC micro-grids are an emerging option as a result of these programs. Examples of such emerging standards are (Rycroft 2014):

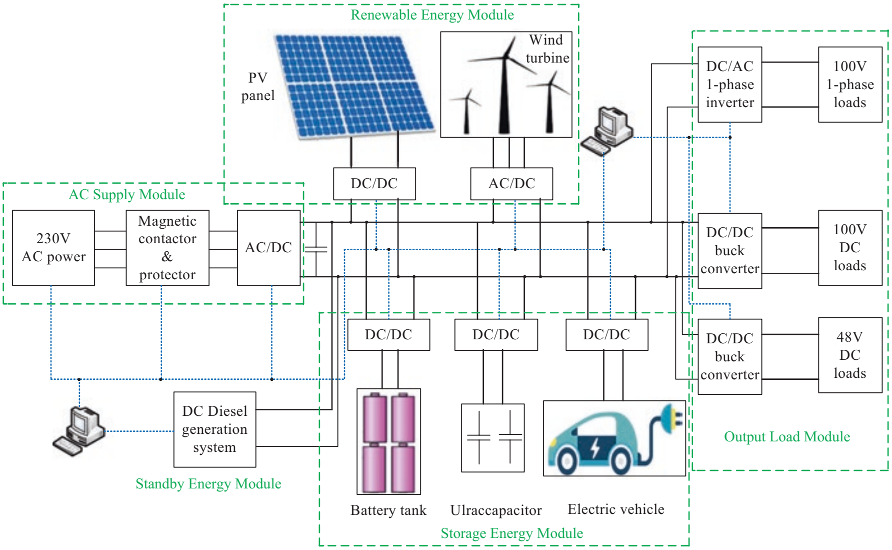


Fig. 5.2 Radial structure of DC micro-grid

- Emerge Alliance: An industry association in conjunction with the EPRI task force is working on a 380 V DC standard to cover telecom and building distribution.
- The European Telecommunications Standards Institute (ETSI) standard: 400 V DC distribution for telecommunications equipment, (ETSI) EN 300132-3-1, released in February 2012. This is primarily intended for use in the telecommunications industry but contains several useful sections which can be transferred to other sectors.
- IEC: SG4 is working on a standard for LVDC distribution with a nominal voltage of 400 V but covering systems up to 1500 V.

Distribution generators in DC micro-grid are connected to a common DC bus using power electronic converters; the common DC voltage must be well maintained with a limited variation band. Ferreira et al. 2012 present a performance study of a DC micro-grid when it is used as a voltage-droop technique to regulate the grid voltage and to control the load sharing between different sources. The control strategies presented in Jin et al. (2014) and Guerrero et al. (2011) consist of a hierarchical control strategy based of three levels of control: Primary control to ensure proper load sharing among the distributed generators, secondary control level to regulate the voltage deviations, and tertiary control level regulate the flow of power between the grid and micro-grid (Liu et al. 2010). So far, various studies have been carried out on radial micro-grid, while very limited research has been done in meshed DC micro-grid. However, it will bring several remarkable benefits: redundancy, better utilization of installed converters, flexible configuration, enhanced system reliability, and availability especially in case of line faults (Chen et al. 2016). Another advantage of meshed DC micro-grid is the ability to reduce the total wire length by minimizing the distance between a load and a grid node, particularly for high power line, that may reduce the global cost of the grid and reduce the needed mass of copper for the same operation.

In meshed DC grids, the control strategy of current or power becomes a critical issue particularly if a modular and generic solution is researched. There are several control strategies for meshed MTDC grids that have been investigated in the literature and will be helpful for the application of meshed DC micro-grid. In a point-to-point link, one converter controls the voltage of the line, and the other one controls the current by a method like the voltage margin method (Nakajima and Irokawa 1999). In a multiterminal DC grid, it is very important to control the power flow by control-flow converters like split-PI converters. A DC current flow controller for meshed modular multilevel converter multiterminal HVDC grids has been designed and demonstrated in Deng et al. (2015). Chen et al. (2016) proposed a novel interline DC power flow controller for meshed HVDC Grids for achieving stable power flow control in different conditions. In Yao et al. (2016), the authors present a DC power flow controller based on dual active bridge (DAB) topology and its control strategy in the DC grid is also presented. Concretely, in this study, a topology of meshed DC micro-grid with a suitable and efficiency control scheme of bidirectional DC/DC converter is presented. The proposed control strategy plays an essential role to control the power flow in DC meshed micro-grid.

2 Targeted Mock-up

In the framework of the ANR project C3µ and the GD3E/CPER project, a mock-up with 20 kW DC/DC converters is under construction (Fig. 5.3). In this mock-up a 20 kW PV panel and a 20 kW electric vehicle plug-in will be emulated. The connection to the AC-grid will be emulated too. The mock-up includes two branches in order to analyze meshed DC micro-grid behavior. In practice, the two branches enable a power flow controlled by a smart node from the PV panel toward the EC plug-in. The system configuration of the targeted mock-up is depicted in Fig. 5.3. Our project deals with meshed DC micro-grids which have the benefit of a simple control, redundancy, and an automatic reconfiguration of the micro-grid (in case of faults or with extensions of the grid). The project focuses on the use of smart nodes to achieve flexible power flow control for the grid. Other tasks will be developed at the end of the project such as consumption measure, transmission, and data processing for exchange between the smart plug and the smart nodes and the centralized supervision even with a decentralized supervision system.

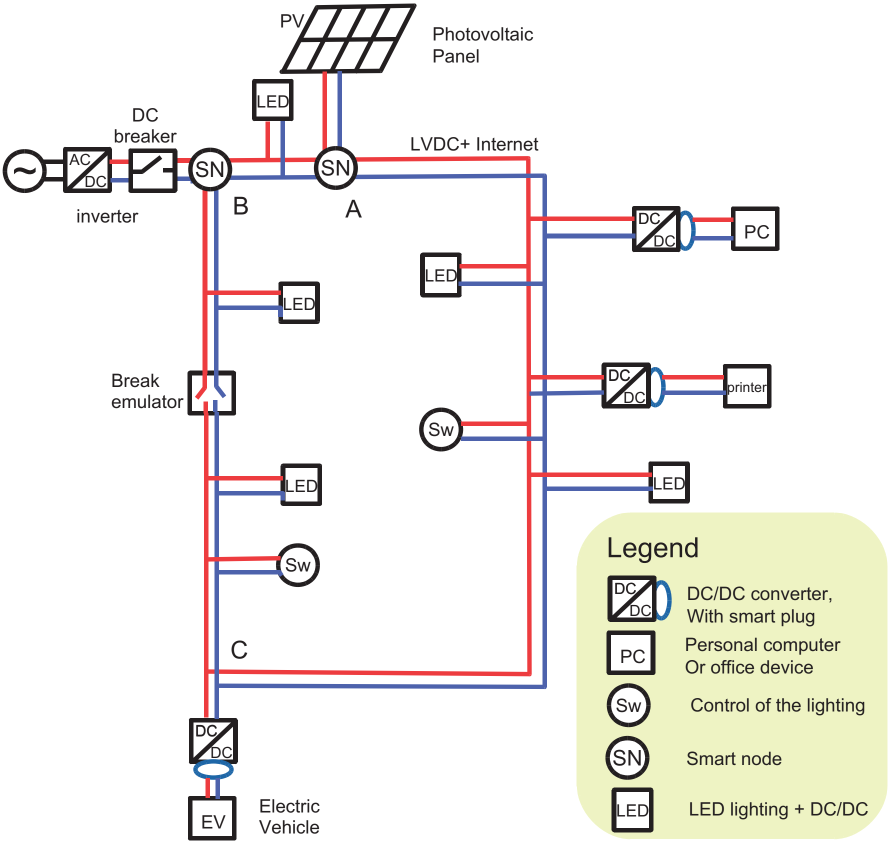


Fig. 5.3 Principle scheme of the targeted mock-up

3 Smart Node

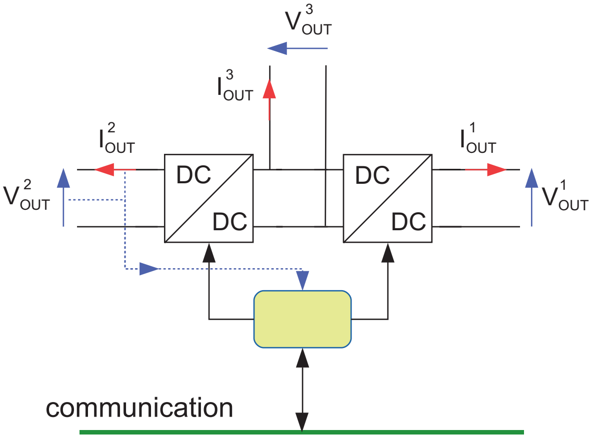
A smart node consists of three power lines with two lines connected via a bidirectional DC/DC converter as shown in Fig. 5.4. Each converter is driven by a controller for generating PWM signals. A communication layer (as Ethernet) enables to communicate with decentralized supervision system for all required data such as the output voltages and currents. Another target of the project is to used carrier current technology on the power line to enable the communication layer. The main objective of a smart node is to control the power flow in the meshed micro-grid. Another role of the smart node is to operate as a DC breaker.

So, the protection strategy will be based on smart node with DC breaking capability. Consequently, each source in the grid must be connected to the meshed DC micro-grid via a smart node (Fig. 5.3). DC breaking capability is the target of an additional PhD study (Ma et al. 2017).

4 Proposed Control Strategy at a Converter Level

In a point-to-point link, one converter controls the voltage of the line, and the other one controls the current by a method like the voltage margin method (Ferreira et al. 2012). In a multiterminal DC grid, MTDC, the issue becomes further complex, and numerous papers proposed control scheme based on the droop control method (Ferreira et al. 2012; Haileselassie and Uhlen 2012; Hu and Weaver 2016). The latter case has some drawbacks as the use of virtual impedance, and our target is to apply a common control strategy to all the converters of the grid. The case of a meshed DC micro-grid is quite different because power flow converters are inserted in the lines to control the power flow, such as split-PI converters (Natori et al. 2014). However, in a general meshed DC grid, some converters must control the voltage,

Fig. 5.4 Smart node configuration



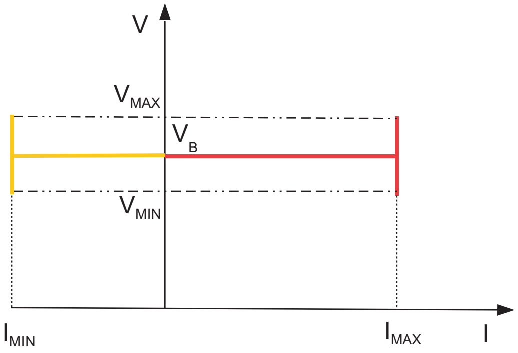


Fig. 5.5 Proposed steady-state control strategy for each output side of smart node converter. The controller may be set for a positive (in red) or a negative power (in yellow)

and other ones control the line current. So, a straightforward question is: Which value of voltage has to be applied when the voltage is controlled?

Since a modular solution is targeted with no need of complex controller settings, our proposal is to apply the unique bus voltage in such a case. In our targeted mock-up, the reference bus voltage is selected to = 400 V. In the case where the line current has to be controlled, a steady-state strategy inspired from the voltage margin method is applied as shown in Fig. 5.5.

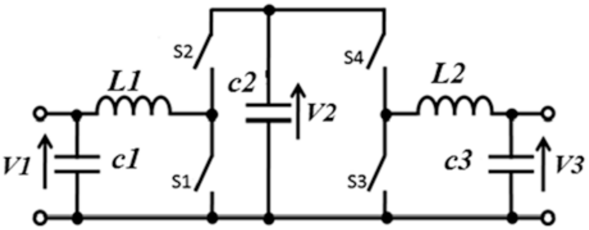
5 Bidirectional Buck-Boost Converter

Generally the bidirectional DC-DC converters are used in applications where bidirectional power flow may be necessary. The principal operation of this converter can be used to operate in both the buck and boost modes with bidirectional power control (Park et al. 2013). It could play a significant role in the future power management in DC meshed micro-grid. We focus in this study to control this type of power converter in order to realize power distribution between energy generation systems and loads systems. Number of topologies are proposed with different control strategies that have been reported in literature to transfer the power from one source to another (Phattanasak et al. 2011; Rathore et al. 2016). Bidirectional DC/DC converter can be classified into isolated and non-isolated; the non-isolated converter has more advantage of lower magnetic bulk, higher efficiency, and compactness.

5.1 Split-PI Converter

The split-PI converter topology (Fig. 5.6) allows bidirectional flow of power. In typical operation, the voltage is applied at the left-hand bridge and operates as a boost converter, and the right-hand bridge operates as a buck converter. When the

Fig. 5.6 Split-PI converter



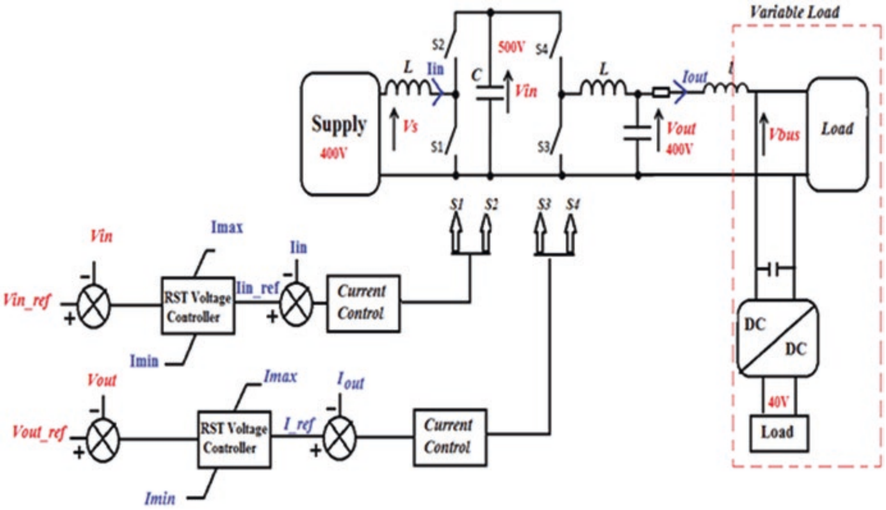


Fig. 5.7 Proposed control scheme for split-PI converter. Test configuration with a voltage source at the input and a variable load at the output

voltage is applied at the right-hand bridge, the reverse can be achieved (Singhai et al. 2014). The advantage of this converter is to reduce switching noise, since both ends of the converter are shielded by a capacitor and inductor resulting in triangular current wave forms, which contain fewer harmonics (Maclaurin et al. 2011; Khan et al. 2014). And it is simpler to design, implement, and control.

5.2 Control Scheme for Split PI

Dual loop control layer is implemented to control current and voltage settings as shown in Fig. 5.7.

The control mechanism of the proposed bidirectional DC-DC converter is shown in Fig. 5.7. It consists of two separate RST voltage controllers in cascades with currents controllers, which are used to regulate the intermediate voltage (boost) and the output voltage (buck) with a maximal and minimal pre-defined current. This configuration can handle reference changes in both the intermediate stage and load side.

6 Results and Discussions

6.1 *First Simulation Result*

A practical control scheme has been defined as shown in Fig. 5.7. It has been tested in several configurations. The first one, presented in Fig. 5.7, corresponds to the case where the DC/DC converter is supplied by an ideal source in the input side and a variable load at the output side. This control has two operation modes: a voltage-mode control and current-mode control. Simulation results obtained using Matlab/Simulink are shown to validate the proposed controller performance. The parameters of the bidirectional DC-DC converter used in this study are listed in Table 5.1.

Load cases are used as described below:

Case A: 0 s < t < 1 s

The load current is lower than Imax (Iout < Imax). The controller operates in a voltage-mode control, Vout = Vbus.

Case B: 1 s < t < 2 s

The load current may be higher than Imax (Iout > Imax). The controller operates in a current-mode control, Iout = Imax.

Case C: 2 s < t < 3 s

The load current is lower than Imax (Iout < Imax). The controller returns to work as voltage-mode control, Vout = Vbus.

As observed in Figs. 5.8 and 5.9, the controller keeps the voltage at a fixed value of Vout = Vbus = 400 V (point A) because the output current is lower than the maximal current Imax = 45 A as defined by the dispatching level. The observed oscillations are related to the high value of the line inductance of the targeted mock-up. After increasing the power of the load, the controller keeps the output current at fixed value of 45 A and the output voltage drop (point B). Finally, the control returns to voltage regulation, when the power of the load decreases and doesn’t exceed Imax (point C), while in all cases the intermediate voltage is always maintained at a constant value of 500 V.

Table 5.1 Specification of bidirectional DC/DC converter

Symbol	Parameter	Value
C	Capacitance	3300 µF
L	Inductance	450 µH
V	Voltage	500 V
A	Current	75A

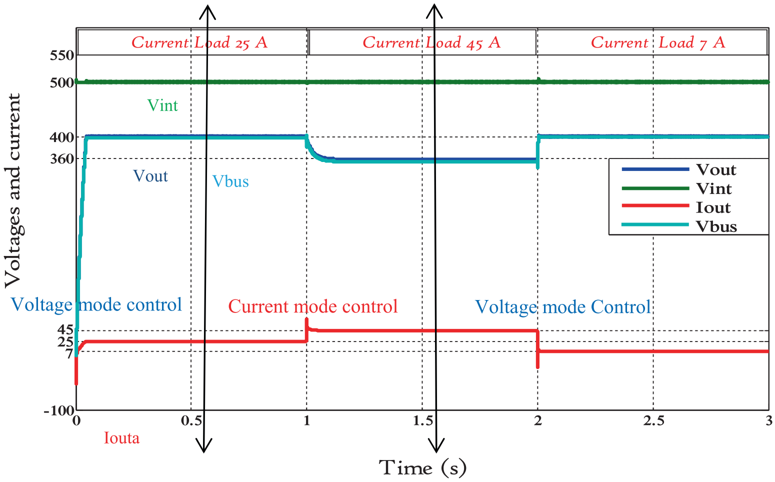


Fig. 5.8 Transient waveforms at sudden change in load (see Fig. 5.4), intermediate voltage, output voltage, output current, and DC bus voltage

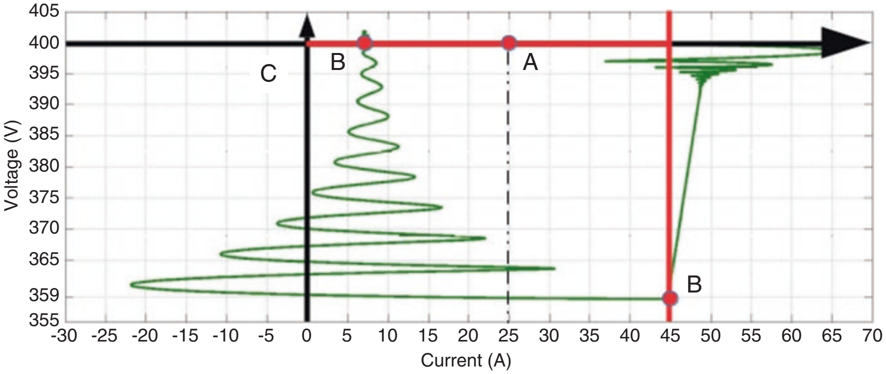


Fig. 5.9 Simulation results of voltage (Vout) and current (Iout) for different operation conditions

6.2 *Experimental Results*

A prototype split-PI converter has been built with a reduced power scale in order to validate our proposed control scheme. A DSPACE DS1103 is used to generate PWM states signals for the converter. The references voltages and limited currents are given by the control desk. The experimental setup is shown in Fig. 5.10. The system parameters used in simulation and experimentation are listed in Table 5.2.

Simulation and experiments are achieved with the same parameters. Figures 5.11, 5.12, 5.13, and 5.14 show the effect of a sudden variation of the load with limited current fixed at 0.7 A.

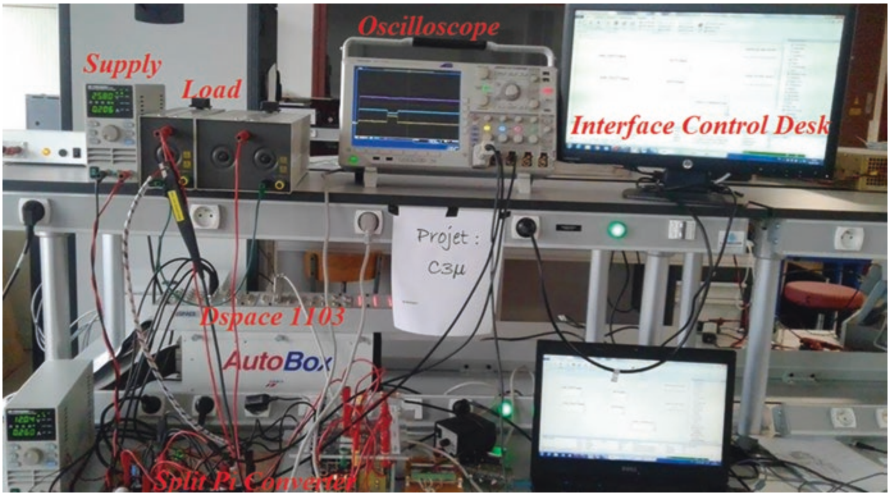


Fig. 5.10 Hardware used in experimental evaluation

Table 5.2 Simulation and experimental system parameters

Symbol	Parameter	Value
C	Capacitance	780 μF
L	Inductance	2.2mF
R	Load	102.6 and 25.4 Ohm
A	Maximal current	0.75 A

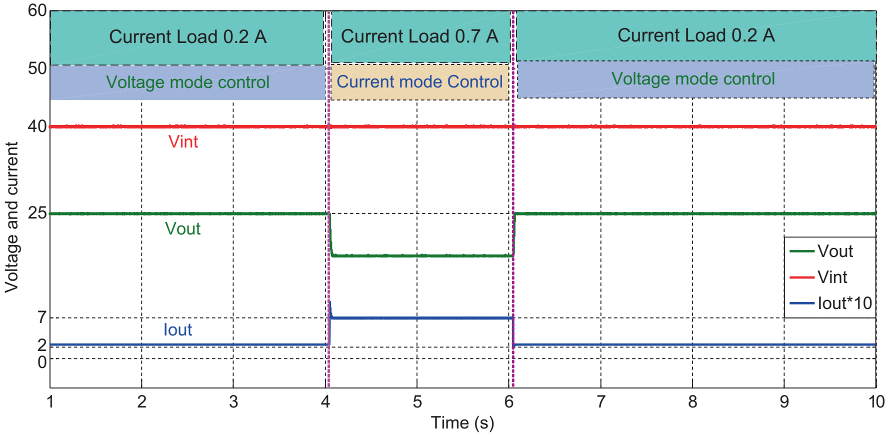


Fig. 5.11 Simulation results transient waveforms at sudden change in load, intermediate voltage (Vint), output voltage, and output current (Iout)

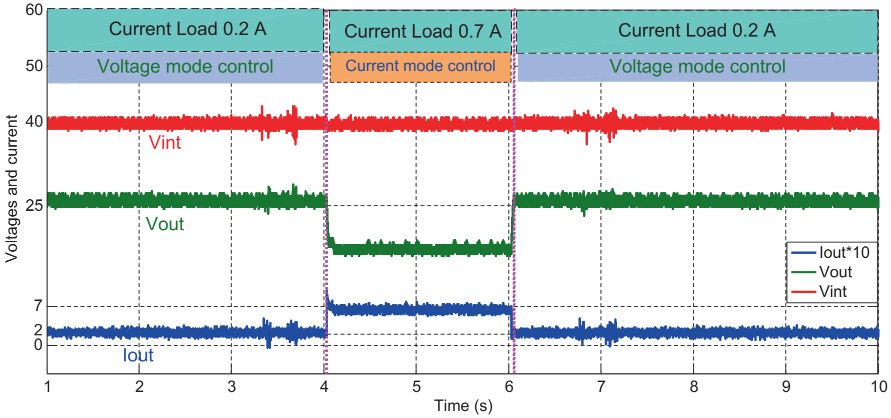


Fig. 5.12 Experimental results transient waveforms at a sudden change of load, intermediate voltage (Vint), output voltage, and output current (Iout)

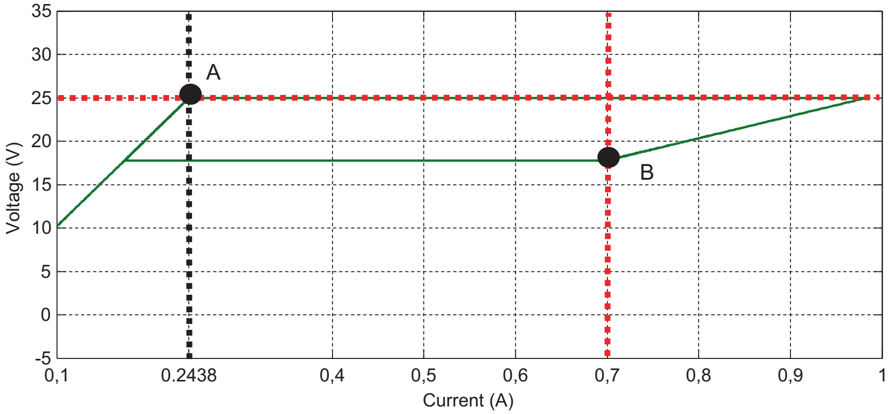


Fig. 5.13 Simulation results of voltage (Vout) and current (Iout) for different operations conditions

As it can be seen in Figs. 5.11 and 5.13, the measured results of the control present a good agreement with the simulation results in Figs. 5.12 and 5.14. It is observed that the output voltage (Vout) is regulated at a fixed value as given in reference (Vref_out = 25 V), because output current is lower than the maximal current defined by the control desk (Imax = 0.7 A). After increasing the power of the load, the controller keeps the output current at a fixed value of 0.7 A and the output voltage drop. Finally, the control returns to voltage regulation when the load decreases and doesn't exceed Imax, while in all cases the intermediate voltage is always maintained at a constant value of 40 V. It can be easily found that the proposed control can achieve much higher efficiency.

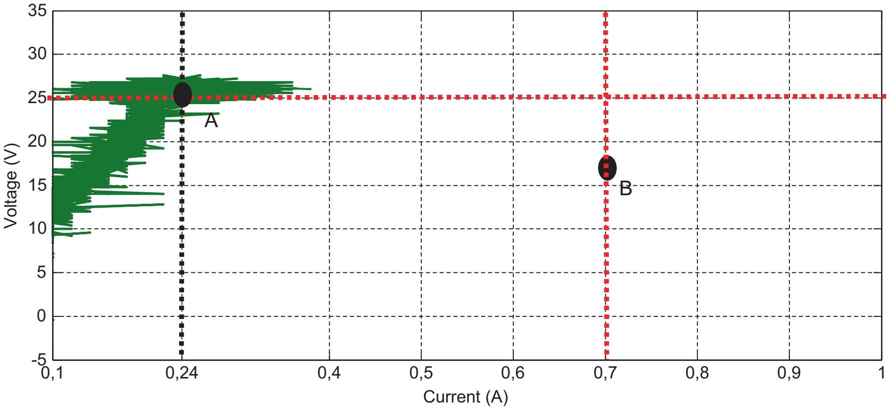


Fig. 5.14 Experimental results voltage (Vout) and current (Iout) for different operations conditions

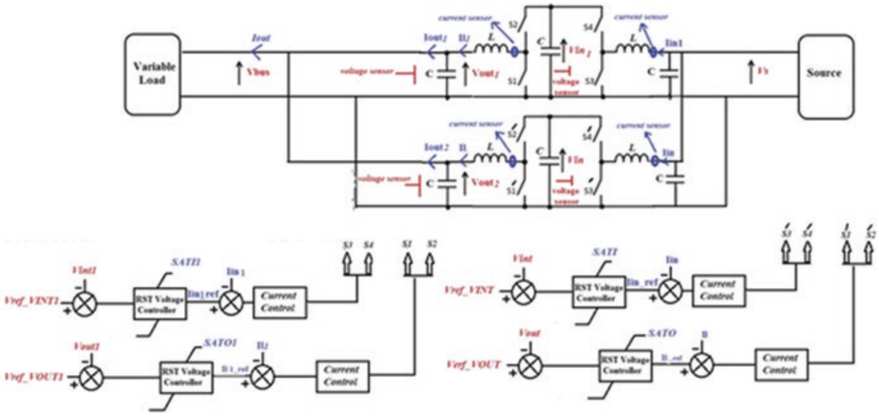


Fig. 5.15 Proposed control scheme for smart node

6.3 Experimental Results of Smart Node

A test configuration with a voltage source at the input and a variable load at the output is done in using the proposed control scheme for smart node as shown in Fig. 5.15.

A prototype of two split-pi converter has been built with a reduced power scale in order to validate our proposed control scheme. A DSPACE DS1103 is used to generate PWM states signals for the converters. The references voltages and limited currents are given by the control desk. The experimental test bench is shown in Fig. 5.16.

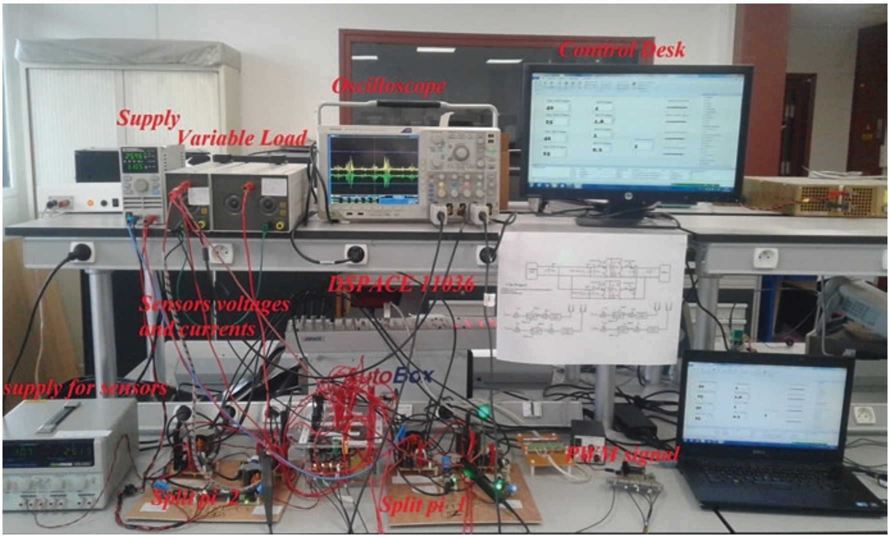


Fig. 5.16 Hardware used in experimental evaluation for smart node

Several test cases have been studied:

(a) Case 1

Converter 1 ensures regulation of DC bus voltage, and converter 2 ensures the regulation of current as depicted in Fig. 5.17:

- The total load current is 0.98 A.
- The reference output voltage for converter 1 and converter 2 is Vref_out1 = vref_out = 25 V.
- The reference intermediate voltage for converter 1 and converter 2 is Vref_vint1 = vref_vint = 40 V.
- The maximal currents of the converters are iout1 = 0.4 A and iout2 = 0.8A (Fig. 5.18).

(b) Case 2

Converter 1 ensures regulation of current and converter 2 ensures the regulation of current:

- The total load current is 0.98 A.
- The reference output voltage for converter 1 and converter 2 is Vref_out1 = vref_out = 25 V.
- The reference intermediate voltage for converter 1 and converter 2 is Vref_vint1 = vref_vint = 40 V.
- The maximal currents of the converters are iout1 = 0.4 A and iout2 = 0.4A (Fig. 5.19).

(c) Case 3

Converter 1 ensures regulation of current and converter 2 ensures the regulation of current:

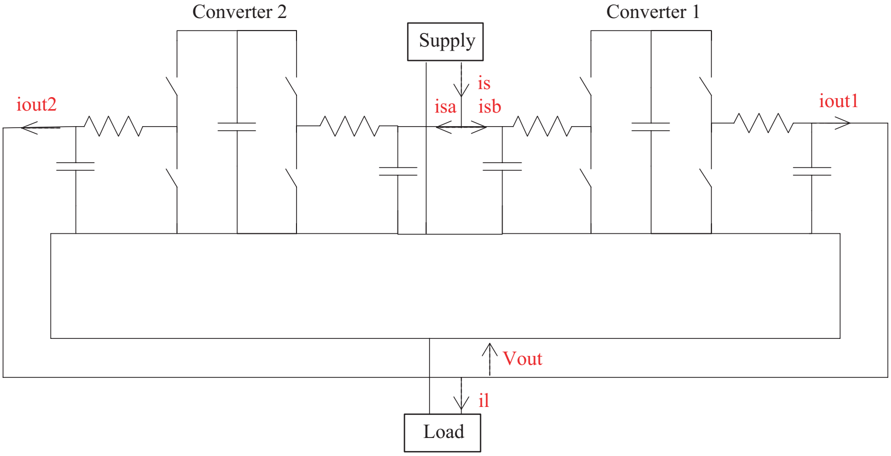


Fig. 5.17 System configuration of case 1, case 2, and case 3

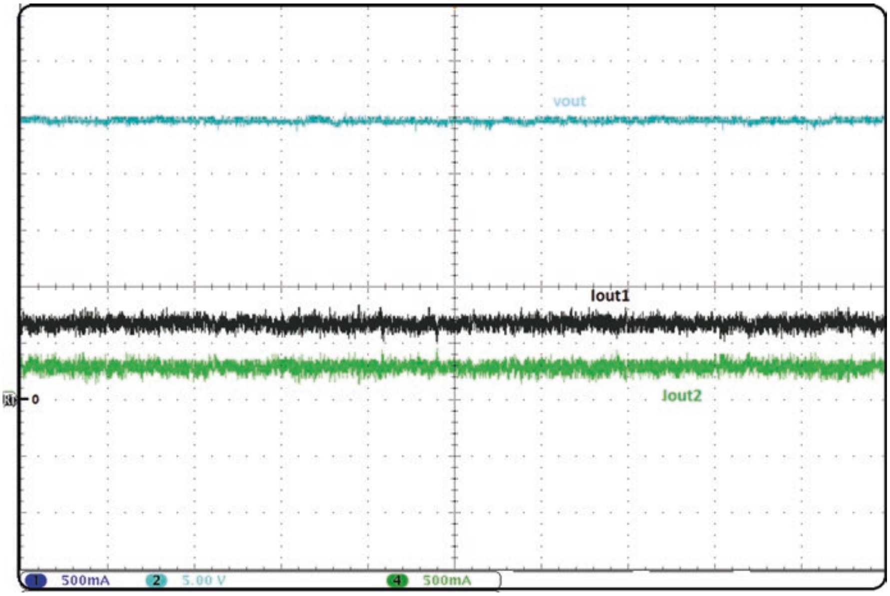


Fig. 5.18 Experimental results waveforms of output voltage (vout), output current of converter1 (iout1), and output current of converter2 (iout2)

- The total load current is 0.24A.
- The reference output voltage for converter 1 and converter 2 is Vref_out1 = 25 V and vref_out = 26 V.
- The reference intermediate voltage for converter 1 and converter 2 is Vref_vint1 = vref_vint = 40 V.

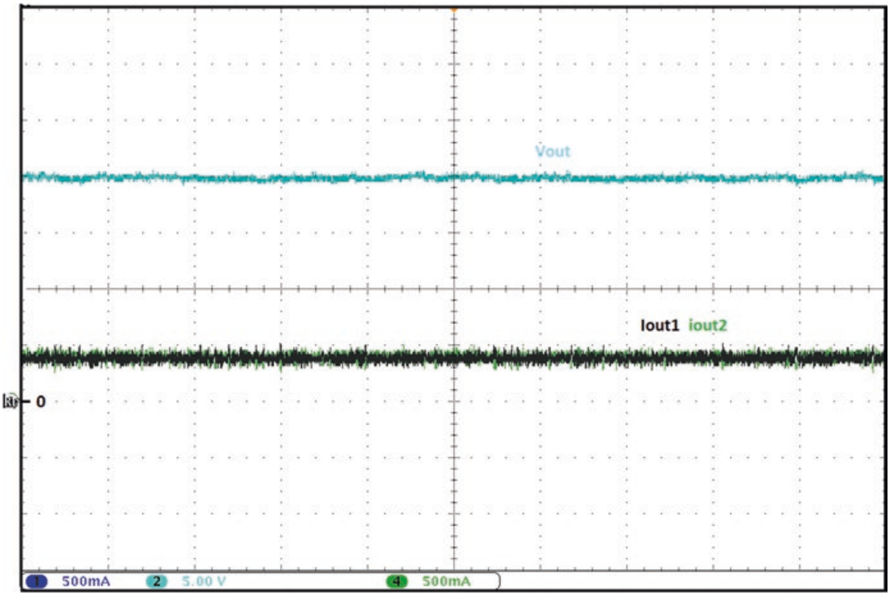


Fig. 5.19 Experimental results waveforms of output voltage (vout), output current of converter1 (iout1), and output current of converter2 (iout2)

- The maximal currents of the converters are iout1 = 1 A and iout2 = 1 (Fig. 5.20).

(d) Case 4

Converter 1 ensures regulation of current and converter 2 ensures the regulation of current as shown in Fig. 5.21:

The total load current is 0.24A.

The reference output voltage for converter 1 and converter 2 is Vref_out1 = 26 V and vref_out = 25 V.

The reference intermediate voltage for converter 1 and converter 2 is Vref_vint1 = vref_vint = 40 V.

The maximal currents of the converters are iout1 = 0.4 A and iout2 = 1 (Fig. 5.22).

As we can see from all cases of experiment test, the controller is well implemented for two bidirectional split-pi converters and effectively tracks to their reference value of voltage or current defined by the decentralized supervision system.

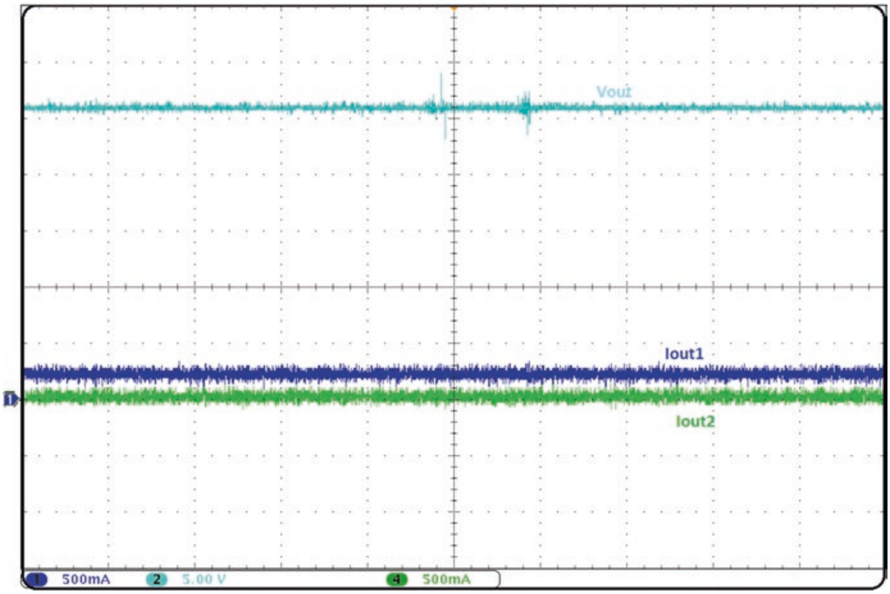


Fig. 5.20 Experimental results waveforms of output voltage (vout), output current of converter1 (iout1), and output current of converter2 (iout2)

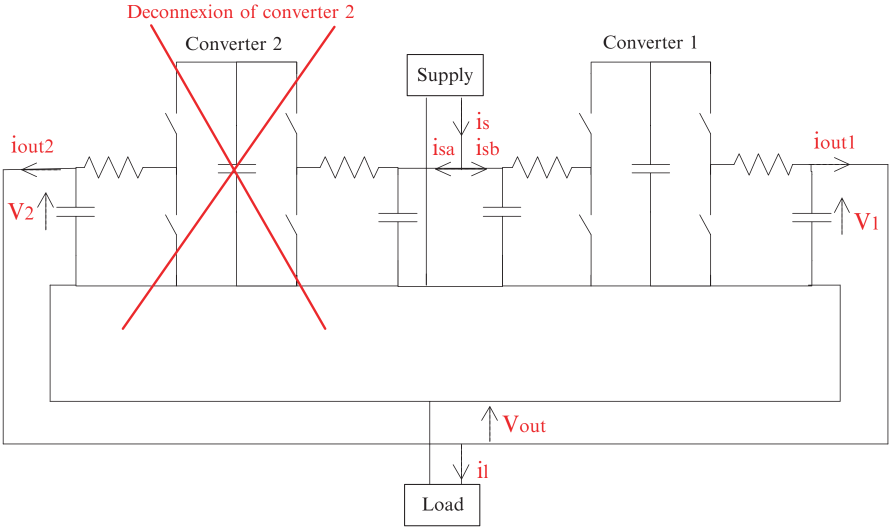


Fig. 5.21 System configuration of case 4

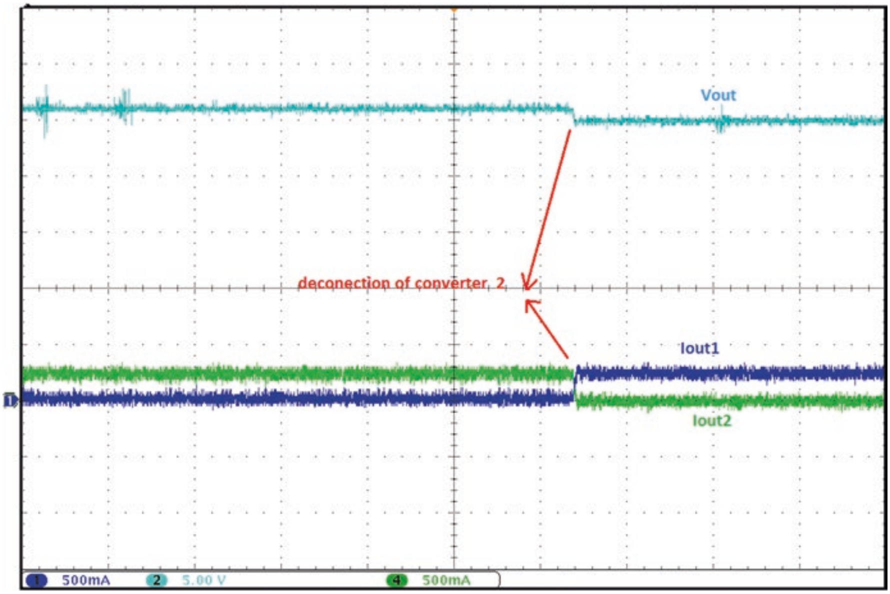


Fig. 5.22 Experimental results waveforms of output voltage (Vout), output current of converter1 (iout1), and output current of converter2 (iout2)

7 Conclusion

The Middle East is in the early stages of smart grid development; this study contributes to renewable energy development in this region, by proposing a novel system operation strategy of DC meshed micro-grid with voltage and current-mode control for the power converter. The simulations test helps to visualize the response from the system and prove the certainty of the proposed algorithm. Experimental test of the power flow in the smart node with DSPACE DS1103 implementation with a reduced power scale using the combined controllers is also presented.

The next step of our work will be the improvement of the regulation of the voltage (V2) between the two split-pi converters of the smart node (Fig. 5.23).

Today this function is realized by a compensating loop which uses the capacitor energy storage within acceptable operating limits in order to improve the voltage regulation of the central node.

In the future, we will try to realize a multi-output multi-input state robust regulation in order to take into account all the output and internal capacitor voltages. All these algorithms will be implemented in the 20 kW converters of our test bench (Fig. 5.24).

We will also increase the size and complexity of our DC network by emulating a photovoltaic injection and a charging terminal.

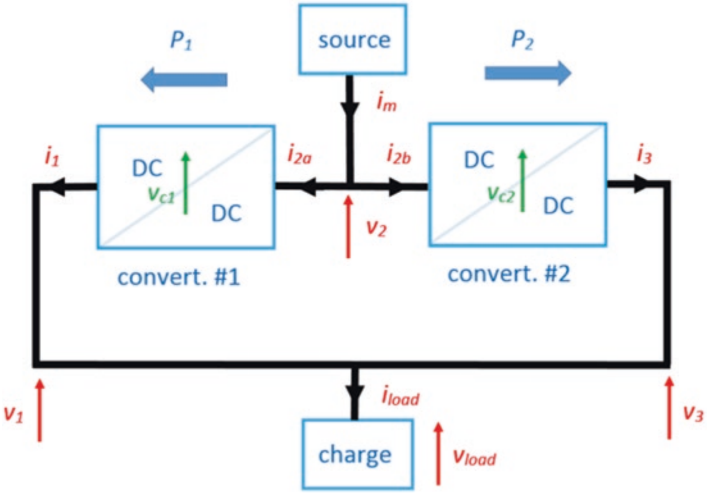
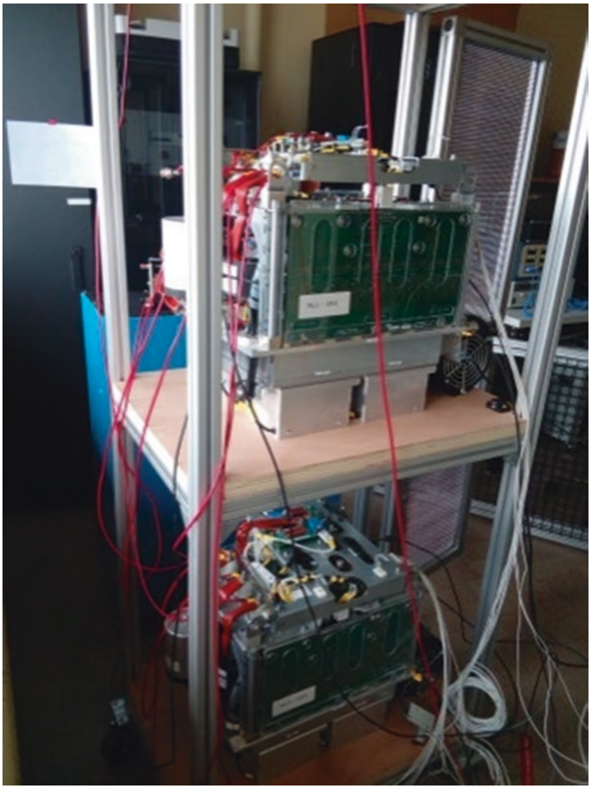


Fig. 5.23 Simplified DC network

Fig. 5.24 20 kW split PI



For the first test, a centralized supervision of the mock-up was applied based on Labview. In the future, we plan to develop a decentralized supervision of the DC meshed grid in the smart node which will be in charge of the energy consumption minimization and the high-level control, such as a user order to switch on LED lighting or some element start and stop.

Acknowledgments The authors would like to thank the ANR project C3μ and the GD3E/CPER for the project funding.

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Chapter 6
The Energy-Water-Health Nexus Under Climate Change in the United Arab Emirates: Impacts and Implications

William W. Dougherty, David N. Yates, Jose Edson Pereira, Andrew Monaghan, Daniel Steinhoff, Bruno Ferrero, Ilana Wainer, Francisco Flores-Lopez, Stephanie Galaitsi, Paul Kucera, and Jane Glavan

Abstract Climate change poses serious energy, water, and health challenges for the United Arab Emirates (UAE). While closely interconnected, the development of sustainable energy, water, and health policies has typically been viewed as independent, sector-specific planning challenges. However, changing demographics, a rapidly growing economy, dependence on desalination, and worsening air quality – all taking place as climate change unfolds – suggest a need for a more integrated approach to risk management. Accounting for the interactions between "energy, water, and health nexus" is one way to ensure that development strategies are considered within a framework that addresses the range of potential trade-offs, risks, and synergies. To address the energy-water-health nexus under a changing climate, research activities were undertaken as part of the Local, National, and Regional Climate Change Programme (LNRCCP) of the Abu Dhabi Global Environmental

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H. Qudrat-Ullah, A. A. Kayal (eds.), *Climate Change and Energy Dynamics in the Middle East*, Understanding Complex Systems,
https://doi.org/10.1007/978-3-030-11202-8_6

Data Initiative (AGEDI). Climate change modeling at the regional spatial scale (Arabian Peninsula; Arabian Gulf) was first carried out to establish the atmospheric and marine physical conditions that will underlie energy, water, and health challenges in the future. The results of this modeling were then used as inputs to an analysis of policies that account for linkages across the energy-water nexus on the one hand and the energy-health nexus on the other. The modeling results show that climate change will render an extreme hyper-arid climate even more so, while the waters of the Arabian Gulf will experience heightened salinity, changing circulation patterns, and higher temperatures as desalination activities intensify. The analysis of the energy-water-health nexus shows that energy efficiency and renewable energy can lead to significant reductions in annual greenhouse gas (GHG) emissions at negative to modest societal cost while leading to substantial decreases in premature mortality and health-care facility visits in the urban environment.

Keywords Climate change · Energy-water-health nexus · Greenhouse gas · Premature mortality · Avoided health-care facility visits · Policy scenarios · Public health co-benefits · Abu Dhabi City metropolitan area · Air pollutants · AGEDI

1 Introduction

Climate change poses serious energy-related challenges for the United Arab Emirates (UAE). Having one of the largest per capita greenhouse gas emissions in the world, it has been active in the identification and prioritization of policies and measures to reduce the carbon footprint of energy production and consumption activities which account for the overwhelming majority of its annual greenhouse gas emissions (MoE 2013). The UAE also faces acute water scarcity, requiring energy-intensive desalination to meet potable water requirements. In addition, many of its urban centers are grappling with the adverse impacts of outdoor air pollution on public health, much of which is closely related to energy use, most notably in the transport sector.

While energy, water, and health issues are closely interconnected, they have typically been viewed as independent planning challenges in the UAE. However, changing demographics, a rapidly growing economy, increasing reliance on desalination, and worsening air quality – all taking place as climate change unfolds – suggest a need for a more integrated approach to risk management. Accounting for the interactions between “energy, water, and health nexus” is one way to ensure that development strategies are considered within a framework that addresses the range of potential trade-offs, risks, and synergies.

Essentially, the “energy-water-health nexus” is an analytical framework that views energy, water, and health as part of an integrated system, rather than as independent resources and activities. Energy is required to extract, convey, purify, and deliver desalinated water to various types of end users in the economy while also used to treat municipal and industrial wastewater. Moreover, water itself is used in all phases of the fuel cycle, from extraction of energy resources like natural gas and oil to energy production and electricity generation. Many public health risks are directly related to energy use in the transport, residential, commercial, and industrial sectors, as well as the ways in which potable water is produced and delivered.

The challenge of integrated management of energy, water, and health challenges, already difficult, will be exacerbated by climate change. The Emirates lie within an arid-semiarid zone with high climatic variability typical of arid regions, and it is expected that climate change will directly increase this variability. Rainfall is erratic and irregular in time and space and clearly insufficient to supply the needs of agriculture, industrial development, and a growing population. Climate is an important driver for the nexus; air temperature and humidity drive the need for space cooling demand and associated electricity production, while ocean temperatures and salinity levels in the Arabian Gulf are key factors in the efficiency of desalination and power production. The heat island effect in urban centers aggravates ground-level ozone and poses health risks such as heat stress and respiratory problems, particularly among vulnerable populations such as the elderly. Wind and desert dust create aerosol particulate matter that are well-established health hazards (Kanatani et al. 2010).

To address the energy-water-health nexus under a changing climate, research activities were undertaken over the period 2014–2017. Known as the Local, National, and Regional Climate Change Programme (LNRCCP), the effort was implemented by the Abu Dhabi Global Environmental Data Initiative (AGEDI), a collaboration between the United Nations Environment Programme (UNEP) and the Environment Agency – Abu Dhabi (EAD). Specifically, climate change modeling at the regional spatial scale (Arabian Peninsula; Arabian Gulf) was first carried out to establish the atmospheric and marine physical conditions that will underlie energy, water, and health challenges in the future. The results of this modeling were then used as inputs to an analysis of policies that accounted for linkages across the energy-water nexus on the one hand and the energy-health nexus on the other.

Energy-water nexus issues were investigated at the national spatial scale in the UAE through an assessment of power and desalinated water supply and demand interactions under a set of sustainability scenarios that accounted for climatic changes in the atmosphere as well as changes in the Arabian Gulf from an intensification of desalination activities. Energy-health nexus issues were explored at the local spatial scale in Abu Dhabi City through an assessment of the public health co-benefits associated with the introduction of measures to reduce greenhouse gas emissions. Figure 6.1 provides an overview of the various components of the analytical framework. The rest of this chapter starts with an overview of the results of regional atmospheric and regional ocean modeling, followed by an overview of the energy-water nexus results and the energy-health nexus results.

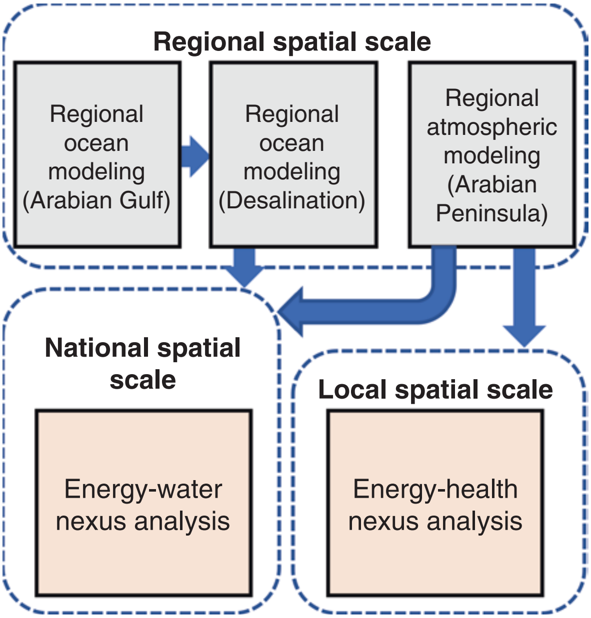


Fig. 6.1 Energy-water-health nexus analytical framework

2 Regional Atmospheric Modeling

Regional climate modeling (RCM) provided a point of departure to explore the energy-water-health nexus under a changed climate. The starting premise was the critical importance of examining climate impacts using higher-resolution climatic models that better capture local conditions influencing climate in the region (Hurrell et al. 2013). Coarse-resolution Atmospheric-Ocean Global Circulation Model (AOGCM) runs from the fourth and fifth Intergovernmental Panel on Climate Change (IPCC) Assessments (AR4 and AR5) that indicate substantial changes in the climate of the Arabian Peninsula (IPCC et al. 2014). However, results from these AOGCM projections summarized in the IPCC reports show that these projections often performed quite poorly in regions of complex terrain due to smoother terrain representation and in those areas that are heavily influenced by local phenomena such as sea surface temperature (SST) anomalies.

The climate of the UAE and the Arabian Peninsula is driven by steep temperature gradients from the Arabian Gulf, the Arabian Desert, and the Al Hajar Mountains in Oman, so climate assessments in this region that rely on global models that apply spatial scales of 100 kilometers or more are particularly uncertain. A higher-resolution regional climate model was therefore essential for understanding how climatic conditions will change within the UAE at specific locations. The regional model more realistically represented local to regional meteorological dynamics, such as orographic precipitation, land-ocean wind breezes and circulations, surface heating and evaporation, onshore and offshore wind patterns, etc. The information and data generated served as fundamental inputs to explore questions surrounding climate change impacts on groundwater recharge, energy demand, as well as air quality, premature mortality, and morbidity.

2.1 Approach

Projections of regional climate for the UAE and Arabian Peninsula were developed at fine spatial and temporal scales up through the late twenty-first century by a team from the National Center for Atmospheric Research (NCAR) in the USA (Yates et al. 2015). Modeling reflected large-scale features and temporal trends from the NCAR AOGCM version 4 of the Community Climate System Model (CCSM4; Gent et al. 2011) and specifically a subset version of Community Earth System Model (CESM, Hurrell et al. 2013). The specific CESM ensemble member simulations (#6) used were "b40.20th.track1.1deg.012"for the twentieth-century period, "b40.rcp4_5.1deg.006" for Representative Concentration Pathway 4.5 (RCP4.5), and "b40.rcp8_5.1deg.007" for RCP8.5. The dataset is available from NCAR's Computational and Information Systems Laboratory (CISL) research data archive (http://rda.ucar.edu/datasets/ds316.0).

Like all AOGCMs, the CESM outputs contain regional-scale biases due to, among other reasons, its coarse spatial resolution and a limited representation of certain physical processes. Such biases can adversely affect the dynamical downscaling process and contribute to uncertainty. To remedy these biases, a bias correction method was applied which corrected for the mean bias in the CESM three-dimensional temperature, geopotential height, wind, and humidity fields, as well as the SST, skin temperature, and soil temperature and moisture fields. Although the bias in the mean state was corrected, the methodology still allowed synoptic-scale and climate-scale variability to change in the future as simulated by CESM (Xu and Yang 2012; Done et al. 2015; Bruyére et al. 2013).

The Weather Research Forecast (WRF) model (version 3.5.1) was deployed to dynamically downscale the climate of the UAE and Arabian Peninsula using the CESM AOGCM lateral boundary conditions. The WRF RCM used in this study is a fully compressible conservative-form nonhydrostatic atmospheric model with demonstrated ability for resolving small-scale phenomena, local topographic features, and clouds (Skamarock and Klemp 2008). WRF was deployed on the Yellowstone supercomputer, a 1.5-petaflops high-performance IBM iDataPlex cluster, which features 72,576 Intel Sandy Bridge processors and 144.6 TB of memory. The mode was configured to include three computation domains as illustrated in Fig. 6.2 and summarized below:

- *Domain D1:* This outer domain has a grid spacing of 36-km resolution and covers much of the eastern hemisphere. This largest domain, which extends eastward beyond the Himalayas, helped to avoid computation problems on the model boundaries.

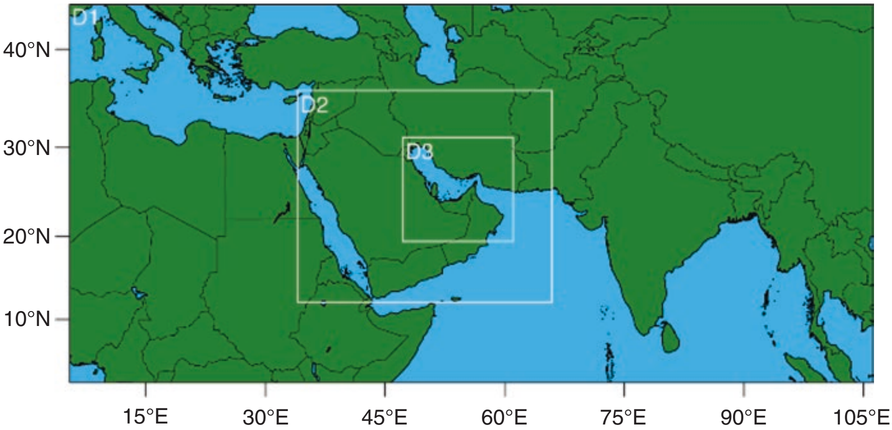


Fig. 6.2 WRF spatial domains

- *Domain D2:* Nested inside the 36-km domain is a domain with a grid spacing of 12 km which covers the Arabian Peninsula region. This was another extensive domain, which extends northward to cover mountain ranges in Iran.
- *Domain D3:* Nested inside the 12-km domain is the innermost domain with a grid spacing of 4 km which covers the UAE and vicinity. This was the highest-resolution domain and computationally the most intensive.

A total of 40 vertical levels were modeled – from the surface to about 30 km above the surface (i.e., 10 hPa). The WRF simulations were reinitialized every 8 days, and each 8-day period was preceded by a 12-hour period that allowed the WRF hydrological fields to spin up and which were subsequently discarded. Throughout the simulations, four-dimensional data assimilation (Stauffer and Seaman 1994) – i.e., "grid nudging" – was employed on the 36-km domain to keep the model solution from diverging from large-scale global boundary conditions. Physical parameterization schemes, which simulated the sub-grid scale processes in WRF empirically, included the Lin microphysics scheme, the RRTM longwave radiation scheme, the Dudhia shortwave scheme, the MM5 surface layer scheme, the Noah land surface model, the YSU PBL scheme, and the Grell-Devenyi convective scheme (36-km and 12-km domains only).

Verifying that the WRF regional model was capable of accurately simulating the historical climate of the region was a fundamental task. First, meteorological station data was obtained from the UAE's National Center of Meteorology and Seismology to establish recent historical patterns. Then, a 30-year baseline simulation was undertaken for the historical twentieth-century period, forced by the bias-corrected output data from CESM. Additional benchmark simulations were undertaken using initial and boundary conditions from the European Centre for Medium-Range Weather Forecasting (ECMWF) Interim Reanalysis (ERA-Interim; Dee et al. 2011).

Table 6.1 Summary of the regional climate modeling experiments

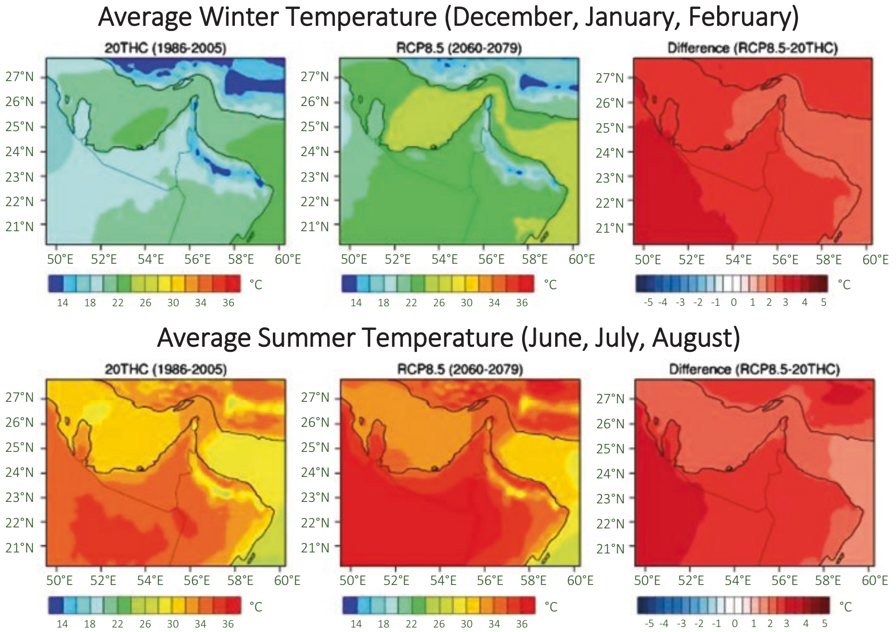
	Spatial domain		
Experiment stage	D1 (36 km)	D2 (12 km)	D3 (4 km)
WRF regional model historical climate validation	ERA-Interim-driven WRF benchmark simulation for historical period, 1981–2010 (30 years)		NA
	Bias-corrected CESM-driven WRF climate simulation for historical period, 1986–2005 (20 years)		Bias-corrected CESM-driven WRF climate simulation for historical period, 1990–1999 (10 years)
WRF regional model future climate projection	Bias-corrected CESM-driven WRF climate simulation for future period, 2060–2079 (20 years) for RCP4.5 and RCP8.5		Bias-corrected CESM-driven WRF climate simulation for future period, 2065–2075 (11 years) for RCP4.5 and RCP8.5

ERA-Interim is considered to be the most accurate atmospheric reanalysis available at the present time (e.g., Lorenz and Kunstmann 2012). The verification process showed that WRF was capable of adequately simulating historical climate and thus reliable for projecting future climatic conditions in the region. Notably, the WRF model was shown to reasonably capture the magnitude of precipitation during January through October; however during November and December, precipitation amounts were consistently too high. This led to a simulated annual cycle of precipitation that is more strongly bimodal than observed, peaking in November/December and again in February/March.

The validated WRF regional model was then used to explore climatic conditions in the region under conditions of increased greenhouse gas concentrations in the atmosphere. Two scenarios of future global greenhouse gas (GHG) emissions were modeled, namely, Representative Concentration Pathways (RCP) 4.5 and 8.5. A summary of both stages of the regional climate modeling experiment (i.e., validation, projection) is included in Table 6.1.

2.2 Results

Future climate results indicate generally wetter and warmer conditions in the UAE and surrounding region under RCP8.5. Average future temperature increases are fairly evenly distributed across the region, on the order of 2° to 3 °C higher over land areas (see Fig. 6.3). Future temperature increases are slightly smaller over many coastal areas. These changes are generally consistent across winter and summer months. The change in average winter temperatures is projected to be similar to the projected change in summer temperatures.


Average Winter Temperature (December, January, February)

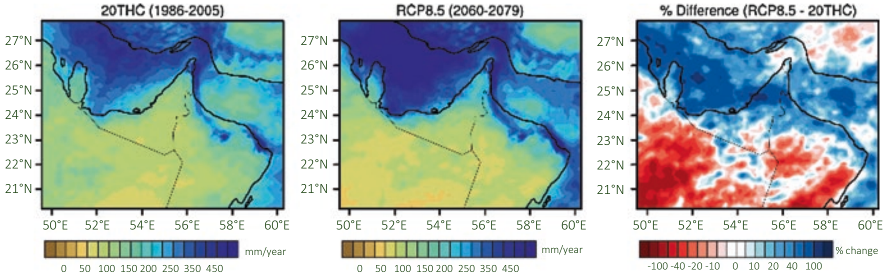
Average Summer Temperature (June, July, August)

Fig. 6.3 Future temperature for historical period (left), 2060–2079 under RCP8.5 (center), and difference (right), averaged over winter and summer

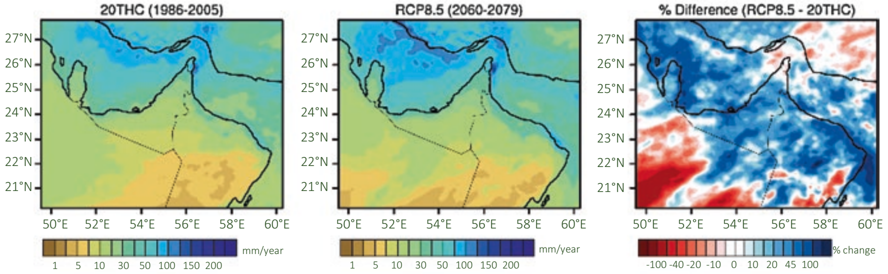
Average annual rainfall is projected to increase over much of the UAE, the Hajar Mountains, and Qatar (see Fig. 6.4). Increases of 50–100% from current amounts are projected for portions of Dubai, Sharjah, and the northern emirates, with increases averaging around 25% over surrounding regions. Decreasing rainfall is projected over much of Oman and eastern Saudi Arabia. Projected rainfall increases over the Arabian Gulf and north of the Hajar Mountains primarily occur during winter. Notably, during the dry summer, rainfall increases over much of the UAE are larger than during the wetter winter season, in both absolute value and percentage change. The rainfall increases over the Hajar Mountains and eastern UAE primarily occur during summer as well.

Wind patterns at 10 meters show great variation across the region. Figure 6.5 illustrates this variation using the Abu Dhabi City vicinity as an example. Under current climate conditions, wind is from the northeast off the Arabian Gulf during early winter mornings (06:00). Under future climate conditions, wind from the interior of the UAE will be stronger during early winter mornings. This will result in a net change in early morning wind from the east to the west or outward into the Arabian Gulf. This is likely the result of a weakening of the ocean-land temperature gradient, which gives rise to an onshore sea breeze, particularly in the afternoon hours. There is a relatively persistent warmer, interior environment relative to the Arabian Gulf that results in a more northwesterly near-surface wind and a weakening of the sea breeze.

Average Annual Rainfall



Average Winter Rainfall (December, January, February)



Average Summer Rainfall (June, July August)

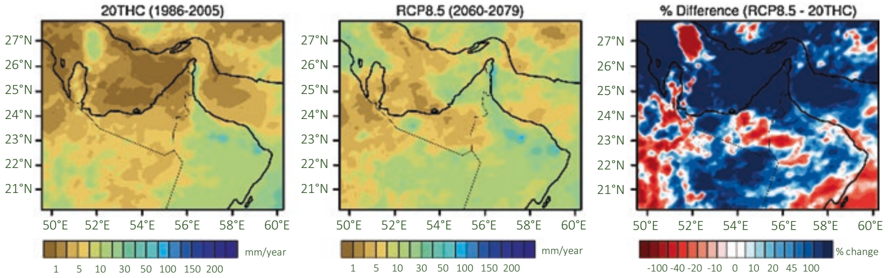


Fig. 6.4 Future average rainfall for historical period (left), 2060–2079 under RCP8.5 (center), and percent difference (right)

During evening hours (18:00) in winter, wind fields are still similarly strong under the current and future climate, with a generally southwesterly change in flow. This is associated with a change of about 0.5 m/s over Abu Dhabi Island, which corresponds to about a 20% mean change. During the summer months, morning hour winds are weak in both the current and future climate simulations, with a net change of flow to the northeast. A relatively strong, onshore sea breeze develops in the evening hour, with a net change in wind similar to the morning hour, with a slight increase in magnitude to the northeast.

Finally, the results show potential changes in the trajectory of cyclonic events (see Fig. 6.6). There are some intense cyclones that originate in the Arabian Sea, off the west coast of India, which initially propagate westward toward the Arabian

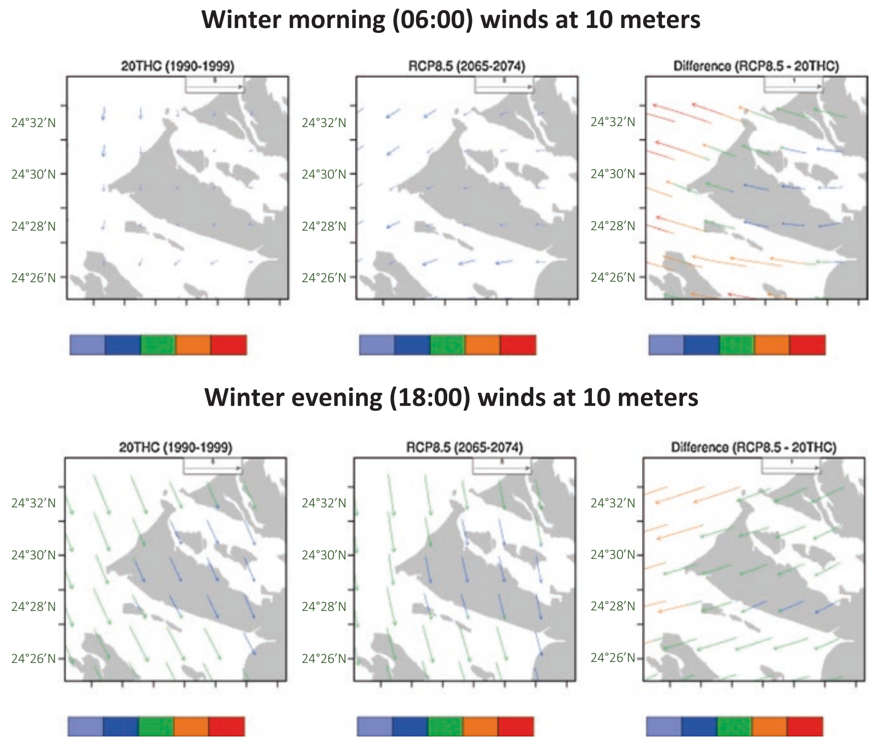


Fig. 6.5 Future wind patterns around Abu Dhabi City for historical period (left), 2060–2079 under RCP8.5 (center), and difference (right), averaged over winter mornings and evenings

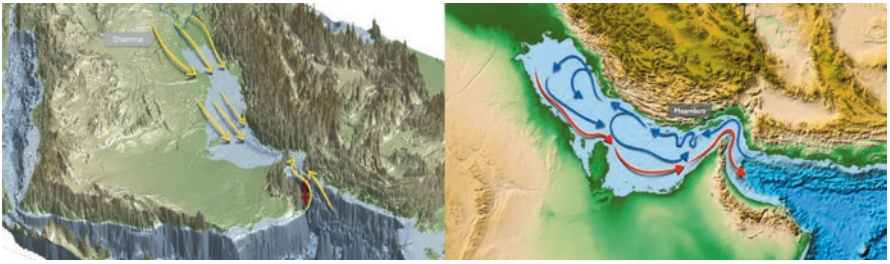


Fig. 6.6 Topography surrounding Arabian Gulf study region showing some schematic wind patterns (left) and a schematic ocean circulation (right)

Peninsula and then veer in the north-northeasterly direction toward Iran. One such event that occurs in CESM (as opposed to the regional model) is in September of 2066, where the colored grid is sea-level pressure and the blue lines show only the 950 to 995 hPa contours, which are indicative of a tropical typhoon. The event remains coherent throughout a 6-day period, reduces in intensity when it makes landfall on the Oman/UAE coast, and then re-intensifies as it tracks into the Arabian

Peninsula. This is quite a remarkable event first because the CESM generates such a tropical cyclone and also that the event persists so far across the Arabian Peninsula. It is important to note that the regional modeling results do not support drawing specific conclusions about the timing or track of extreme regional events.

3 Regional Ocean Modeling

The Arabian Gulf, a semi-enclosed, highly saline marginal sea, is already one of the most stressed marine environments on earth (Sheppard et al. 2010; Van Lavieren et al. 2011). Located between latitudes 24°N and 30°N, it is surrounded by a hyper-arid environment and is impacted by northwesterly winds, an atmospheric phenomenon known as Shamal (Perrone 1979; Emery 1956). The UAE is located in the southern portion of the Arabian Gulf, a region that extends from the southern parts of Bahrain throughout the Strait of Hormuz to the northern area of the Gulf of Oman. Northwesterly winds affect Gulf waters in the winter, while southeasterly winds dominate in the summer (Fig. 6.7, left). Such winds significantly affect the Gulf circulation patterns leading to seasonally freshening of surface waters (Fig. 6.7, right). Its bathymetry shows large areas of shallow water (less than 10 meters deep) with a maximum depth reaching about 110 meters along the main Arabian Gulf channel, near central areas. The vertical water structure of the Gulf displays a clear seasonal oscillation signal, characterized by a strong stratification during summer and a fairly mixed vertical profile during winter months (Thoppil and Hogan 2010).

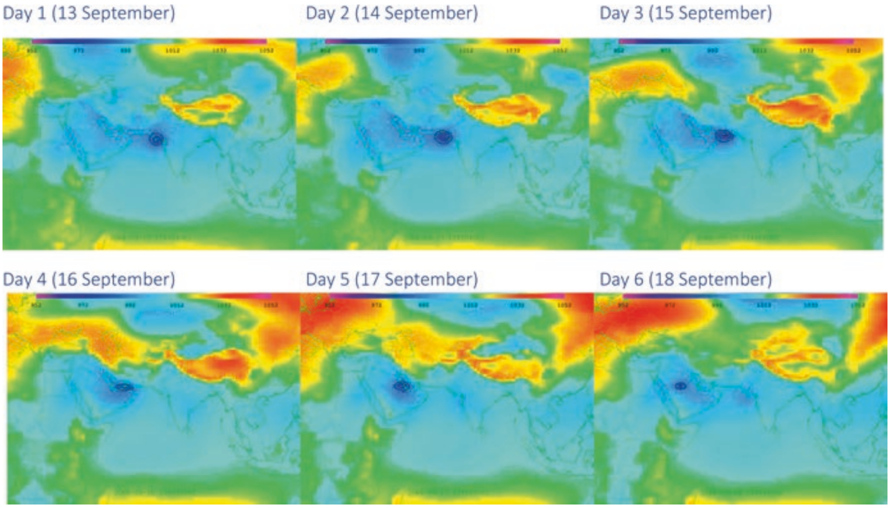


Fig. 6.7 A future cyclone in the CESM model that tracks first across the Arabian Sea and then the Arabian Peninsula, showing sea-level pressure for the color-composite grid and a minimum contour range of 950 to 995 (hPa)

The UAE is highly dependent on the Arabian Gulf as a feedstock for the production of desalinated water. Today, most of the power and freshwater needs in the Arabian Peninsula region are met by the desalination of seawater (Uddin 2014). Of the 100 largest desalination plants in operation, in construction, or planned in the world as of 2005, 47 plants, accounting for 13.7 million cubic meters per day in production capacity, or 64%, are in the 8 countries bordering the Arabian Gulf, namely, Bahrain, Iraq, Iran, Kuwait, Oman, Qatar, Saudi Arabia, and the UAE (GWI 2015). The majority of these large plants (i.e., 43 out of 47) use seawater from the Arabian Gulf as the feedstock to produce potable water, with the rest using either brackish water or wastewater to produce potable water.

Most desalination plants in the UAE are combined with power plants for electricity generation to meet on-site requirements and to satisfy national electricity needs. There are three major types of desalination technology currently used: reverse osmosis (RO), multi-stage flash (MSF), and multi-effect distillation (MED). The environmental impacts of desalination are associated primarily with the waste stream that is discharged into the Arabian Gulf. This waste stream consists of hot brine, treatment chemicals, and other trace elements. The environmental impacts associated with such concentrated brine discharges include increasing levels of biocides, chlorination, and descaling chemicals (Hoepner and Lattemann 2002; Younos 2005; Dawoud 2012; Uddin 2014; Xu et al. 2013). This can lead to chronic toxicity and small-scale alterations to community structure in near-field marine environments, particularly for corals (Jenkins et al. 2012; Uddin 2014). Moreover, the salinity of the hot brine effluent can be up to 85 ppt for reverse osmosis (RO) desalination plants and 50 ppt for multi-stage flash (MSF) units. As the effluent is heavier than seawater, it sinks to the bottom and slowly circulates causing harm to sea grasses and other ecosystems on which a large range of aquatic life (e.g., dugongs) depend (Areiqat and Mohamed 2005; Lattemann and Höpner 2008; Mohamed 2009).

The combination of climate change and future intensification of desalination activity poses risks to the Arabian Gulf. Increasing concentrations of GHGs in the atmosphere will affect physical properties such as temperature, salinity, and circulation patterns. Increasing levels of desalination activity, absent brine mitigation measures, will likely deepen these changes. Taken together, climate change and intensifying desalination may impact the future effectiveness and efficiency of seawater desalination technology, given that current technologies can operate at feedstock salinity levels up to 50 ppt (World Bank 2004).

To explore these implications on the water-energy sub-nexus, a high-resolution regional ocean model of the Arabian Gulf was developed. The overall goal of the modeling effort was to better understand the future impact of climate change alone, as well as combined with desalination activity impacts. Several core research questions were addressed: 1) How will the high levels of socioeconomic growth projected in the region affect the magnitude of brine discharges into the Gulf over time? 2) How are key Gulf physical properties affected by the middle of the twenty-first century due to the combination of climate change and intensified desalination activities? And 3) to what extent does climate change potentially exacerbate the environmental impacts of future desalination activity? The regional model accounted for the influences of climate change and desalination and provided a point of departure to understand the linkages between climate, water, and energy in the UAE. Unlike regional atmospheric modeling, the outputs of the modeling effort were not used to assess public health impacts within the UAE.

3.1 Approach (Climate Change Alone)

Earth System Models (ESM) considered in IPCC assessments indicate substantial future changes in the world's oceans. However, due to their complexity, these models are formulated at too low a spatial resolution to solve the Arabian Gulf area. While they provide essential oceanographic information, they nevertheless do not provide sufficient spatial resolution to make useful regional climate change projections. They are particularly poor in representing regions such as the small semi-enclosed Arabian Gulf due to a range of factors (i.e., complex bathymetry, circulation, oceanographic processes, sea surface temperature profiles, circulation patterns, freshwater influxes, balancing of ocean currents, and topographical features of the ocean bottom).

Therefore, a climate downscale of the Arabian Gulf, using the Regional Ocean Model System (ROMS), was developed to better account for such complexities and provides a basis for better understanding how Arabian Gulf conditions may evolve under climate change through the late twenty-first century. Researchers at Rutgers University and the University of California Los Angeles, together with contributors worldwide, developed ROMS in the 1990s (Penven et al. 2006; Shchepetkin and McWilliams 2005). This system – a free surface, terrain-following, hydrostatic primitive equations ocean model – was used as the numerical framework to represent the Arabian Gulf. It incorporates complex physical and numerical algorithms, as well as several coupled models, for analysis of ocean parameters such as salinity, temperature, sea level, current, vertical mixing, and others.

A three-step process was used in developing the Arabian Gulf ROMS. First, an ESM was identified that best captures large-scale features of the Arabian Gulf and could be used to establish boundary conditions for the Arabian Gulf ROMS climate projections. The Max Planck Institute for Meteorology's ESM using the Mixed Resolution experiments (hereafter called MPI-MR) was selected as the most suitable ESM relative to Gulf conditions. MPI-MR is 1 of 42 models that were part of the Coupled Model Intercomparison Experiment Phase 5 (CMIP5) cited in the IPCC's fifth Assessment Report (Knutson et al. 2013). From this ensemble, a suitable experiment was selected on the basis of a pre-validation process. This evaluation was based on comparison of the present time air and sea exchange fluxes (e.g., surface temperature differences) in the Gulf region to results obtained from the MPI-MR historical period, 1950–2005. It displayed clear advantages over other potential ESMs, such as the CCSM4 model used for regional atmospheric modeling, in accurately capturing large-scale Arabian Gulf conditions.

Second, extensive local information was collected from a variety of sources to better understand Gulf dynamics. Four major sources of data on the Arabian Gulf were obtained and examined. These included sea surface temperature, bathymetry, salinity, currents, and other characteristics from published literature (Johns et al. 2003; Reynolds 1993; Johnson et al. 2013); satellite-based high-resolution surface temperature from the Advanced Very High-Resolution Radiometer (AVHRR) datasets; conductivity-temperature-depth profiles and high-resolution bathymetry data from the World Ocean datasets (Locarnini et al. 2006); as well as numerical inferences from previous local modeling in the area (Kampf and Sadrinasab 2006; Yao and Johns 2010). This information revealed essential insights regarding key oceanographic characteristics that would be central to subsequent model validation and ground-truthing processes.

Third, the outputs of MPI-MR were dynamically downscaled using the Arabian Gulf ROMS for the entire Gulf using a 1.1-km horizontal resolution orthogonal discretization. Twenty sigma levels were used for the vertical resolution, to maximum depth of 101 meters at the Hormuz channel. All two- and three-dimensional equations were time-discretized using a third-order accurate predictor and sigma dispersion corrector time-stepping algorithm. In the horizontal, the primitive equations were evaluated using boundary-fitted, orthogonal curvilinear coordinates on a staggered Arakawa-C grid. In the vertical, the primitive equations were discretized over variable topography using stretched terrain-following coordinates.

Model validation of the Arabian Gulf ROM was conducted for the 2002 to 2005 period, using EMS historical forcing. This involved a series of diagnostic experiments on temperature and salinity to ensure that the resulting numerical representation of the Arabian Gulf retained key large-scale signals from the ESM while also being consistent with additional and more detailed historical patterns. Figure 6.8 shows that ROMS simulations of the historical period agree reasonably well with the Gulf's observed characteristics for average sea surface (i.e., top 30 cm) temperature (top plot) and average surface salinity (bottom plot) within the modeled domain. For both variables, model simulations (black lines) exhibit good agreement with observed patterns (green lines).

Internal microphysics schemes associated with mixing processes were adjusted within the ROM to produce salinity contours and local circulation dynamics consistent with the effect of "fresher" seawater inflows from the Gulf of Oman and Arabian Sea. Other variables for which diagnostic experiments were run and corrections made include specific humidity, shallow water salt production, coastal current jets, residual current structure, and vorticity. For all variables, specific adjustments were made so that historical conditions in the Gulf were adequately reproduced using the Arabian Gulf ROMS. The outcome of this process was a validated model that was used as a basis for projecting climate change effects for the entire Arabian Gulf.

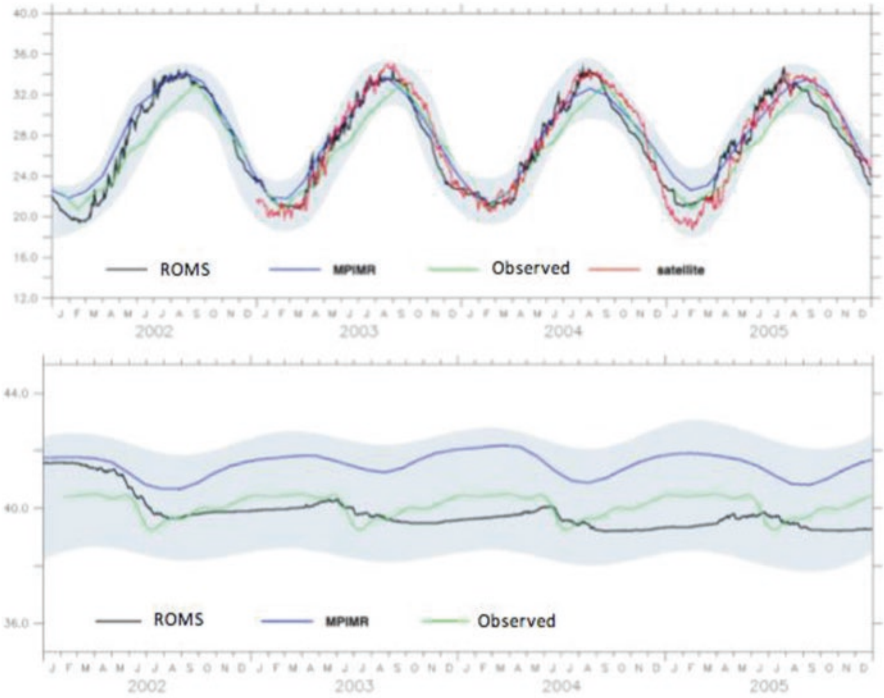


Fig. 6.8 Comparison of the Arabian Gulf ROM with historical data and MPI-MR outputs. Top plot, sea surface temperature (degrees Celsius); bottom plot, sea surface salinity (practical salinity units)

3.2 Results (Climate Change Alone)

The validated Arabian Gulf ROMS was then used to first explore the impact of climate on the physical properties of the Gulf under conditions of increased greenhouse gas concentrations in the atmosphere. The business-as-usual scenario of future global greenhouse gas (GHG) emissions was modeled, namely, RCP8.5. The analysis focused on two 5-year, time slice periods, namely, a mid-twenty-first-century period of 2040–2044 and a late twenty-first-century period of 2095–2099. A summary of both stages of the regional ocean modeling experiment (i.e., validation, projection) is provided in Table 6.2.

Figure 6.9 summarizes current, mid-century, and late-century spatial patterns in the Arabian Gulf for sea surface temperature and sea surface salinity. Sea surface temperatures are projected to increase throughout the Gulf. By mid-century, small temperature increases are evident in the Southern Gulf. By late century, the area showing the lowest increase relative to historical conditions, about 1.7 °C, is the central Gulf area where most of the large-scale summer eddies associated with fresher Gulf of Oman waters are concentrated. The areas showing the largest tem-

Table 6.2 Summary of the Arabian Gulf regional climate modeling experiment

	Spatial domain/resolution	
Experiment stage	Horizontal: 1.1 km	Vertical: 20 levels (stretching from 0.1 cm to 4 meters)
Arabian Gulf ROMS historical climate validation	MPI-MR-driven benchmark simulation for historical period, 2002–2005 (4 years)	
	Arabian Gulf-specific information (published literature, satellite-based high-resolution surface temperature from the Advanced Very High-Resolution Radiometer (AVHRR) datasets; conductivity-temperature-depth profiles and high-resolution bathymetry data from the World Ocean datasets; numerical inferences from previous local modeling in the area)	
Arabian Gulf ROMS future climate projections	MPI-MR-driven climate simulation for future periods, 2040–2044 and 2095–2099 for RCP RCP8.5	

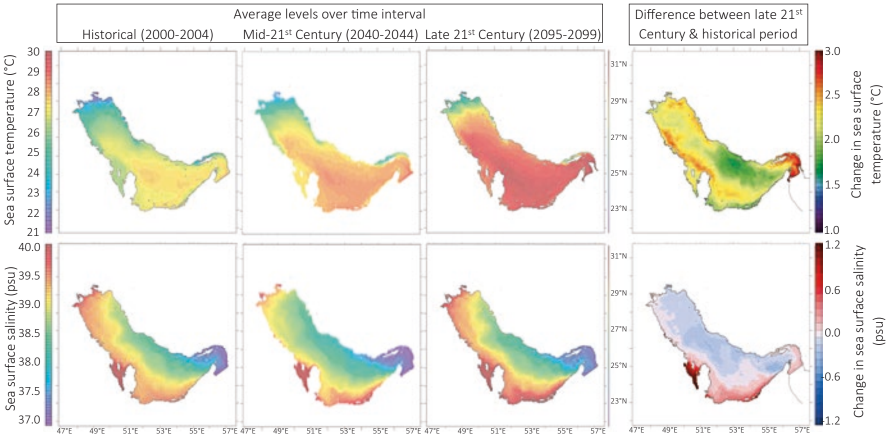


Fig. 6.9 Time-averaged sea surface temperature and sea surface salinity (left three columns) and projected change by the late twenty-first century (right column) in the Arabian Gulf under RCP8.5

perature increases relative to current conditions, about 2.8 °C, are located at the Strait of Hormuz and along the coastline of Saudi Arabia and Qatar.

Sea surface salinity is projected to both decrease and increase, depending on location. By mid-century, an uneven distribution of salinity is observed throughout the Arabian Gulf, with increased levels mostly along the UAE coast and freshening (i.e., lower salinity levels) along the Gulf's main channel. By late century, areas showing decreasing salinity, about 0.2 practical salinity units (psu), are located along the entire length of the deep channel from the Strait of Hormuz to Iraq. Areas showing modest increases in salinity, about 0.5 psu, are located along the UAE coast south of the northern emirates. The largest increases in surface salinity, about 1.1 psu, are located in Salwa Dawhat, a bay to the west of Qatar. These changes are

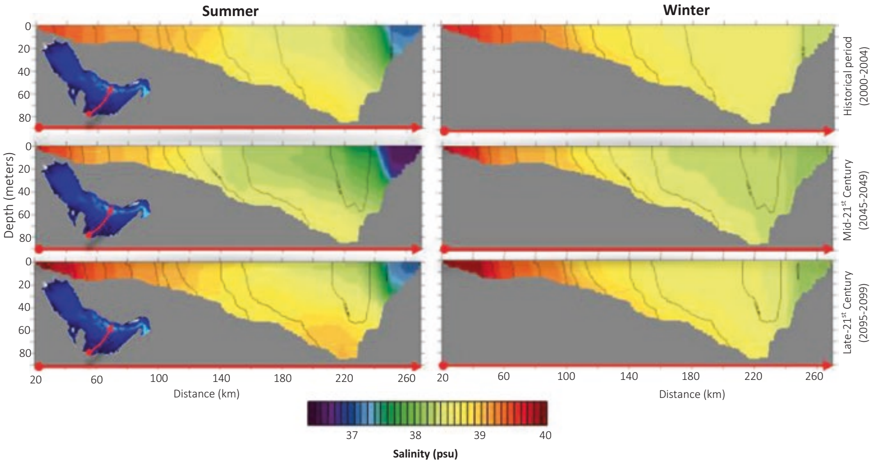


Fig. 6.10 Vertical profile of salinity levels for the historical, mid-twenty-first- and late twenty-first-century periods for summer and winter periods

due to the Gulf's dilution processes that progressively flush high-density waters out of the system along the deep channel but are more dynamically constrained in other locations.

The vertical profile of salinity also is projected to be altered under climate change, as shown in Fig. 6.10. During winter months, salinity on the eastern side of the Gulf is typically higher than summer months, although always by less than 1 psu, during all time slice periods. This is due to the fact that inflows from the lower-salinity waters of the Arabian Sea are always highest during summer months. By mid-century, freshwater inflow reaches a maximum for this vertical section and results in reduced salinity levels compared to the early period. By late century, a pattern emerged of more saline and denser waters prevailing throughout the year along the western shallow gulf areas and clearly along the main channel bottom layers.

Figure 6.11 illustrates changes in annual circulation dynamics in the Arabian Gulf for two zones, a deep zone located in the central area and a shallow zone located along the UAE coast. Circulation changes are typically measured by the net volume transport metric and are highly related to salinity change, the key driver for most of the internal density balances and mixing processes in the Gulf. Net volume transport occurs unevenly, depending on season and depth. Moreover, there is a systematic increase in net volume transport in the mid- and late-century results at surface layers as indicated by the pink and red lines, respectively, that is sustained yearlong. Notably, in the main channel bottom, there is a decrease in the volume transport but an increase in water density (see Fig. 6.11, late twenty-first century). These results indicate a slight increase in Gulf stratification even during winter, when vertical mixing due to turbulence is more pronounced.

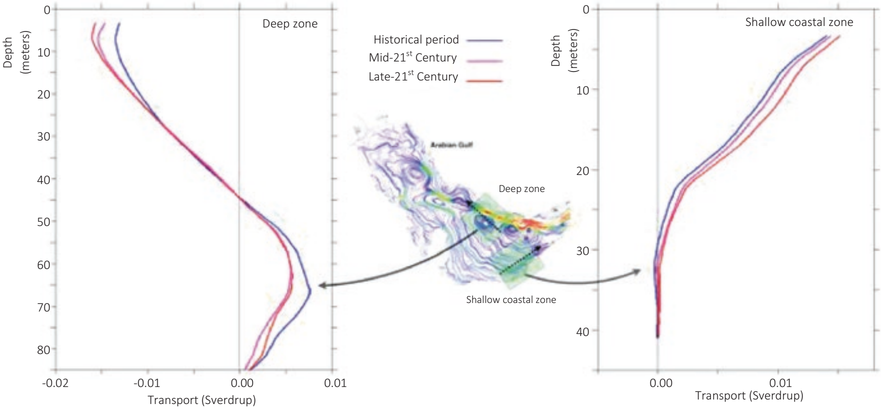


Fig. 6.11 Early (blue), mid-century (pink), and late-century (red) time-averaged climatological net transport along the main circulation direction. The map in the center shows the locations of the zones, with the black dashed arrows pointing to the circulation direction

3.3 Approach (Combined Effects of Climate Change and Intensifying Desalination)

The validated Arabian Gulf ROM was then used to explore the combined impact of climate and desalination on the physical properties of the Gulf. A "saline river" approach was used to simulate the spatial distribution of future hot brine discharges to the Gulf. The number and location of desalination plants were spatially reduced from 486 plants around the region into fourteen (14) representative points whose annual brine discharges were collectively equivalent to the magnitude from all plants. These "saline rivers" were modeled as direct injections of hot brine into the Gulf.

It is important to note that this modeling approach does not account for local effects in the immediate vicinity of the underwater brine discharge structures. That is, only far-field modeling was undertaken (i.e., using a roughly 1.1-km resolution). Near-field modeling of the immediate zones of brine discharge (i.e., requiring less than a 5-meter resolution) was beyond the scope of the study.

Four brine discharge scenarios – ranging from 50 tonnes per second to 220 tonnes per second – were modeled in an effort to bracket uncertainty temperature and salinity levels throughout the Gulf. These brine loadings were assumed to be reached in the 2040–2049 period. An overall summary of average and maximum temperature and salinity for each brine discharge scenario was developed relative to the spatial configuration shown in Fig. 6.12 and described in the bullets below.

- *Northern Gulf:* This region extends from the Shatt al-Arab in Iraq to just south of Jubail in Saudi Arabia.
- *Southern Gulf:* This region extends from the southern parts of Bahrain throughout the Strait of Hormuz to the northern area of the Gulf of Oman.

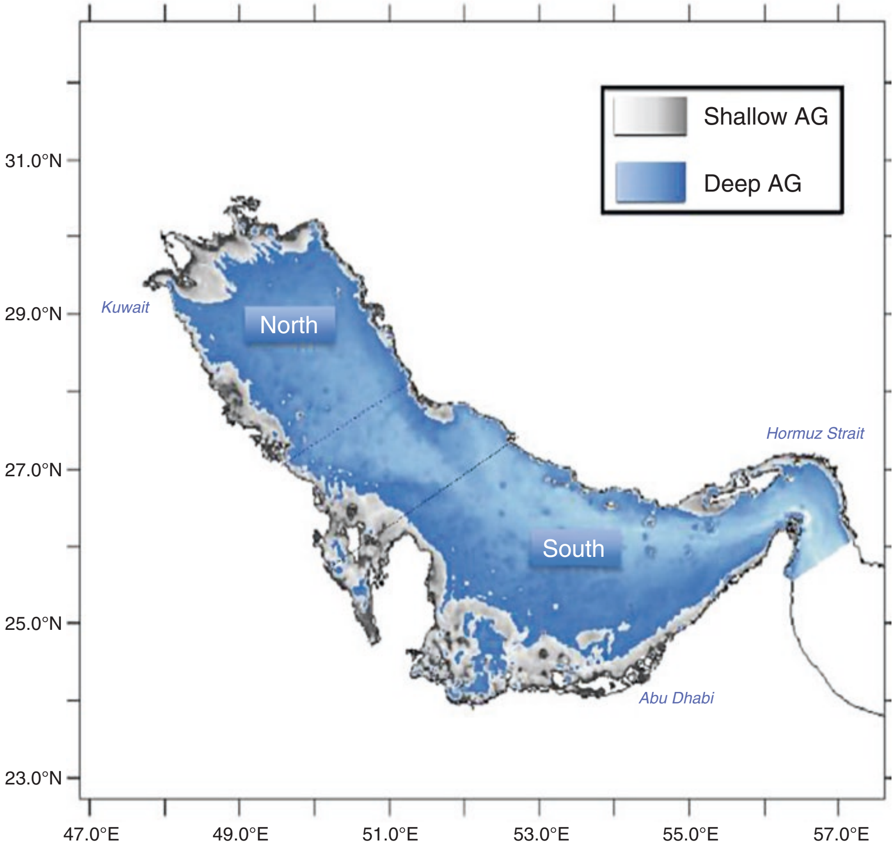


Fig. 6.12 Key areas of the Arabian Gulf for regional modeling

- *Shallow areas:* These areas refer to shallow water less than 20 meters in depth. These areas are shown in gray on Fig. 6.12. Within shallow areas, the focus is on the surface layers (top 30 cm) and bottom layers (lowest 30 cm).
- *Deep areas:* These areas refer to deeper waters greater than 20 meters in depth. These areas are shown in blue on Fig. 6.12. Within deep areas, the focus is also on the surface and bottom layers.

It is important to note that there are several caveats and limitations, as outlined in the bullets below. Combined, these caveats and limitations introduce a not unexpected level of uncertainty into the results. Nevertheless, while uncertainty levels can be reduced with finer levels of resolution and additional data ground-truthing, there is a high level of confidence in overall direction of the conclusions and their validity for use in subsequent marine biodiversity assessments.

- *Brine discharge quantities:* Future quantities of saline discharges into the Gulf were estimated on the basis of past trends in desalination technology and

desalinated water demand. Projected brine discharges in 2050 were based on four plausible scenarios governed by economic growth and other assumptions.
- *"Saline river" approach:* From a modeling perspective, the optimal number of brine discharge points (or "saline rivers") that could be efficiently modeled was fourteen (14), together with and a freshwater source, Shatt al-Arab, in the northernmost part of the Gulf. The total magnitude and temporal characteristics of future brine discharge were distributed across the saline rivers consistent with projected national levels of desalinated water supply.
- *Near-field modeling:* There was no near-field modeling of the immediate zones of the brine discharge plume. Specific routines were included in the model formulation to allow a thermodynamic balance between the high saline and hot brine with the surrounding Gulf waters. This approach avoids microphysics anomaly contamination in the spatial domain. The disadvantage of this process is the limitation in the number of brine sources. A much finer resolution model (up to 100 meters) would have been required to resolve a larger number of saline river sources, together with much greater computation resources.

3.4 Results (Combined Effects of Climate Change and Intensifying Desalination)

The results of average and maximum temperature and salinity are summarized in Table 6.3 for the mid-twenty-first-century period. A total of six scenario results are provided. Results for the first two scenarios correspond to historical conditions without climate change. Results for the remaining four desalination scenarios correspond to the combined impact of climate change and desalination.

The average temperature impacts on the Arabian Gulf from climate change and desalination are illustrated in Fig. 6.13. A summary of key observations is offered in the bullets below the figure.

- In surface layers throughout shallow and deep areas of the Gulf, climate change represents the overwhelming majority of the impact on average temperature. In the Southern Gulf region, climate change accounts for about 95% of the roughly 0.8 °C increase in average temperature while accounting for 89% to 95% in the northern region.
- In bottom layers throughout shallow and deep areas of the Southern Gulf, desalination dominates the impact on temperature. Desalination accounts for between 27% and 53% of the roughly 1 °C increase in average temperature in shallow areas, across all brine discharge rate scenarios. In deep areas, desalination accounts for between 41% and 95% of the roughly 1.4 °C increase in average temperature.
- In bottom layers throughout shallow and deep areas of the Northern Gulf, desalination represents the overwhelming majority of the impact on average temperature. Desalination accounts for between 41% and 95% of the roughly 1.4 °C

Table 6.3 Summary of regional ocean modeling results, accounting for climate change and desalination for key areas in the Arabian Gulf, 2040-2049

(a) Average temperature (degrees Celsius)

Regional model run	Scenario#	Time period	GHG emissions	Brine discharge rate to Arabian Gulf (tonnes per second)	Arabian Gulf south region								Arabian Gulf north region							
					Shallow area				Deep area				Shallow area				Deep area			
					Surface		Bottom		Surface		Bottom		Surface		Bottom		Surface		Bottom	
					Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max
Historical – no climate change	1	1985–2005	NA	0	27.0	41.4	27.2	46.4	27.3	37.2	26.5	39.4	24.3	44.5	25.2	48.9	25.9	37.0	25.2	40.2
Mid-twenty-first century – no climate change; no desalination	2	2040–2049	RCP8.5	0	27.7	42.5	27.7	42.7	28.0	38.9	26.6	38.9	25.1	40.1	25.1	40.2	26.6	37.6	25.6	37.6
Mid-twenty-first century – climate change; reference desalination	3	2040–2049	RCP8.5	50	27.7	42.6	27.9	49.2	28.0	38.6	27.2	41.9	25.1	45.6	25.9	49.9	26.7	39.0	26.0	41.0

(continued)

Table 6.3 (continued)

(a) Average temperature (degrees Celsius)

					Arabian Gulf south region								Arabian Gulf north region							
					Shallow area				Deep area				Shallow area				Deep area			
					Surface		Bottom		Surface		Bottom		Surface		Bottom		Surface		Bottom	
Regional model run	Scenario#	Time period	GHG emissions	Brine discharge rate to Arabian Gulf (tonnes per second)	Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max
Mid-twenty-first century – climate change; low desalination	4	2040–2049	RCP8.5	80	27.7	42.6	28.0	48.3	28.0	38.7	27.4	41.7	25.1	46.1	26.1	50.9	26.7	39.2	26.1	41.5
Mid-twenty-first century – climate change; medium desalination	5	2040–2049	RCP8.5	120	27.7	42.9	28.1	46.7	28.0	38.4	27.7	42.8	25.2	46.0	26.3	51.7	26.7	39.4	26.3	41.8
Mid-twenty-first century – climate change; high desalination	6	2040–2049	RCP8.5	220	27.7	42.6	28.1	46.8	28.1	38.5	28.0	42.9	25.2	46.0	26.5	51.8	26.8	39.4	26.5	41.6

(b) Average salinity results (psu)

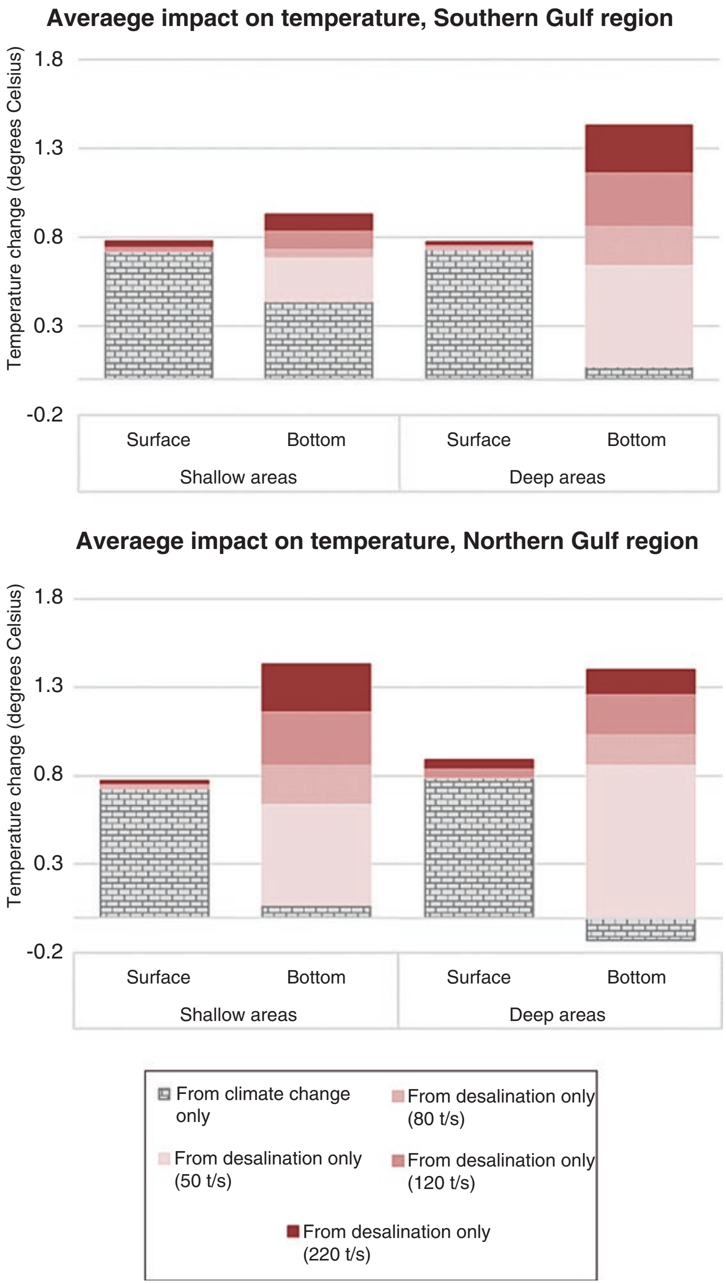
Regional model run	Scenario#	Time period	GHG emissions	Anthropogenic brine discharge rate to Arabian Gulf (tonnes per	Arabian Gulf south region								Arabian Gulf north region							
					Shallow area				Deep area				Shallow area				Deep area			
					Surface		Bottom		Surface		Bottom		Surface		Bottom		Surface		Bottom	
					Ave	Max	Ave	Max	Ave	max	Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max
Historical – no climate change	1	1985–2005	NA	0	40.5	56.8	40.7	56.7	38.8	47.6	39.3	50.0	38.2	56.5	39.2	57.2	39.0	48.5	39.2	52.6
Mid-twenty-first century – no climate change; no desalination	2	2040–2049	RCP8.5	0	39.4	42.2	39.4	42.2	38.5	41.8	38.7	41.8	39.1	40.6	39.1	40.6	38.7	39.9	38.7	39.7
Mid-twenty-first century – climate change; reference desalination	3	2040–2049	RCP8.5	50	40.4	56.8	40.7	56.7	38.7	47.2	39.2	49.5	38.3	56.6	39.2	57.2	39.0	47.8	39.2	52.4

(continued)

Table 6.3 (continued)

(b) Average salinity results (psu)

Mid-twenty-first century – climate change; low desalination	4	2040–2049	RCP8.5	80	40.8	57.0	41.1	56.8	38.8	48.9	39.5	50.9	38.5	56.2	39.6	57.2	39.2	49.8	39.5	53.6
Mid-twenty-first century – climate change; medium desalination	5	2040–2049	RCP8.5	120	41.2	56.5	41.6	57.1	39.0	50.4	39.9	52.6	38.7	56.5	40.0	56.6	39.4	52.0	39.8	54.3
Mid-twenty-first century - climate change; high desalination	6	2040–2049	RCP8.5	220	41.5	56.8	42.0	56.9	39.1	52.1	40.2	53.5	38.9	56.9	40.3	56.2	39.6	53.5	40.1	54.8


Averaege impact on temperature, Southern Gulf region

Averaege impact on temperature, Northern Gulf region

Fig. 6.13 Average temperature impacts in the Arabian Gulf from climate change and desalination increase in average temperature in shallow areas, across all brine discharge rate scenarios. In deep areas, desalination accounts for *all* of the 1.5 °C increase in average temperature.

The maximum temperature impacts on the Arabian Gulf from climate change and desalination are illustrated in Fig. 6.14. A summary of key observations is offered in the bullets below.

- Desalination impacts on *maximum* temperatures far exceed those on *average* temperatures. This is most evident for surface layers in deep areas of the Northern Gulf where maximum temperature increases from desalination are about 6.0 °C compared to only a 0.1 °C average temperature increase for the same area, or roughly 60 times greater. This is also evident for bottom layers in deep areas of the Southern Gulf where the maximum temperature increase from desalination is about 3 times greater than the average increase, 4.1 °C average temperature increase compared to only a 1.4 °C average temperature increase.
- In surface layers in the Southern Gulf, climate change represents the overwhelming majority of the impact on maximum temperature. In this region, climate change accounts for about between 74% (1.0 °C) and 91% (1.7 °C) of the total increase in maximum temperature.
- In bottom layers throughout shallow and deep areas of the Southern Gulf, desalination represents the entire impact on maximum temperature. Under climate change, maximum temperatures actually *decrease* in bottom layers through the Southern Gulf. With desalination, maximum temperatures are projected to rise up to 6.6 °C and 4.2 °C in shallow and deep areas, respectively.
- In bottom layers throughout deep areas of the Northern Gulf, desalination represents the entire impact on maximum temperature. Under climate change, maximum temperatures actually *decrease*. With desalination, maximum temperatures are projected to increase up to 4.2 °C and 11.6 °C in shallow and deep areas, respectively.
- In surface layers in the Northern Gulf, the impact of desalination shows mixed results. In shallow areas, climate change represents the overwhelming majority of the increase in maximum temperature, 1.7 °C or 91%. In deep areas, maximum temperatures actually *decrease* under climate change, whereas maximum temperatures increase by up to 6.0 °C due to desalination activities.

The average salinity impacts on the Arabian Gulf from climate change and desalination are illustrated in Fig. 6.15. A summary of key observations is offered in the bullets below.

- In shallow areas throughout surface and deep layers of the Northern and Southern Gulf, desalination represents the entire impact on average salinity. Under climate change, average salinity actually *decreases*. Depending on the brine discharge rate scenario, average salinity is projected to rise between 1.1 and 2.6 psu in the Southern Gulf and between 0.6 and 1.6 psu in the Northern Gulf.
- In bottom layers throughout deep areas of the Northern and Southern Gulf, desalination represents the entire impact on average salinity. Under climate

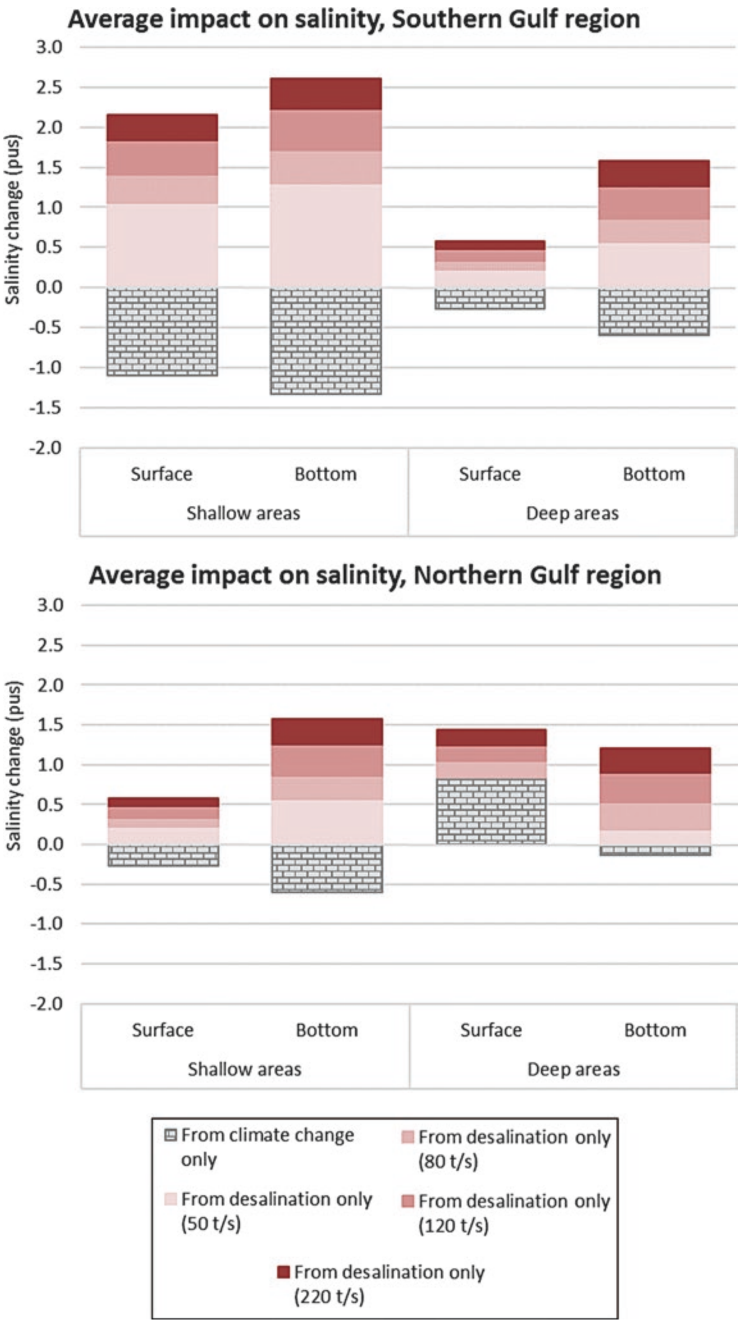


Fig. 6.14 Average salinity impacts in the Arabian Gulf from climate change and desalination

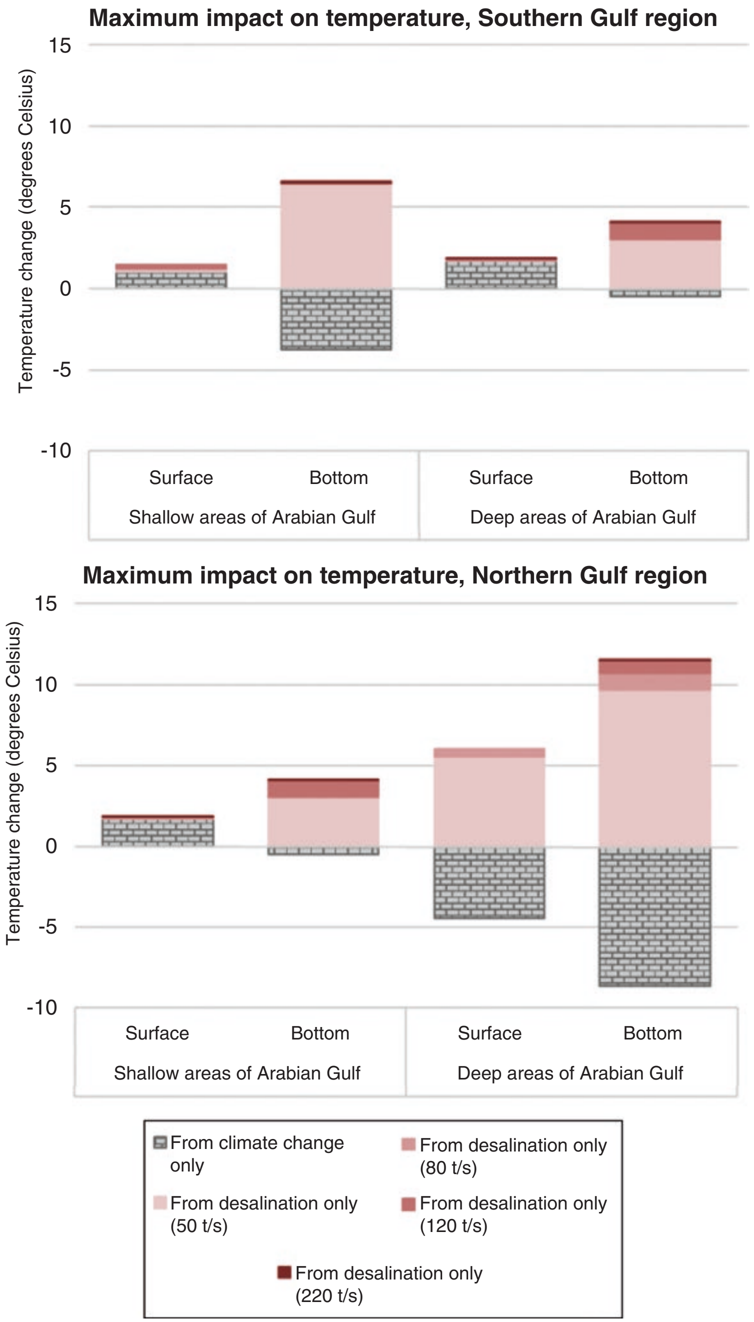


Fig. 6.15 Maximum temperature impacts in the Arabian Gulf from climate change and desalination

change, average salinity actually *decreases*. With desalination, average salinity is projected to rise up to between 0.6 and 1.6 psu in the Southern Gulf across the range of desalination scenarios. In the Northern Gulf, average salinity is projected to rise up to between 0.1 and 1.2 psu.

- In surface layers throughout deep areas of the Northern and Southern Gulf, the impact of desalination shows mixed results. In the Southern Gulf, desalination represents the entire increase on average salinity (0.2–0.6 psu) as average salinity actually *decreases* under climate change. In the Northern Gulf, desalination represents between 0 and 1.4 psu (0%–42%).

The maximum salinity impacts on the Arabian Gulf from climate change and desalination are illustrated in Fig. 6.16. A summary of key observations is offered in the bullets below.

- In surface and bottom layers throughout shallow and deep areas of the Northern and Southern Gulf, desalination represents the entire impact on maximum salinity. Under climate change, maximum salinity actually *decreases*. With desalination, maximum salinity is projected to rise from 5.5 psu in the lowest brine discharge scenario up to 16.5 psu in the highest brine discharge scenario.
- Desalination impacts on *maximum* salinity far exceed those on *average* salinity. This is evident throughout all regions of the Gulf. The ratio of maximum to average salinity under the highest brine discharge scenario ranges from 6 to 27. This is equivalent to a range in maximum salinity increase from 14.8 to 16.5 psu.
- Throughout the Gulf, the greatest impact on maximum salinity is associated with the lowest brine desalination scenario.
    - For shallow areas in the Southern Gulf, about 95% of the impact on maximum salinity is due to an average brine discharge rate of 50 tonnes per second. Even higher shares are evident for deep areas in the Northern Gulf for the same scenario. For both these regions, salinity increases by about 0.3 psu for every increase of 1 tonne per second of brine discharge, up to 50 tonnes per second; above this discharge rate (i.e., between 50 and 220 tonnes per second), salinity increases by only 0.003 psu for every increase of 1 tonne per second of brine discharge.
    - For deep areas in the Southern Gulf, between 53% and 66% of the impact on maximum salinity is due to an average brine discharge rate of 50 tonnes per second. Similar shares are evident for shallow areas in the Northern Gulf for the same scenario. For both these regions, salinity increases between 0.11 and 0.15 psu for every increase of 1 tonne per second of brine discharge, up to 50 tonnes per second; above this discharge rate (i.e., between 50 and 220 tonnes per second), salinity increases by a range of only 0.02 to 0.03 psu for every increase of 1 tonne per second of brine discharge.
    - The natural subsidence of high saline waters in the AG mostly explains the results described above. There is an initial impact from brine discharges on the overall salinity of the Gulf, especially on its bottom layers. Increasing salinity increases the density of these bottom waters, which will be flushed

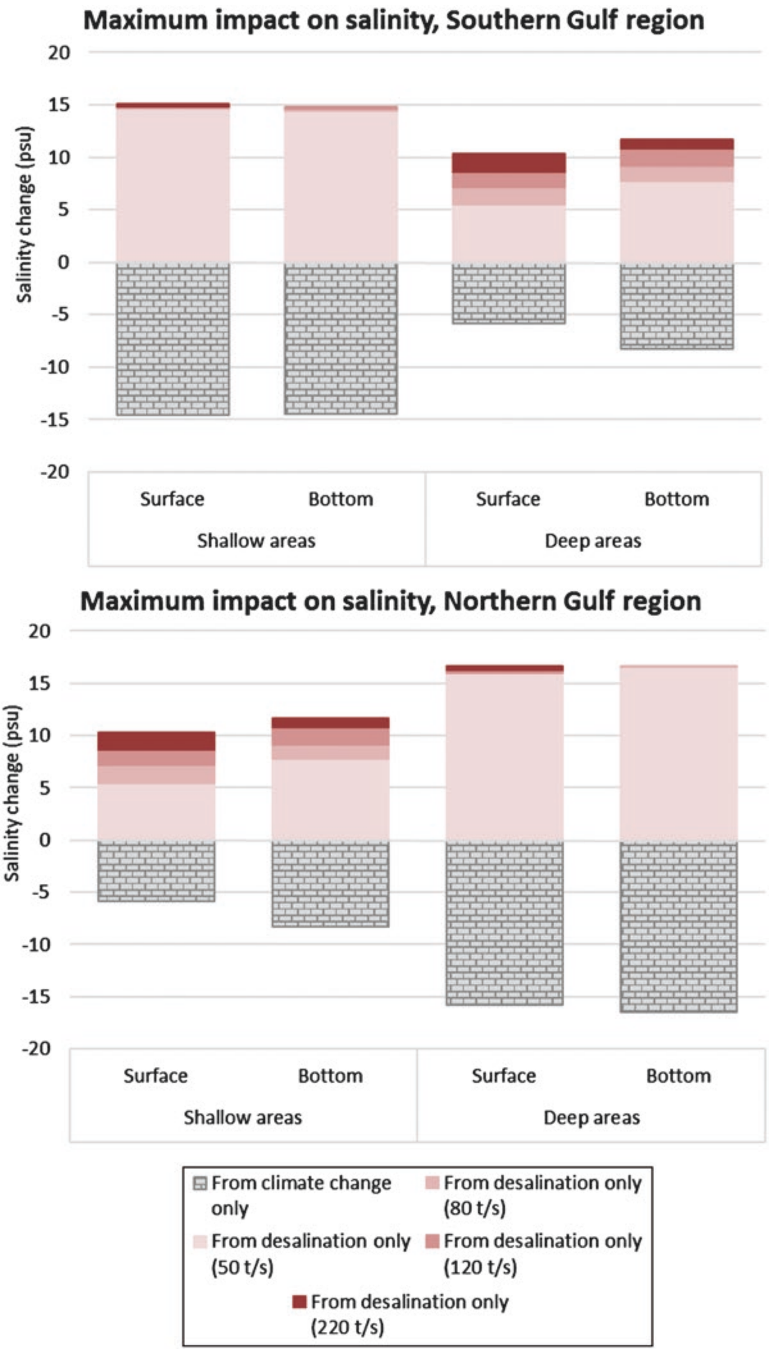


Fig. 6.16 Maximum salinity impacts in the Arabian Gulf from climate change and desalination

> out of the system. This effect, combined with the maximum freshwater inflow at surface, through Hormuz strait will slightly speed up the overturning system by the mid-twenty-first century.

The results pose significant implications for water resource management in the region. Water stress is a chronic condition for the Arabian Peninsula countries that has become one of the region's greatest planning challenges. The regional modeling results further complicate an already difficult water stress planning challenge. Increasing reliance on the Arabian Gulf as the sink for highly saline brine discharges from intensifying desalination activity will affect the physical properties of the Arabian Gulf such as temperature-salinity profiles, horizontal residual current patterns, and vertical mixing processes. In short, desalination activities – combined with what has been learned previously about climate change impacts – will significantly alter the Gulf's major physical properties, depending on location and depth. This is particularly noteworthy for RO technology, the preferred future desalination technology in the UAE, experiences efficiency losses with greater salinity levels of the seawater intake. Increased salinity of nearshore shallow areas in the Gulf may render the future use of reverse osmosis technology problematic.

There are numerous options and measures to mitigate the incremental changes in salinity and temperature from brine concentrate disposal (Cooley et al. 2013; Younos 2005; Laspidou et al. 2010; Bombar et al. 2016; Jenkins et al. 2012; NRC 2008). Each disposal method has a unique set of advantages and disadvantages. It is recommended that planners in the region consider a number of key factors within future efforts to limit adverse impacts to the Gulf from desalination activities. These factors include the volume or quantity of the concentrate, the quality of the concentrate, the location of the desalination plant, capital and operating costs, and the ability for future plant expansion, among others. A brief overview of selected potential options is provided in the bullets below (Younos 2005).

- *Disposal to Front of Wastewater Treatment Plant.* This option would involve the delivery of brine via pipeline to the front of a wastewater treatment plant. This would eliminate brine discharges to the Gulf, but one major concern would be that if the concentrate volume is too large, the level of total dissolved solids in the brine concentrate could have a significant impact on the biological treatment process, possibly to the point of disrupting treatment performance.
- *Disposal to End of Wastewater Treatment Plant.* This option would involve the delivery of brine via pipeline to the back of a wastewater treatment plant and mix the brine concentrate with the treated water effluent. Mixing the treated wastewater with the high total dissolved solids of the brine concentrate would dilute the brine.
- *Land Application.* This option would involve the disposal of brine on land using spray irrigation, infiltration trenches, and/or percolation ponds. In this option, the brine concentrate could be used to irrigate salt-tolerant crops and grasses such as those used on golf courses. The feasibility of the option depends on the availability of land, the local climate, vegetation tolerance to salinity, and the location of the groundwater table.

- *Deep Well Injection.* This option would involve the injection of brine concentrate into deep aquifers that are not used for drinking water or amenity purposes. The depth of the injection wells typically ranges between 0.3 and 2.6 km below the earth's surface. Factors controlling the viability of this option are geologic conditions, regulatory constraints, and proximity to aquifers for drinking water.
- *Evaporation Ponds.* This option would involve the construction of evaporation ponds where brine evaporates while salts accumulate at the bottom of the pond. The Gulf region's high evaporation rates actually favor this option. Pond liners would be needed in order to prevent saline water from leaking into the groundwater.
- *Zero Liquid Discharge.* This option would involve the use an evaporator device to convert the liquid brine concentrate into a dry solid which could then be disposed of in a landfill. As a result, the brine water disposal challenge is converted into a solid waste disposal. Proper design of the landfill would be needed to prevent chemical leaching into the groundwater.
- *Brine Concentrators.* This option would involve the use of brine concentrators to reduce the volume of concentrate to about 2% of intake flow. Brine concentrators consist of heat exchangers, deaerators, and vapor compressors to convert liquid concentrate to concentrated slurry. With this technology, roughly 95% of wastewater can be recovered as high-purity distillate with a concentration of total dissolved solids less than 10 mg/liter.

4 Water-Energy Nexus

In the UAE, water resource management has been recognized as a serious emerging challenge to long-term sustainable development (Rizk and Alsharhan 2003; Bollaci et al. 2010; Dawoud and Sallam 2012). Domestic, agricultural, and industrial water consumption have increased at annual rates roughly consistent with the population growth rate, suggesting that little conservation or efficiency improvements are taking place. Energy management has also been recognized as a serious challenge to long-term sustainable development (Mezher et al. 2011; Alfaris et al. 2016; Aswad et al. 2013; Sgouridis et al. 2013). This is in large part due to the role of energy-intensive desalination activities which accounts for an increasing share of water supply. This suggests that reliance on desalination is as much an energy challenge as it is a water challenge in the UAE.

The overall goal of the study was to better understand water-energy nexus challenges in the UAE in the face of climate change and rapid socioeconomic development. The major research questions underlying the methodological approach were twofold. First, what would be the future benefits – as measured in water savings, energy savings, and greenhouse gas emission reductions – associated with various scenarios that aim to promote energy efficiency, renewable energy, and water resource conservation under climate change? Second, what would be the costs associated with shifting to such scenarios and away the current baseline development trajectories? A planning period of 2010 through 2060 was considered.

4.1 Approach

Addressing these questions required an analytical framework capable of accounting for water, energy, and climate interactions in an integrated way at the national level in the UAE. On the water demand/supply side, the Water Evaluation And Planning (WEAP) modeling system was used (Yates et al. 2005). On the energy demand/supply side, the Long Range Energy Alternatives and Planning (LEAP) modeling system was used (Heaps 2008). Extensive data acquisition efforts were undertaken to populate both model databases relative to historical water and energy supply/demand, power plant inventory, future energy/water demand projections under business-as-usual conditions, and associated capacity expansion plans. Information was obtained from local agencies including the Abu Dhabi Water and Electricity Company (ADWEC); the Abu Dhabi Water and Energy Authority (ADWEA); the Dubai Electricity and Water Authority (DEWA); the Sharjah Energy and Water Authority (SEWA); and the Environment Agency of Abu Dhabi (EAD). In addition, publicly available international data from the International Energy Agency (IEA 2015) and the US Energy Information Administration (EIA 2016) were also obtained to address data gaps. Extensive stakeholder consultations were convened to vet the collected data, solicit feedback on system challenges, and establish appropriate cost, performance, and other assumptions (Yates et al. 2016).

The WEAP water system model was disaggregated by water use type and geographic location to capture current and future water use trends. Drivers of the water system include agricultural production, population growth, and demand across the municipal sector, wastewater treatment capacities, desalinated water production, groundwater availability/recharge, and other characteristics. The model was calibrated relative to historical water use patterns using a monthly time step to examine water quantity availability and to balance supplies and demands across the country. To capture the impact of climate change, a soil moisture model was incorporated into WEAP that tracked the relationship between temperature change and outdoor water use. Indoor water use was assumed to occur on a per capita basis and independent of climate. A schematic view of the model is shown in Fig. 6.17 showing water supply (green lines) and demand (red dots) and their linkages.

The energy system model accounted for all processes, sectors, resources, technologies, and policies implicated in the fuel cycle from resource extraction to end use. On the energy demand side, residential, industrial, commercial, and transport energy demand sectors were included. Within each demand sector, all energy uses (i.e., of liquid petroleum gas (LPG), coal, natural gas, fuel oil, electricity) were accounted for throughout the planning period. On the energy supply side, the model included transformation of primary fuels that include all possible energy sources. This included fossil-based resources such as natural gas, crude oil, and coal. It also

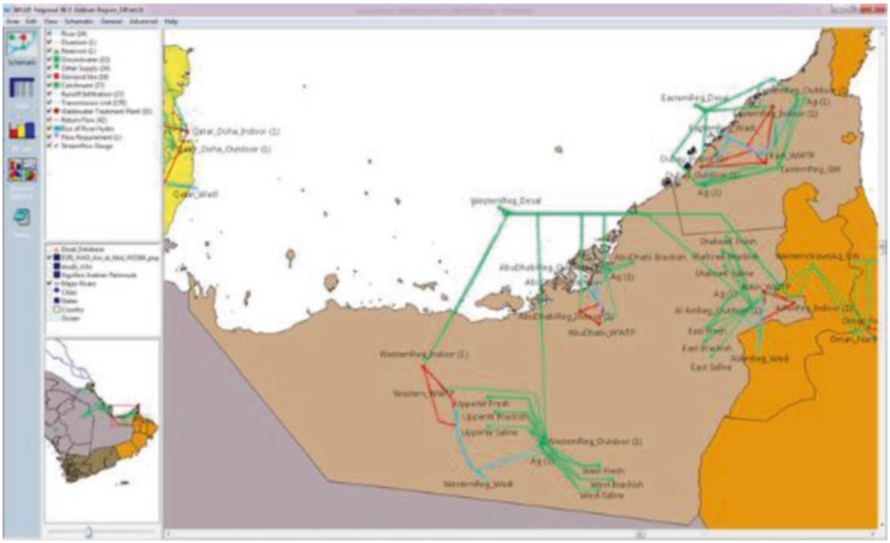


Fig. 6.17 Schematic representation of the national water system model

accounted for renewable resources such as solar thermal, solar photovoltaics, wind, and biomass. Nuclear power was also included in the model to account for the Baraka power station due online in the coming years. The structure of the energy system model focused particularly on the power supply sector because it figures so prominently in the production of desalinated water through cogeneration. The model was calibrated relative to historical energy demand and supply patterns and accounted for the impact of higher future temperatures under climate change on electricity use (primarily air conditioning loads). Figure 6.18 provides the outputs of a simulation of energy flows in the form of a Sankey diagram.

The two calibrated models were then coupled via a software link, producing an integrated water-energy system model that was used to characterize the water-energy nexus over the 50-year planning period under a business-as-usual (BAU) scenario, with and without climate change. The integrated model was then used to explore three policy scenarios under climate changed conditions, as summarized in Table 6.4 and described below:

- *High efficiency and conservation scenario:* Assumes the implementation of aggressive policies to reduce the consumption of water and electricity on the demand side. The overall aim of this policy scenario is to reduce per capita water and energy use across the country.
- *Natural resource protection scenario:* Assumes the implementation of aggressive supply-side policies to conserve its natural resources, specifically groundwater and energy. The overall aim of this policy scenario is to protect fossil groundwater resources from any further depletion and to reduce the use of fossil fuels.
- *Integrated policy scenario:* Assumes the collective implementation of all policies collectively. The overall aim of this policy scenario is to optimize efficiency

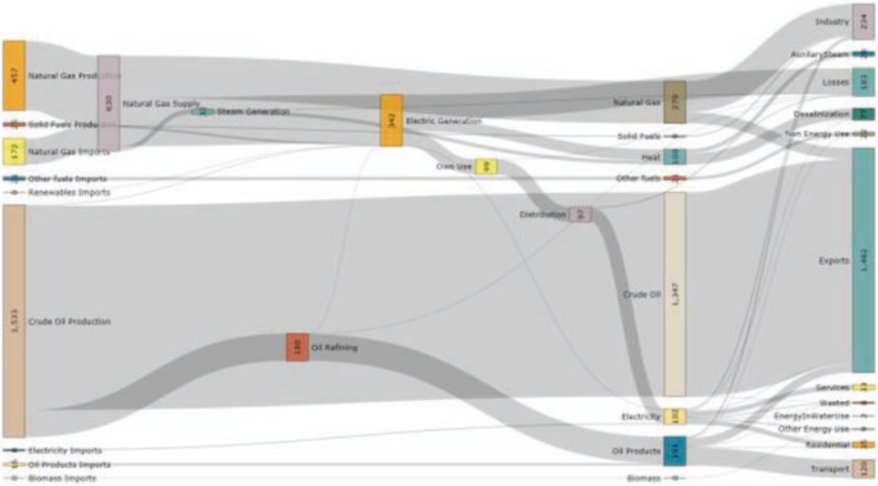


Fig. 6.18 LEAP simulated energy flows given as a Sankey diagram in GWh, 2013

Table 6.4 Specific policies analyzed within the water-energy nexus policy scenarios

Sector	High efficiency and conservation scenario	Natural resource protection scenario
Water policies	1. Indoor water use efficiency and conservation program	1. Fossil groundwater phaseout
	2. Introduction of outdoor garden and amenity caps	2. Increased use of treated sewage effluent
	3. Improved irrigation efficiency	3. Sustainable desalination
	4. Water loss reduction program	
Electricity policies	5. Demand side electric efficiency and conservation program	5. Carbon dioxide cap
	6. Peak load management of space cooling load	6. Renewable portfolio standard 7. Clean coal capacity cap

and natural resource protection in the country. The scenario assumes a future in the UAE where there is a broad consensus among national policymakers that the policies and measures embedded in the *high efficiency* and *natural resource protection* scenarios are essential to the sustainability of water and energy.

4.2 Results

Table 6.5 summarizes the resulting costs and benefits associated with the implementation of the policy scenarios within the water-energy nexus. Costs represent the costs to society from the implementation of the policies, rather than any segment of society. Benefits are presented in physical units and are associated with water savings, electricity savings, and greenhouse gas emission reductions. Costs and

Table 6.5 Summary of costs and benefits associated with the implementation of the policy scenarios

Impact	Alternative scenario	Starting scenario	Cumulative benefits (2015–2060)			Total incremental cost (billion 2015$)	Avoided CO2e emissions from policies ($ per tonne
			Water savings (BCM)	Fossil fuel savings (GWh)	CO2e reductions (million tonnes)		
From climate change, only	BAU-RCP8.5	BAU	−5	−470	−138	4	NA
From introduction of improved efficiency and conservation measures	High efficiency and conservation	BAU-RCP8.5	28	1600	283	−3	−$10.2
From introduction of renewable energy and reductions in groundwater withdrawals	Natural resource protection	BAU-RCP8.5	0	4200	933	12	$13.2
From introduction of all sustainable development measures	Integrated policy	BAU-RCP8.5	28	4400	845	3	$3.4

benefits are incremental in nature; that is, they result from shifting the development pathway from the BAU to each of the other alternative development pathways. Major highlights are briefly described in the bullets below relative to cumulative impacts over the 2015–2060 planning period.

- Under the BAU-RCP8.5 scenario (i.e., with climate change), there is a net increase in cumulative GHG emissions of 138 MMT when compared to the BAU scenario. Climate change results in increased water use and energy use and results in an additional cost of about $4 billion to meet water and energy demand over the period.
- Under the high efficiency scenario, there are cumulative reductions of GHGs (i.e., 283 million tonnes of CO2e avoided) that come at a negative cost (i.e., −$3 billion). This means that the implementation of efficiency measures *saves* money and offers a cost-effective way to reduce greenhouse gas emissions (i.e., UAE society would receive a $10.2 benefit for every tonne of CO2e avoided). This is true even at the conservatively assumed high value of the levelized cost of achieving efficiency targets used in this study.
- Under the natural resource protection scenario, there are the largest savings of GHGs but at the highest incremental costs of saved CO2e, as the shift from fossil

fuel generation to solar-based generating increases the incremental costs of energy by $12 billion and a positive cost to society of reducing CO2e emissions (i.e., $13.2 per tonne avoided). The scenario implies the need to add solar energy at an extraordinary level to maintain projected levels of future energy consumption. While there are cost savings due to reduced groundwater pumping, water supply costs are shifted to the electricity generation sector, as desalinated water is the substituted source for avoided groundwater use.

- Under the integrated policy scenario, there is a modest increase in the incremental cost, which again is heavily dependent on the assumption of the levelized costs of efficiency and conservation, the levelized costs associated with new solar capacity, and the assumption that new solar capacity can be accommodated on the power system, particularly with regard to energy storage. Both the cost of saved CO2e and water are positive, albeit smaller than those of the natural resource protection scenario, since the demand for water and energy have been reduced from the implementation of efficiency and conservation measures.

The results of the study confirm that green growth objectives that will increase the resilience of the water-energy nexus in the UAE under climate change can be achieved cost-effectively. Some key implications for green growth in the UAE include the following:

- Assessing national green growth scenarios in the context of climate change in a hyper-arid environment where energy-intensive desalinated water makes up a significant share of water supply requires a focus on both water and energy. The water-energy nexus approach offers an analytical framework that considers water and energy as an integrated system where alternative policy scenarios can be readily evaluated.
- Pursuing an economic diversification agenda employing a green growth framework can lead to significant environmental benefits. These benefits can be achieved at net economic savings in the case of a scenario emphasizing energy/water efficiency investments (−$10.2 for each tonne of CO2e avoided) and at modest economic cost in the case of a scenario emphasizing renewable energy investments ($13.2 for each tonne of CO2e avoided). Taking advantage of the synergies across efficiency and renewable green growth strategies achieves maximum benefits at very low cost ($3.4 for each tonne of CO2e avoided).

5 Health-Energy Nexus

Climate change threatens human health and well-being, particularly in urban areas (Barata et al. 2011; Campbell-Lendrum and Corvalán 2007; Ebi 2011). A warmer climate with greater frequency of extreme weather events will exacerbate a range of adverse health impacts associated with deteriorating air quality, increasing transmissivity of water; vector and foodborne diseases, an expanding geographical range of certain diseases; heat-related illnesses; and casualties related to more frequent flash-flooding episodes (Fann et al. 2016; McMichael 2011; Smith et al. 2014). Of these, the health-energy nexus under climate change has been explored through a selective focus on urban air quality; specifically, the linkages between urban morbidity/mortality and energy-related air pollutant emissions occurring in an increasingly warmer climate.

Air pollutant emissions from the combustion of fossil fuels in the power supply, transport, and industrial sectors contribute to a number of adverse impacts on human health in urban areas (WHO, 2010; Ostro 2004; Costello et al. 2009; Pascal et al. 2013). They are a function of many factors such as urban population, economic activity, modes of travel/movement, energy sources of electricity, and the efficiency with which energy is used. Particulate matter (PM) emissions, especially fine particulates less than 2.5 microns in diameter, pose a serious threat to human health as they can penetrate deep into the lungs, while emissions of nitrogen oxides (NO_x) and volatile organic compounds (VOC) react in the presence of sunlight to form ground-level ozone (O_3), a primary ingredient in smog that reduces visibility in urban areas and irritates the respiratory system, causing coughing, choking, and reduced lung capacity (Chen et al. 2013; Fajersztajn et al. 2013; Stern et al. 2013). Epidemiological studies have reported associations between an increase in daily levels of O_3 and PM and an increase in days following of mortality and hospital admissions predominantly related to respiratory and cardiovascular diseases (Pascal et al. 2013).

Caring for and improving the health of the overall population is a key policy priority in the UAE, with growing interest on the linkages between outdoor air quality and human health (Mohamed et al. 2017; Barakat-Haddad et al. 2015;MacDonald Gibson et al. 2013). In Abu Dhabi, the largest emirate in the UAE, addressing environmental factors such as air pollution from industrial and other activities are explicitly understood to intersect with public health goals and priorities (DHAD 2018). Addressing climate change has also become a key policy priority, particularly in the Abu Dhabi emirate, where a draft climate change strategy (hereafter the "Strategy") was developed in 2014 that focused on reducing energy-related emissions of greenhouse gases (GHG) through accelerating the adoption of low carbon fuels and technologies, practices, and processes by utilities and end users across the residential, commercial, transport, and industrial sectors.

Specific measures within the Strategy aim to improve fossil-fired power generation efficiency, reduce transportation demand, introduce renewable energy, and reduce per capita electricity and water use. If implemented, these measures will result in significant GHG emission mitigation in Abu Dhabi while also reducing emissions of local air pollutant emissions and thereby improving local air quality. Ultimately, lower atmospheric concentrations of O_3 and PM will enhance public health, an important though unquantified co-benefit of the Strategy. Hence, to explore the energy-health nexus under climate change, a public health co-benefits analysis was undertaken for the Abu Dhabi City metropolitan area.

The overall goal of the study was to quantify the linkages between morbidity/mortality and energy-related air pollutant emissions as the metropolitan area experiences increasing temperatures associated with climate change. The major research question was: Are there significant public health co-benefits in the greater Abu Dhabi City metropolitan area associated with the Strategy? Specifically, can a reliable estimate be developed regarding the number of avoided premature deaths and the number of avoided excess health-care facility visits due to the Strategy's implementation, in part or in whole? Addressing this question involved extensive local data acquisition and focused on several interlinked issues such as regional climate change modeling, energy demand projections, air pollutant emission inventory development, air quality modeling, demographic characterizations, and epidemiological research.

5.1 Approach

The key elements of the analytical approach are illustrated in Fig. 6.19. It first involves estimating energy use and associated air pollutant emissions with and without the implementation of the Strategy. The impact of emissions on air quality was estimated through parameterized air quality modeling techniques. Changes in air quality were then calculated as the difference in ambient air pollutant concentrations of PM and O3, again with and without the Strategy. Finally, these changes in ambient air pollutant concentrations were translated into public health co-benefits (i.e., avoided premature deaths, avoided excess health-care facility visits) through the application of a series of UAE-specific dose-response functions that have been developed as part of the Abu Dhabi Environmental Burden of Disease Assessment (MacDonald Gibson et al. 2013).

The greater Abu Dhabi City metropolitan area was the spatial focus of the assessment. This is a region of approximately 3800 square kilometers and is shown in Fig. 6.20. The metropolitan and adjacent offshore areas were divided into a total of 462 grid cells, each sized 4 km by 4 km matching the previously discussed regional atmospheric modeling spatial resolution. The area includes current high population density areas of about 1030 people/km^2 within Abu Dhabi Island. It also includes surrounding areas where urban expansion plans call for significant future residential and industrial zones to the south and east.

The analysis focused on energy and water supply and demand in several key sectors, namely, electricity generation, transport, and industry. A total of 17 specific measures from the Strategy were evaluated, along with potential targets, as summarized in Table 6.6. Three pollutants were modeled, $PM_{2.5}$, VOCs, and NO_x, together with chemical transformation in the atmosphere in the presence of sunlight for O_3. The years 2007 through 2035 comprised the planning period.

A scenario framework was developed to estimate the impact of GHG mitigation policies, as illustrated in Fig. 6.21. The "Business-as-usual" (BAU) or baseline scenario corresponded to a development pathway in which the Strategy is not implemented, and air pollutant concentrations increase over the planning period. The "policy" scenario corresponded to a future where Abu Dhabi's Climate Change Strategy is implemented in whole and air pollutant concentrations in the Abu Dhabi

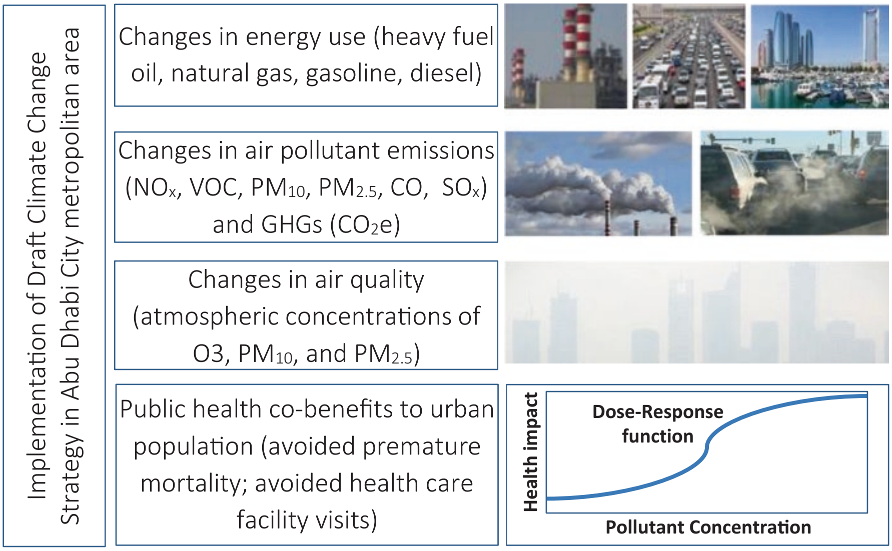
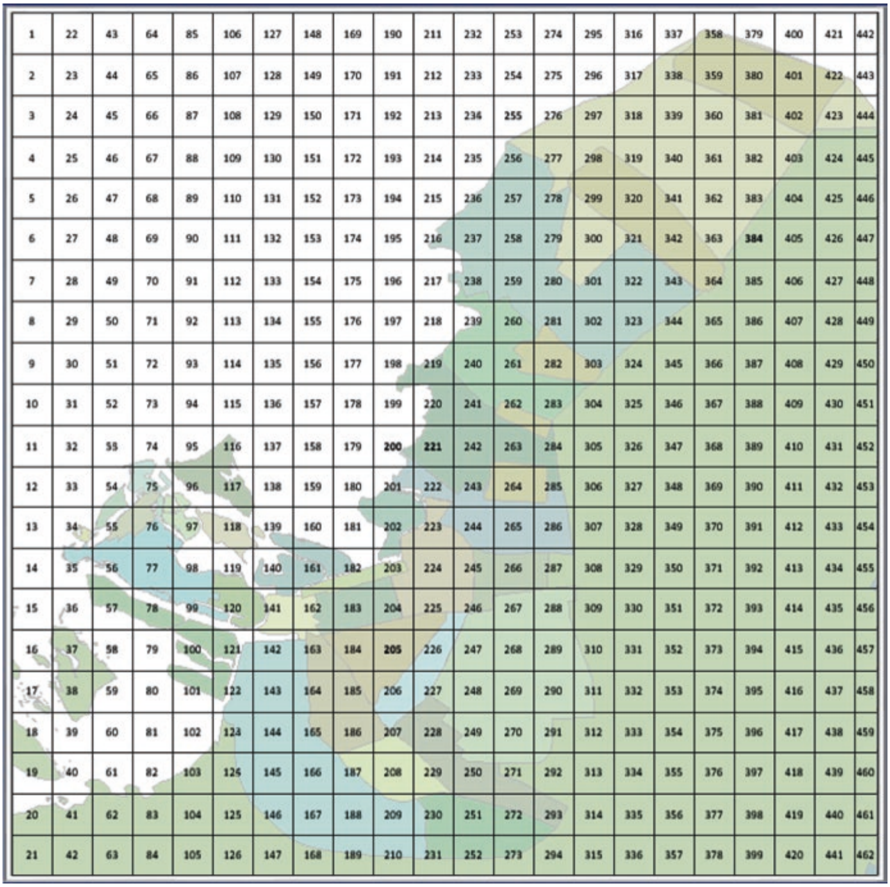


Fig. 6.19 Conceptual framework



1	22	43	64	85	106	127	148	169	190	211	232	253	274	295	316	337	358	379	400	421	442
2	23	44	65	86	107	128	149	170	191	212	233	254	275	296	317	338	359	380	401	422	443
3	24	45	66	87	108	129	150	171	192	213	234	255	276	297	318	339	360	381	402	423	444
4	25	46	67	88	109	130	151	172	193	214	235	256	277	298	319	340	361	382	403	424	445
5	26	47	68	89	110	131	152	173	194	215	236	257	278	299	320	341	362	383	404	425	446
6	27	48	69	90	111	132	153	174	195	216	237	258	279	300	321	342	363	384	405	426	447
7	28	49	70	91	112	133	154	175	196	217	238	259	280	301	322	343	364	385	406	427	448
8	29	50	71	92	113	134	155	176	197	218	239	260	281	302	323	344	365	386	407	428	449
9	30	51	72	93	114	135	156	177	198	219	240	261	282	303	324	345	366	387	408	429	450
10	31	52	73	94	115	136	157	178	199	220	241	262	283	304	325	346	367	388	409	430	451
11	32	53	74	95	116	137	158	179	200	221	242	263	284	305	326	347	368	389	410	431	452
12	33	54	75	96	117	138	159	180	201	222	243	264	285	306	327	348	369	390	411	432	453
13	34	55	76	97	118	139	160	181	202	223	244	265	286	307	328	349	370	391	412	433	454
14	35	56	77	98	119	140	161	182	203	224	245	266	287	308	329	350	371	392	413	434	455
15	36	57	78	99	120	141	162	183	204	225	246	267	288	309	330	351	372	393	414	435	456
16	37	58	79	100	121	142	163	184	205	226	247	268	289	310	331	352	373	394	415	436	457
17	38	59	80	101	122	143	164	185	206	227	248	269	290	311	332	353	374	395	416	437	458
18	39	60	81	102	123	144	165	186	207	228	249	270	291	312	333	354	375	396	417	438	459
19	40	61	82	103	124	145	166	187	208	229	250	271	292	313	334	355	376	397	418	439	460
20	41	62	83	104	125	146	167	188	209	230	251	272	293	314	335	356	377	398	419	440	461
21	42	63	84	105	126	147	168	189	210	231	252	273	294	315	336	357	378	399	420	441	462

Fig. 6.20 Gridded 4-km spatial domain of the Abu Dhabi City metropolitan area

Table 6.6 Policies considered in assessing public health co-benefits in the Abu Dhabi City metropolitan area

Policy		
No	Description	Targets
1	Nuclear power generation	4 units each with a net capacity of 1345 MWe, coming online in 2017, 2018, 2019, and 2020
2	Renewable energy power plants	Start year: 2020, with 10% of all generation coming from non-GHG-emitting renewable sources by 2035
3	One renewable energy water desalination pilot project	Online year: 2020 for a 100-MW solar PV station
4	Renewable energy water desalination plants	Online year: 2020 for 100-MW concentrating solar power stations (Shams 1) and 10 MW concentrating solar power stations (Masdar)
5	Waste-to-energy power plants	Online year: 2020 for a 50-MW waste-to-energy plant
6	Feed in tariff to sell power to the grid	Start year: 2020, with the feed-in tariff leading to an incremental 10% of all generation coming from non-GHG-emitting renewable sources by 2035
7	Solar roofs	Start year: 2020, resulting in 10% of all generation coming from distributed generation in solar roofs by 2035
8	Supply-side energy efficiency strategy for electricity and water production	Start year: 2020, resulting in 1.0%/year improvement through 2035 in the heat rate (i.e., combustion efficiency) of the following power stations: Taweelah New Extension, Taweelah A2, Shuweihat S1, and Sas Al Nakhl
9	Demand-side management strategies for electricity and water production	Start year: 2020, 10% savings in new residential construction by 2035
10	Current Estidama initiative	Start year: 2020, 10% electric savings of new commercial buildings by 2035
11	More stringent building codes for energy conservation	Start year: 2020, 10% of new home floor space included in program by 2035
12	Energy efficiency standardization and labeling program	Start year: 2020, 10% electricity savings in residential sector by 2035
13	Transportation demand strategies	Start year: 2020, with passenger car and passenger light vehicle kilometer traveled growth rates half of what they were in the baseline scenario (i.e., 0.17%/year versus 0.34%/year)
14	Encourage purchase of high-efficiency vehicles	Start year: 2020, with sales of passenger cars and light duty trucks reaching 50%–50% mix of plug-in hybrid and electric vehicles by 2035 and all other vehicle sales (taxis, motorcycles, heavy trucks, buses, minibuses) reaching 100% high-efficiency vehicles by 2035
15	Gas flaring reduction in oil and gas industry	Start year: 2020, with flaring growth rates half of what they were in the baseline scenario
16	Energy efficiency at industrial cogeneration facilities	Start year: 2020, resulting in 1.0%/year improvement through 2035 in the heat rate of the following facilities: Asab Agd II, Ruwais Refinery, Habshan, Bu Hasa Adgas, Al Wagan, Sheikh Khalifa hospital, Mussafah Industrial City
17	Energy efficiency in aluminum production	Start year: 2020, resulting in 1.0%/year improvement through 2035 in the heat rate of the Taweelah aluminum smelter

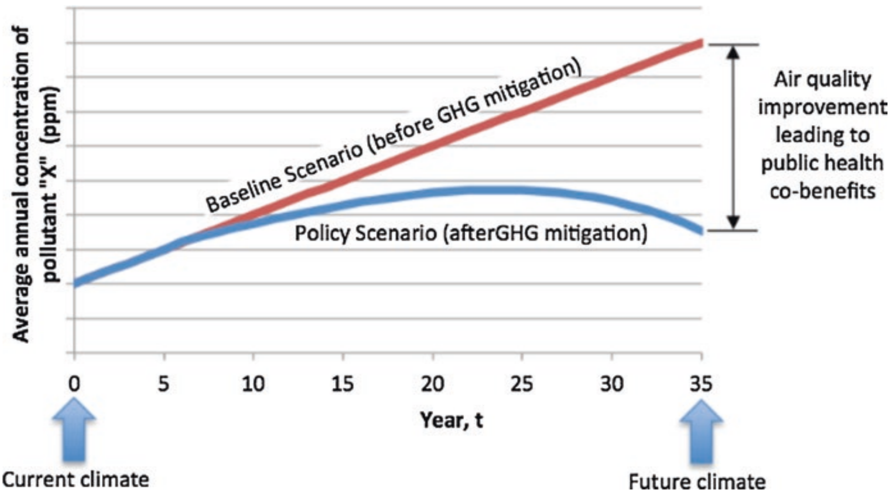


Fig. 6.21 Idealized representation of the scenario analysis approach

City metropolitan area decrease over the planning period, leading to public health co-benefits.

A comprehensive modeling framework was constructed for modeling energy use to air emissions to air quality impacts to health co-benefits. An idealized representation of the key components and analytical flow sequence appears in Fig. 6.22 and briefly described below.

Three source emission models for the power supply, transport, and industrial sectors were developed. These models tracked energy consumption over time and associated stationary and mobile air pollutant emissions. Each model is briefly described in the bullets below.

- *Power/water supply:* This model represented the capacity planning and dispatching of electricity and desalinated water within the Abu Dhabi emirate. It included all capacity, generation, and electricity transmission components that together comprise operations of the Abu Dhabi Water and Electricity Authority (ADWEA). The model captured changes in power supply system characteristics under both the BAU and policy scenarios.
- *Transport:* This model represented current and future travel conditions within the Abu Dhabi City metropolitan area. It codified assumptions embedded in the travel demand model developed by the Department of Transportation for Abu Dhabi's Surface Transportation Master Plan (DoT 2009; DoT 2013). Transport sector emissions were associated with private, commercial, and public on-road vehicles (i.e., passenger cars and light trucks, taxis, heavy trucks, buses, and minibuses). The model accounted for conventional internal combustion and compression vehicle technology, higher gasoline/diesel vehicles, compressed natural gas (CNG) vehicles, as well as emerging light duty vehicle technologies such as hybrid electric, plug-in hybrid electric, and all-electric vehicles.

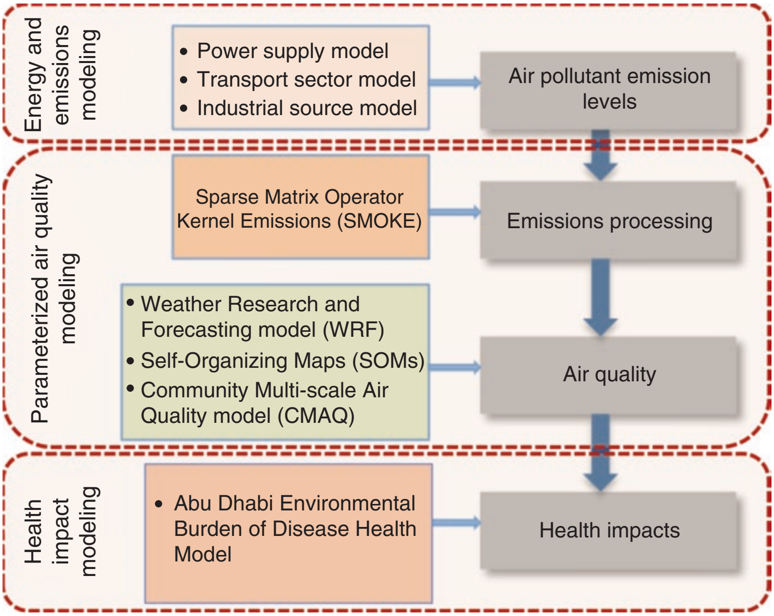


Fig. 6.22 Idealized representation of the modeling framework

- *Industry:* The industrial model represented current and future productive activities within key sub-sectors in the Abu Dhabi City metropolitan area. Both onshore and offshore industrial facilities were considered. For onshore facilities, the focus was on process heat and power generation aluminum production and oil refining. For offshore facilities, the focus was on oil and gas operations. Together, these activities represent a large share of air emissions associated with industrial activities.

The starting point for the air quality parameterization process was previous CMAQ modeling for the UAE for 2007. This modeling effort was undertaken by researchers at the University of North Carolina as part of the Environmental Burden of Disease Assessment (MacDonald Gibson et al. 2013). The CMAQ pollutant concentrations dataset was post-processed to create pollutant concentrations centered over the Abu Dhabi City metropolitan area for the 2007 base year. Broadly, this involved extracting CMAQ pollutant concentration output data at a 12-km resolution and interpolating these outputs to the 4-km spatial resolution used in the regional atmospheric modeling using WRF.

For 2035, the parameterization of pollutant concentrations of NO_x, VOCs, and $PM_{2.5}$ from stationary and mobile sources involved several steps. These steps aimed at accounting for the lateral dispersion and vertical mixing of the projected pollutant emissions over the Abu Dhabi City metropolitan area and involved accessing stationary/mobile source emission inventories; developing gridded pollutant dispersion estimates; developing vertical pollutant dispersion estimates; and accounting for increasing temperatures in 2035. Finally, average annual air pollutant concentrations were estimated for each of the 462 grid cells. For the 2008–2034 intervening years, grid cell air pollutant concentrations were estimated by simple interpolation techniques using results from 2007 and 2035 and calibrated to policy start years.

Ozone concentrations for the 2007 base year were estimated using the observations from available air quality monitoring stations located around Abu Dhabi. The distribution of ozone was then estimated by using the spatial distribution pattern of the NO_X emissions and scaled to the distribution of ozone observed at the air quality monitoring stations for the 2007 base year. For 2035, the NO_X change fields for the baseline and policy scenarios were used to adjust the level of ozone from the 2007 baseline. The spatial distribution of ozone was then mapped to the spatial distribution of NO_X for 2035. For the 2008–2034 intervening years, grid cell air pollutant concentrations of O_3 were estimated by simple interpolation techniques using results from 2007 and 2035 and calibrated to policy start years.

The final step in the analytical sequence was to translate changes in ambient air pollution concentration associated with the Strategy to public health co-benefits within the Abu Dhabi City metropolitan area. The scope and calculation of public health benefits associated with a change in air pollutant concentrations relied exclusively on the algorithms in the outdoor air quality health model from the Abu Dhabi Environmental Burden of Disease Assessment (Macdonald Gibson et al. 2013). Quantification metrics were avoided premature deaths and avoided excess healthcare facility visits. These categories focus on a range of adverse health impacts associated with ambient air concentration of particulate matter (which include sulfates) and ozone (which is formed from emissions of nitrogen oxides and volatile organic compounds). Health impact quantification was calculated for each grid cell taking into account population characteristics and aggregated overall grid cells to estimate the total health co-benefits in the Abu Dhabi City metropolitan area associated with the implementation of the 17 policies in the Strategy.

5.2 Results

The energy savings and emission reductions associated with the implementation of all policies are shown in Table 6.7. The collective impact of the Strategy is significant, resulting in a sharp decrease in fossil fuel use and associated air emissions.

Relative to the BAU scenario in 2035, the fuel savings achieved by the policies range from 41% for natural gas, mostly associated with lower per capita electricity consumption and new solar photovoltaic installation and nuclear units, to 91% for gasoline, mostly associated with the introduction of high-efficiency, plug-in hybrid, and all-electric vehicle technology. Cumulative fuel savings over the planning period reach 371 million tonnes of oil equivalent (TOE) by 2035, roughly equivalent to 6 years of average annual energy consumption in the Abu Dhabi City metropolitan

Table 6.7 Fuel savings and air emission reductions associated with the Strategy

Category	Fossil fuel	Fuel savings		
		In 2035, relative to BAU		Cumulative (million TOE)
		Million TOE	% reduction	
Energy	Natural gas	26	41%	312
	Diesel	3	42%	26
	Fuel oil	0	39%	0
	Crude oil	1	38%	9
	Gasoline	4	91%	24
	Total	35	44%	371
Air emissions	Pollutant or greenhouse gas	Emission reductions		
		In 2035, relative to BAU		Cumulative (physical units) 2035
		Physical units	% reduction	
	NO$_x$ (Gg)	457	60%	3057
	VOC (Gg)	539	46%	5215
	PM$_{2.5}$ (Gg)	484	41%	5710
	CO2$_e$ (000 Gg)	86	44%	902

area over the 2020–2035 period. Relative to the BAU scenario in 2035, air emission reductions achieved by the Strategy range from 41% for PM$_{2.5}$ to 60% for NO$_X$, while CO$_2$e emissions that contribute to climate change show a 44% reduction.

Air quality changes in 2035 for PM$_{2.5}$ and O$_3$ associated with the implementation of all policies are shown in the maps in Fig. 6.23. As shown in the figure, the collective impact of the Climate Change Strategy is significant, resulting in improvements in air quality, especially around the location of stationary sources of pollution. For PM$_{2.5}$, most grid cells show air quality improvement between 274 and 549 μg/m^3, with improved air quality exceeding 800 μg/m^3 in the industrial area in the northern part of the metropolitan area. For O$_3$, most grid cells show air quality improvement between 82 and 164 μg/m^3, with improved air quality exceeding 245 μg/m^3 in the industrial area.

Public health co-benefits associated with the improvement in air quality are summarized in Table 6.8. As shown in the table, the collective benefits to public health in the Abu Dhabi City metropolitan area from the implementation of the Climate Change Strategy are significant, resulting in a cumulative 3209 avoided premature deaths from reductions of particulate matter and ground-level ozone atmospheric concentrations, or roughly 9 premature deaths avoided per TOE of fossil fuel savings. A cumulative total of 82,853 excess health-care visits are projected to be avoided by 2035 due to the implementation of all policies, or roughly 223 excess health-care visits avoided per million TOE of fossil fuel savings.

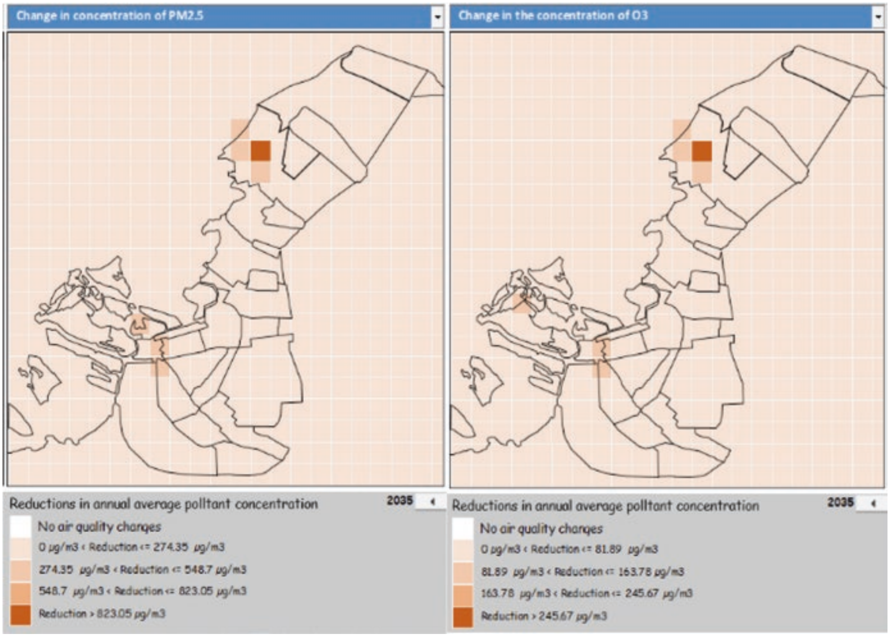


Fig. 6.23 Air quality changes by grid cell associated with the implementation of the Strategy, 2035

Table 6.8 Public health co-benefits associated with the Strategy

		Health co-benefits	
Parameter	Associated with	In 2035, relative to BAU	Cumulative through 2035
Avoided premature deaths	Lower $PM_{2.5}$ concentration	317	2896
	Lower O_3 concentration	34	313
	Total	351	3209
	Per million TOE saved	10	9
Avoided excess health-care facility visits	Lower $PM_{2.5}$ concentration	4512	40,769
	Lower O_3 concentration	4486	42,084
	Total	8998	82,853
	Per million TOE saved	259	223

6 Conclusions

The results of study provide a window into the scale of challenges and potential opportunities associated with the management of energy, water, and health under climate change in the UAE. First, the regional modeling studies indicate that climate change will render an extreme hyper-arid climate even more so, while the waters of the Arabian Gulf will experience heightened salinity, changing circulation patterns, and higher temperatures under intensifying desalination activities rendering several locations in the Arabian Gulf where the increased salinity of intake water may render the future use of reverse osmosis technology problematic. The results of scenario analysis of the energy-water nexus show that a range of water/energy efficiency and renewable energy measures can lead to significant increases in system stability while reducing annual greenhouse gas emissions, all coming at negative societal cost. Finally, the results of scenario analysis of the energy-health nexus study show that the gradual introduction of energy efficiency and renewable energy measures can lead to substantial decreases in premature mortality and health-care facility visits in urban areas.

Acknowledgments The authors would like to thank all the stakeholders of the Abu Dhabi Global Environmental Data Initiative's (AGEDI) Local, National, and Regional Climate Change (LNRCC) Programme for their valuable feedback. Special thanks go to Marco Vinaccia of AGEDI. The LNRCC Programme was a stakeholder-driven initiative designed to build upon, expand, and deepen understanding of the impacts of climate change on water, energy, health, and other resources at the local (Abu Dhabi), national (UAE), and regional (Arabian Peninsula) levels.

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Part III

Understanding the Dynamics of Climate Change and Energy Using Optimization and Econometric Modelling

Chapter 7
Leapfrogging to Sustainability: Utility-Scale Renewable Energy and Battery Storage Integration – *Exposing the Opportunities Through the Lebanese Power System*

Ahmad Diab, Hassan Harajli, and Nesreen Ghaddar

Abstract The current status of the Lebanese power system is characterized by a structural power supply deficit and transmission and distribution inefficiencies. In this chapter, the Lebanese power system is used as a case in point to showcase the importance of shifting the foundations of conventional thinking in power system planning into a new paradigm where renewable energy is adopted as priority choice.

The technical and economic feasibility of wind farms, solar PV, and battery energy storage systems is studied. Simulations are run using Homer pro to optimize for the lowest cost of electricity. Results show that incorporating utility-scale renewable energy systems and battery energy storage can decrease the overall levelized cost of electricity (LCOE) to $c7/kWh. Furthermore, without the integration of considerable storage capacity, an economic limit of approximately 20–25% renewable energy penetration is reached.

Sensitivity analysis is undertaken while adopting various values for the cost of natural gas and internalizing the social cost of carbon. Results confirmed a positive correlation between the cost of carbon and the price of natural gas on the one hand and system renewable energy fraction on the other hand. Introducing demand side management and increased grid flexibility also showed a high level of sensitivity to both system LCOE and the renewable energy fraction.

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H. Qudrat-Ullah, A. A. Kayal (eds.), *Climate Change and Energy Dynamics in the Middle East*, Understanding Complex Systems,
https://doi.org/10.1007/978-3-030-11202-8_7

Based on these results, the research strongly recommends that power system planning in the Middle East integrates modeling of renewable energy systems and the stacked benefits of utility-scale storage with the objective to achieve the highest combined technical, economic, and environmental benefits.

Keywords Sustainable energy transitioning · Utility-scale solar PV farm · Utility-scale wind farm · Utility-scale battery storage · Integrated energy system · Capacity value · Renewable penetration · Grid flexibility · Battery storage value streams · Economic carrying capacity

1 Introduction

1.1 Background and Objective

Power systems and technologies are constantly changing. New possibilities arise with new innovations, improved technical efficiencies, and better economic outlooks of alternative prevailing solutions, among other driving circumstances. A key current question for policy makers to respond to is when and how to introduce and/or expand on policies and measures that expedite the transition from a conventional "passive" power system into a more dynamic and "active" one with a high penetration rate of renewable energy. The motivation for this transition is sustainable development, in particular when social, economic, and environmental gains are expected. The transition to a more sustainable power system thus brings forward the need for power sector modeling and analysis in order to demonstrate both the technical viability and performance of the power system, in terms of adequacy and reliability, in addition to the social, economic, and environmental implications of different power provision pathways. The need to transition to a more sustainable energy mix is a commitment undertaken by all of the Middle East countries, as expressed in their climate change mitigation commitments under the Paris Agreement signed in 2015. Lebanon, for example, plans to meet 15% of the total power and heat demand by 2030 with renewable energy sources under the unconditional target and 20% of the total power and heat demand by 2030 under the conditional target (GoL 2015).

In this chapter, we study and model different combinations of utility-scale solar PV (photovoltaic) plants, onshore wind farms, and grid-connected battery energy storage systems (BESS) integrated into a power system. Different simulations are undertaken in order to provide a more thorough and comparative analysis of the outcomes of various renewable energy integration scenarios under assumptions of varying natural gas prices, carbon pricing, and availability of both demand side management and flexibility of conventional power plants.

The Lebanese power system is adopted as a case in point for two reasons. The first is internal to Lebanon, where the study will showcase the possibility for Lebanon's electricity sector to "leapfrog" from its current below-par performance (see Sect. 1.2) into a more sustainable system. The second is motivational. The methodology and analysis and results and implications of this study can serve as motivation for other countries in the region to undertake similar exercises and explore the benefits of such rapid paradigm shifts in power provision.

1.2 The Lebanese Electricity System

Lebanon's electricity sector is characterized by substandard operation with a significant gap between power supply and demand. On the generation side, the real onshore generation capacity of the national utility (EDL) is approximately 1800 MW, increasing to 2300 MW when considering the rented power ships and the power imported from Syria. The power generation units are split between heavy fuel oil-fired steam turbines, diesel-fired combined cycle gas turbines (CCGT), and diesel-fired open cycle gas turbines (OCGT). With respect to the electricity network, technical losses associated with the transmission and distribution of power amount to 13%, whereas nontechnical losses (i.e., uncollected bills and illegal connections) add a further 18% loss of power from a financial payback perspective. In 2018, the peak power demand is estimated at 3450 MW, yielding a physical power deficit of 1450 MW (reaching 1810 MW deficit if the total physical power and unbilled power deficits are combined) (CoM 2018). This situation causes daily structured blackouts that average 6 hours per day; however, this average masks areas such as the administrative capital Beirut, where 21 hours per day is secured from the national utility, and other areas where power cuts are more than 12 hours per day such as in the Bekaa (North-East Lebanon) region.

The current average cost of generating one unit of energy and delivering it to the consumer through the T&D network is approximately $c16.5/kWh, considering a price of oil of $65 per barrel (CoM 2018). The price has been as low as $c12/kWh and as high as $c26/kWh, depending mainly on the international price of oil.

The electricity tariffs in Lebanon have been set in 1996 when the price of oil was around $21 per barrel and to this day remain unchanged due to political reasons. This has caused and causes a large gap between the electricity tariff that is paid by consumers (approximately $c9.6/kWh for residential consumers and $c7.6/kWh for small industries) and the generation, transmission, and distribution costs that are incurred, as outlined above. The Government of Lebanon subsidizes the deficit of the utility company. Over the period 1992–2017, the sum of the public debt including interest that went to subsidize the operation of the utility company is USD 36 billion and forms approximately 45% of the gross public debt of the government (CoM 2018). Using an average value of lost load of 700 $/MWh, a recent study calculated a total loss for the Lebanese economy from the power sector over the period 2009–2014 of $23.23 billion (Bouri and El Assad 2016; EDF 2008; MEW 2010). The problems of the electricity sector have only been further augmented by more pressure due to an additional demand of approximately 486 MW emanating from the presence of over one million Syrian refugees in the country (UNDP 2017).

From an environmental perspective, the use of diesel and fuel oil and the presence of diesel-run neighborhood generators have severe environmental consequences.

In a study by (El-Fadel et al. 2010), the environmental performance of the Lebanese electricity system was studied and investigated using the life cycle assessment method. Results show that the electricity sector fares poorly on almost all environmental attributes, including human and terrestrial toxicity and greenhouse gas emissions.

In response to the abovementioned condition of the electricity sector, several policies and plans have been put forward, beginning with the Ministry of Energy and Water (MEW) Policy Paper. MEW (2010) put forward an action plan to transform the Lebanese power sector into an adequate and reliable one. The policy paper stresses on the immediate intervention in terms of rehabilitation of existing power generation plants, constructing new ones, investing in the transmission and distribution networks, and reforming the national utility. The main premise of the policy paper lies in the objective of meeting at least three-fourth of our power needs from natural gas and one-third from renewable energy sources. Renewable energy was further stressed in the National Renewable Energy Action Plan (NREAP), where the objectives of the MEW in terms of renewable energy are outlined. In specific, wind energy, solar PV and concentrated PV (CPV), concentrated solar power (CSP), solar water heaters (SWH), hydroelectric power, geothermal energy, and bioenergy are targeted (LCEC 2016). The NREAP indicated that Lebanon would reach a renewable energy share of 12% of primary energy demand (excluding transport) by 2020 and 15% by 2030. The latter target masks the fact that the predicted primary energy demand in 2030 is 52,000 GWh, whereas it is predicted to be only 29,500 GWh in 2020 (LCEC 2016). However, these targets are subjected to delays that are inherent in the Lebanese political system. To date, and since the publication of the policy paper (MEW 2010), only 220 MW of wind power projects have signed a power purchasing agreement (PPA) with the Government of Lebanon, whereas many of the other outlined objectives of the NREAP (LCEC 2016) in terms of utility-scale renewable energy penetration are still in the tendering phase and thus subject to the overall functioning of the political system.

1.3 Chapter Structure

Section 2 of this chapter presents a review and description on utility-scale solar PV plants, wind farms, and grid-connected battery energy storage systems while forecasting their costs and highlighting their combined prospects and limitations. Section 3 covers the methodology adopted and the simulation software used, along with their limitations. The results of the simulations and sensitivity analyses are presented and discussed in Sect. 4. Section 5 talks about the relevance of this work to the Middle East region. Recommendations and conclusions are presented in Sect. 6.

2 Solar PV, Wind Energy, and BESS as an Alternative

According to (IRENA 2018), “falling renewable power costs signal a real paradigm shift in the competitiveness of different power generation options.” This section outlines the latest and predicted technical and economic standings of utility solar PV, wind farms, and battery energy storage systems (BESS).

2.1 Utility-Scale PV Systems Review

Technology Overview and Description

Utility-scale solar PV refers to the generation of bulk power from a solar PV plant and the direct injection into the power grid (Wolfe 2018). As of 2017, 402 GW of solar PV power were available worldwide with an addition of 98 GW of capacity in 2017 only (Fig. 7.1). Solar PV power contributed to 1.9% of the world electricity consumption in 2017. Over the past decade, an exponential growth is witnessed in the installed capacity of solar PV plants (Fraunhofer Institute for Solar Energy Systems 2017; REN21 2018).

The output of a solar PV plant depends on the local climatic and environmental conditions, mainly the intensity and amount of solar irradiation, the clearness index, and the ambient temperature. In order to acquire an approximate figure on the potential of solar PV energy production in Lebanon, we look at the global horizontal

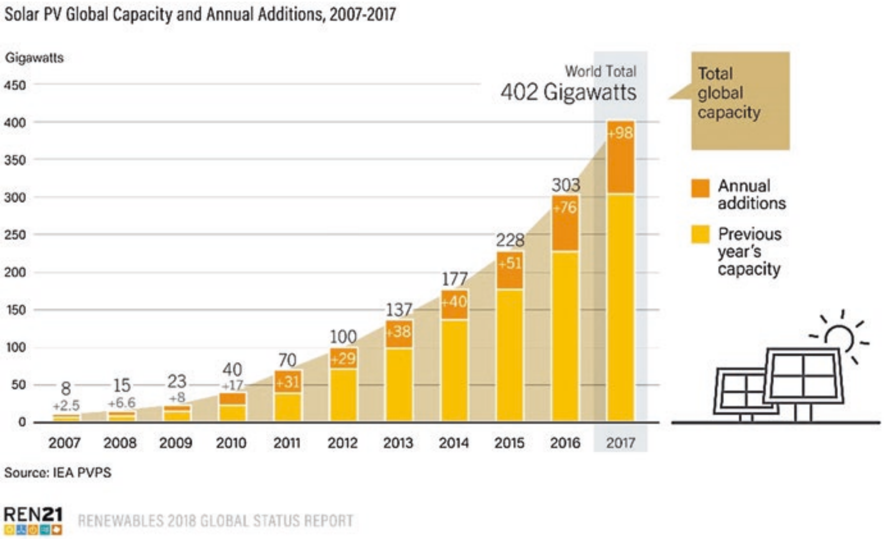

Fig. 7.1 Global solar PV capacity and annual additions. (REN21 2018)

irradiation (GHI) in Lebanon and the land availability. Data on the GHI for Lebanon is imported from the Global Solar Atlas (Fig. 7.2) and shows the average GHI over the period 1999–2015. It can be seen that based on the selected location, the GHI in Lebanon can vary from approximately 1680 kWh/m^2 to 2100 kWh/m^2 with the average being around 1900 kWh/m^2 (Atlas). In a study done by the Lebanese Ministry

Fig. 7.2 GHI for Lebanon (Atlas)

of Environment and the UNDP to assess the renewable energy sector in Lebanon, it was shown that Lebanon has the potential to install and make use of 110 GW of solar PV plants in areas of high irradiance (MoE and UNDP 2014). In our study, we consider a conservative value of 1700 kWh/kWp for the specific yield which is equivalent to a capacity factor of approximately 19.2%.

Cost Study for Utility-Scale Solar PV: International and Local

According to the International Renewable Energy Agency (IRENA), the global weighted average of the levelized cost of electricity (LCOE) for utility-scale solar PV plants has fallen 73% from 2010 to 2017 reaching $0.1/kWh. Furthermore, the fifth percentile of the data collected is at $0.07/kWh with the LCOE of systems having a high capacity factor being well below that figure. In addition, the average capital cost of utility-scale PV systems was reported at 1388 $/kW with the fifth percentile of the data collected being below 1000 $/kW. This price fall can be attributed to the 81% price decrease of PV modules since the end of 2009 along with the reduction in the balance of system costs. IRENA states that the price decline trend is likely to continue to 2020 and beyond and forecasts the global weighted average to reach a value between $0.5 and $0.6/kWh by 2020 (IRENA 2018).

Lazard's Levelized Cost of Energy Analysis report states that an 86% price decrease has been witnessed in the LCOE of utility-scale solar PV plants between 2009 and 2017. Furthermore, the analysis presents the capital costs related to a crystalline utility-scale PV plant to be in the range of 1100–1375 $/kW. For the Middle East region and for a utility-scale PV plant with a capacity factor between 18% and 20%, a weighted average LCOE of $0.056/kWh is indicated (Lazard 2017).

Zheng and Kammen (2014) show the importance of considering the effects of research, development, and innovation, measured by patent activity as a proxy, for the price forecasting of a certain developing technology. The research developed a two-factor learning curve model based on the annual installed capacity and the number of patents issued and revealed that innovation can have a major role in further decreasing the price of PV systems (Zheng and Kammen 2014). This may explain the discrepancy in the price forecast of PV systems from different organizations and analysts as some may not consider or may place less weight on the effects of research, development, and innovation in the solar PV field.

For instance, IRENA states that near-future price reductions for solar PV plants can be attributed more to improvements in the production process and efficiency gains associated with newer PV cell designs, such as diamond wafer cutting and reactive ion etching methods, passivated emitter rear cell (PERC) architectures, and others, rather than the capacity deployment upsurge and economies of scale (IRENA 2018). IRENA forecasts the global weighted average for the LCOE of solar PV to fall to below $0.06/kWh in 2019–2020 and to $0.03/kWh beyond 2020 in some regions (IRENA 2018).

Table 7.1 Current and projected LCOEs for utility-scale solar PV plants in Lebanon

Electricity price of utility-scale solar PV plants	2017	2022	2025+
LCOE ($/kWh)	0.06	0.04	0.033

As a solar PV plant's balance of system costs is location-specific with a wide variation in soft costs, labor costs, and component costs from country to country (Feldman et al. 2016), it is required to get an accurate figure on the local prices and LCOE in Lebanon for solar PV plants. Therefore, data was collected on six different commercial solar PV sites in six different locations in Lebanon that were awarded a contract in 2017 for the supply and installation of solar systems ranging from 60 to 600 kWp under the UNDP CEDRO program (www.cedro-undp.org). The average turnkey cost was $955/kWp, which is below IRENA's and LAZARD's average capital cost. Furthermore, the largest project of a size of 600 kWp had a capital cost of $783/kWp, and the lowest cost was $775/kWp for a roof mounted 105 kWp system.

The above prices give an indication for the capital cost of commercial-scale PV plants in Lebanon; however, no further information was provided on the cost of capital and the projected yearly energy yield. Furthermore, the above plants do not have any land rental or purchasing costs. Recently, the Lebanese Ministry of Energy and Water has received bids for the building and operation of 12 utility-scale solar PV plants in various areas of high irradiation across the country. The plants will operate under a power purchasing agreement (PPA) between the government and the investors and thus can give us a reassuring figure for the LCOE of utility-scale PV systems in Lebanon. In areas of high irradiance and good climatic conditions, a fixed tilt PV system will have a PPA with a value of approximately $0.06/kWh as the price of electricity. Therefore, and to be conservative with the estimates, we will consider the LCOE for utility-scale solar PV plants in Lebanon to be $0.06/kWh in 2017 and projected to drop to $0.04/ kWh in 2022 (33.33% decrease) and to $0.033/ kWh in 2025 and beyond (17.5% decrease). Table 7.1 summarizes the price estimates:

2.2 Utility-Scale Wind Farm Systems Review

Technology Overview and Description

Wind power technologies are considered mature and are categorized by two main characteristics being the location, which can either be onshore or offshore, and the axis, which can either be vertical or horizontal. Most onshore wind turbines are of horizontal axis type and have three blades that are "upwind." Generally, a wind turbine's power output is determined mainly by the quality of the wind resource, the height of the turbine tower, and the diameter of the rotor blades. A typical wind speed at which a wind turbine starts generating electricity is 3–5 m/s and usually reaches its peak power at approximately 11–12 m/s with the cutoff speed being around 25 m/s (IRENA 2018).

As regards the wind energy potential in Lebanon, a wind map for Lebanon was produced and presented in the National Wind Atlas for Lebanon to calculate the potential of wind energy over the entire country (Hassan 2011). A mean value of 6.1 GW of onshore wind power potential was calculated after omitting areas with high population density, high political instability, military sites, sites having commercial interests, civilian aviation sites, areas near radar or telecommunication sites, national parks, conservation areas, historic sites, sites of religious significance, and complex terrains having a slope greater than 14 degrees. Furthermore, high-level assumptions were made that considered only sites having an average wind speed greater than 6.5 m/s at 80 meters hub height and an installation density of 8 MW/km^2 as viable areas for wind farms (Hassan 2011).

Cost Study for Utility-Scale Wind Farms: International and Local

The global weighted average of the LCOE for wind power declined 85% between 1983 and 2017, decreasing from US$0.4/kWh to $ 0.06/kWh. Furthermore, a learning rate of 21% is observed between 2010 and 2020 based on auction projects that will be commissioned out to 2020 (IRENA 2018).

Lazard's levelized cost of electricity analysis estimated that the LCOE for an onshore wind farm with current capital costs ranging between $1.2/Watt and $1.65/Watt and a capacity factor between 30% and 35% to be in the range of $0.047–$0.075/kWh (Lazard 2017). The range of all wind power LCOE, considering regional sensitivities, is indicated to be between $0.03 and $0.075/kWh (Fig. 7.3).

Wind energy is a mature technology; however, Lebanon only recently ventured into its first ever wind farm project having an agreed-upon electricity price under a PPA agreement signed in 2018 of $0.1045/kWh for the first 3 years of the contract and $0.096/kWh for the remaining 17 years (Lebanon turns to wind farms for electricity 2018). This price is above the prices quoted by Lazard or IRENA for onshore wind farms. This is the case primarily because of Lebanon's relatively high-risk profile (therefore integrating a high weighted average cost of capital). A UNDP study has indicated a cost of debt of 9% and a cost of equity of 16% for investments in utility wind and solar power in Lebanon (UNDP 2017). And the fact that most of the related infrastructure works, such as the construction of a substation, other grid reinforcement requirements, and road works related to the transport of wind turbines, structure, and blades from the port of entry to the designated locations of the wind farms, is to be done by the winning consortiums. It is not uncommon to find higher prices contracted to firstcomers in new energy technology applications.

In order to forecast the LCOE of wind farms to 2022, and having in mind the second round of wind farms recently announced by the Ministry of Energy and Water (LCEC 2018), we shall assume that many of the de-risking measures outlined

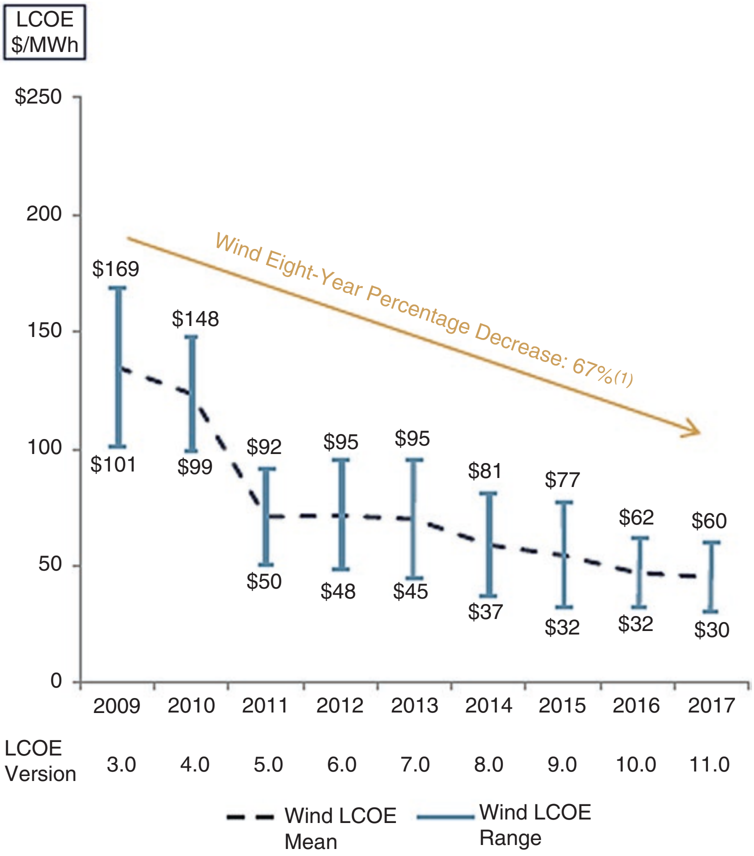

Fig. 7.3 LCOE of wind farms decline over time. (Lazard 2017)

in (UNDP 2017) have been implemented. Therefore, and to remain conservative, we assume an LOCE of $0.055/kWh for wind farms in 2022 which is in the midrange of current prices for similar sites.

2.3 Limitations and Intermittency Problem of Variable Renewable Energy Systems

A high penetration of solar PV and wind energy comes with its limitations and drawbacks. The inherent nature of the variable renewable energy technology renders it variable with the instantaneous power output correlated with the instantaneous climatic conditions such as irradiation, temperature, clearness index, and wind speed. Thus, the increased penetration of such technologies into an electric power system stipulates an increased need for greater flexibility and additional spinning reserve in the network. Furthermore, such systems have limited to no dispatchability in response to the power demand (Chua et al. 2015; Zou et al. 2016; Denholm and Hand 2011).

One may find consensus in literature about the diminishing returns of increasing the integration of variable power generation into an electric grid. Deploying variable generation technologies such as wind and solar with very high penetration levels (greater than the 50% mark) will make further capacity additions uneconomic due to increased curtailment and the subsequent decrease in the capacity factor of the variable generation systems (Denholm et al. 2018; Denholm and Hand 2011; Denholm and Margolis 2007; Bistline 2017; Yekini Suberu et al. 2014; Denholm et al. 2016).

Bistline J. (2017) built a model to show that the operational constraints and investments in dispatchable power such as minimum load levels, start-up costs, and ramping limits can negatively impact the economics of the integration of variable renewable energy. Conventional power generation units will have to undergo larger hourly ramp rates, more frequent starts, and extended periods with lower utilization leading to increased operation and maintenance costs and negatively impacting the unit availability factor. Thus, oversizing variable generation systems comes with an increased operational and financial cost (Bistline 2017).

Denholm P. et al. use a dispatch model to quantify the curtailed variable generation under different flexibility options. The simulations show that for a system having a flexibility factor of 100% and using wind and load data for Texas in the United States of America (USA), it is not possible to have a penetration of variable generation greater than 50% if the percentage of curtailed energy is to be limited to 10% of the energy produced. Furthermore, the work done shows a substantial increase in costs as the penetration of variable generation and the curtailment percentage increases due to increased ramping rate and ramping range, the increased need for frequency regulation (higher operational costs), and the decreased capacity factor of the variable generation units. Thus, the conclusion that power systems with a high penetration of variable generation must include generating plants that are capable of starting, stopping, and ramping quickly has been made while highlighting that electric energy storage provides a critical role in the large-scale integration of variable generation (Denholm and Hand 2011). As regards the economic carrying capacity of variable generation, it is defined as the capacity limit or level of penetration beyond which system costs outweigh the benefits and any addition of variable generation would no longer be economically desirable. Figure 7.4 provides an illustration for the two main factors that could increase the economic carrying capacity of variable generation and the penetration of variable generation plants into a power system. It could be seen that the cost of electricity from the renewable energy resource (y-axis) has to decrease or the power system flexibility (red and blue curve) has to increase in order for the solar PV penetration (x-axis) to increase while remaining within the economic carrying capacity limits.

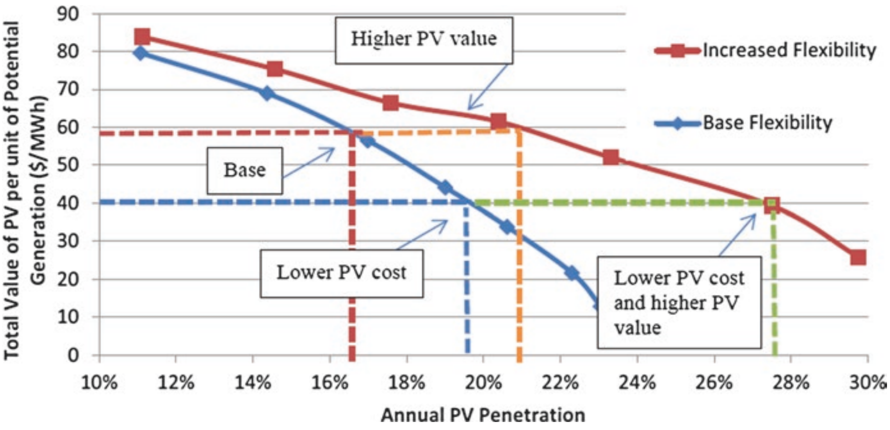

Fig. 7.4 Increased economic carrying capacity either by decreased cost of PV or increased flexibility. (Denholm et al. 2016)

2.4 *Utility-Scale Battery Energy Storage Systems Review*

Technology Overview and Description

Lithium-ion (Li-ion) batteries were first introduced by Sony Corporation in the early 1990s and have become one of the most important technologies for mobile electronics. The basic principal of operation for Li-ion batteries is the exchange of lithium ions between the anode and the cathode electrode through an electrolyte. It is often the case that the cathode is made up of a lithium-ion oxide and the anode is made up of graphite (carbon). Compared to other types of batteries, Li-ion batteries provide a higher specific energy and a higher energy density (Wh/L). They also have a long lifetime (up to 20,000 cycles), a high round-trip efficiency (80–100%), a low self-discharge rate, and a high-power discharge capability (IRENA 2017).

Different types of lithium ion battery chemistries are commercially available with varying properties of safety, power density, energy density, lifetime, and overall performance. Lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminum (NCA), and lithium iron phosphate (LFP) chemistry technologies are currently available and mature Li-ion cell technologies.

From the collected data, average qualitative values for the different characteristics of Li-ion battery technologies were considered to be used in this study (Hesse et al. 2017; Lai and McCulloch 2017; Zou et al. 2016; Müller et al. 2017; IRENA 2017). They assume a round-trip efficiency of 90%, design lifetime (calendar life) of 15 years or 10,000 cycles, 20% capacity degradation over the lifetime, and a 90% maximum depth of discharge.

A stationery Li-ion battery storage system connected to the grid generally includes the following main components: the Li-ion battery packs connected in a specific configuration, the battery thermal management system and the overall system thermal management system (TMS), the energy management system (EMS),

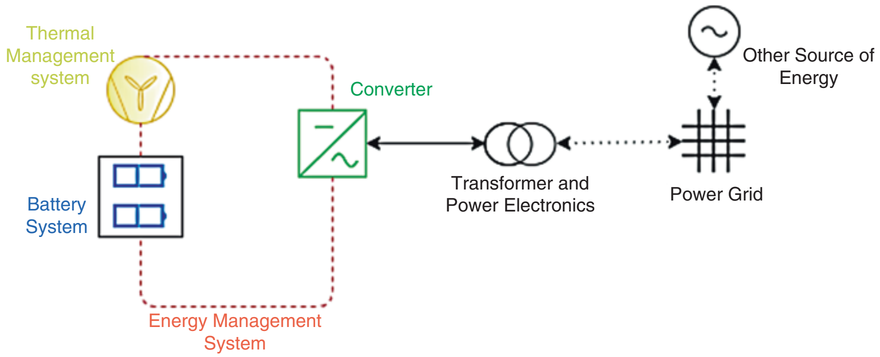

Fig. 7.5 Schematic drawing of a Li-ion battery storage system. (Adopted from Hesse et al. 2017)

the power electronics mainly made up of converter units (inverters and rectifiers), and a transformer to couple the system with the high-voltage grid lines if needed (Hesse et al. 2017). Figure 7.5 gives a general idea of the configuration and components of a Li-ion battery storage system.

Cost Study for Utility-Scale Battery Energy Storage

To obtain accurate values on current and projected prices for large scale Li-ion battery energy storage systems (BESS), we look at both the studies and projections of market analysts and the academic work done using scientific methodologies centered on learning rates. We subdivide the costs of a BESS into two main components that are the Li-ion battery modules and the balance of system (BoS) components that aggregate all software, hardware, and soft components other than the battery itself (McLaren et al. 2016; IRENA 2017; Ardani et al. 2017; Lazard 2016).

It was found that a lower contribution of the battery module to the overall system cost is witnessed as system size increases (Müller et al. 2017). Furthermore, the ratio of the cost of the battery module to the entire system cost was found to vary in the range of 35% for large systems and up to 60% for smaller systems (IRENA 2017; Ardani et al. 2017; Denholm et al. 2017).

The main drivers of the cost decline in Li-ion battery storage systems are the uptake in electric vehicles that use these batteries and the increased penetration of variable renewable energy sources into power grids (Berckmans et al. 2017; Müller et al. 2017; Zheng and Kammen 2014; Feldman et al. 2016). Bloomberg New Energy Finance reported a cost decrease of 73% between 2010 and 2016 for Li-ion battery packs with a learning rate of 19% attributed to technology improvement, economies of scale, and fierce competition between manufacturers (Curry 2017). In comparison, a learning rate of 9% was presented in 2014 by a study done by NREL (Denholm et al. 2017). Figure 7.6 summarizes the current and projected prices for Li-ion battery packs imported from the different market analysts. The data is organized based on the date of analysis and projection.

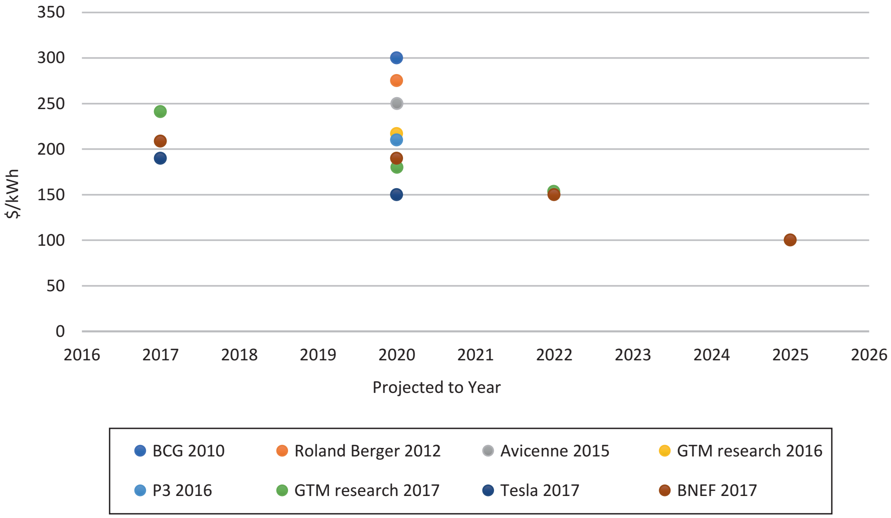

Fig. 7.6 Price forecast for Li-ion batteries based on market analysts. (Curry 2017; Berckmans et al. 2017; Gupta 2017)

It can be observed that price forecasts done at earlier stages tended to underestimate the price reduction which is a phenomenon previously witnessed in the solar PV industry. As an example, 2017 Li-ion battery prices are well below the 2020 price projections done by BCG, Roland Berger, and Avicenne assumed in 2012, 2010, and 2015, respectively. Furthermore, in 2016, GTM Research projected a price of $217/kWh for 2020, and yet in 2017 they readjusted that projection to $180/kWh.

One of the main methodologies applied to project the prices of Li-ion batteries is the learning curve. Schmidt O. et al. (2017) derive an experience curve based on Wright's law (Wright 1936) while using historic product pricing and cumulative installed capacities as inputs. The work done showed that independent of the technology used for energy storage, the technology that brings the most installed capacity to the global market is the one likely to be the most cost competitive. The study calculates a price range of $290–$520/kWh for stationery energy storage systems by 2030; however, it notes that the price of the Tesla Powerwall 2 is already within that range at $500/kWh in 2017. To explain this, the authors resort to the synergetic learning effects of the stationery energy storage technology across different applications which led to cost reductions that were not accounted for (Schmidt et al. 2017). This outcome is in congruence with the learning rate gap that was found above with a learning rate value of 9% in 2014 (Feldman et al. 2016) and 19% in 2016 (Curry 2017).

Berkmans G. et al. (2017) built a model to forecast the price of a Li-ion battery pack for electric vehicles while considering the aspects of increased research, the commercialization of new chemistries and mass manufacturing, and production cost optimization that come with increased uptake and the maturing of the market. The study found that with current chemistries of Li-ion batteries, NMC specifically, prices are expected to drop to $195/kWh by 2020 and reach the $100/kWh threshold in the period 2025–2030 (Berckmans et al. 2017).

Similar to Zheng and Kammen (2014), Kittner N. et al. (2017) utilize an empirical dataset that analyzes technology deployment and innovation to build a two-factor model and project the prices of Li-ion battery storage systems. Using patent activity as a proxy for innovation, the authors present a solid argument on why forecasting and utilizing experience curves solely based on technology deployment tend to underestimate the future price decline of a technology as the synergies between deployment and innovation are overlooked. The two-factor model showed a learning rate of 16.9% for economies of scale and deployment and a price decrease of 2% for every 100 patents issued. The authors forecast the price of a Li-ion battery for energy storage to drop to $124.24/kWh by the year 2020 and the price of Li-ion cell for consumers to drop to $85.55/kWh by 2019. This is in line with what was stated by IHS Markit (Kittner et al. 2017).

In order to settle on a price projection for Li-ion batteries for large-scale energy storage by 2020, we adopt an average projection from the market analysts and scientific methods referenced in Gupta (2017), Curry (2017), Kittner et al. (2017), and Berckmans et al. (2017). The mean value obtained for Li-ion batteries in 2020 is approximately $172/kWh.

In regard to the price forecasts for entire battery storage systems, IRENA indicated that in 2017, the average price of a turnkey NCA-based Li-ion battery storage system is at $350/kWh and is projected to drop to $145/kWh in 2030 (IRENA 2017). A study by Navigant Research states that in 2017, the price of a Li-ion battery storage system was approximately $500/kWh and is projected to drop to approximately $400/kWh in 2020 and to $350/kWh in 2022 (Eller and Dehamna 2017). A report by Lazard states that the average price of a grid-connected Li-ion battery storage system will drop from approximately $650/kWh in 2016 to approximately $400/kWh in 2020, with the low end dropping from $386/kWh to $239/kWh (Lazard 2016).

Australia has recently (2017) installed a 129 MWh grid-connected Li-ion battery using Tesla technology for an estimated price going at $388/kWh (Spector 2017; Roberts 2017; Dent 2017). This is below many estimates of utility-scale battery system costs outlined above. However, to keep in line with the conservative approach of this study, we assume a turnkey Li-ion battery system cost of $380/kWh by 2020, $315/kWh in 2022, and approximately $240/kWh in 2025. This is within the higher conservative range of $239–$400/kWh indicated by the various market analysts for 2020 and assumes a compound annual growth rate of −9% between 2020 and 2025 (in accordance with Gupta (2017)).

2.5 *Benefits and Drawbacks of BESS*

Battery energy storage systems can be sited at three different levels, (1) behind the meter of an institution or household, (2) at the distribution level, and (3) at the transmission level. BESS can provide multiple services and increase the value to the three main stakeholder groups that include utilities, customers, and system operators. BESS installed behind the meter have the largest potential for service provision due to their location downstream of the electricity system (Fitzgerald et al. 2015).

Main Services Provided by BESS

As the integration and penetration of variable renewable energy sources increase in a power system, the need for enhanced control and reaction times on the grid level increase. Several literature studies have identified key services that a grid-connected BESS can provide for the utility operator that become increasingly important as higher levels of renewable power are integrated. Muller M. et al. (2017) report that the main applications of a grid-connected BESS to include are the provision of emergency energy units or uninterrupted power supply connected to crucial nodes in the grid; the provision of black-start capabilities; the provision of primary, secondary, and tertiary control reserves to ensure synchronized and matched generation and consumption; and the provision of grid support with the instant injection of active or reactive power as well as peak shaving, shifting, and managing (Müller et al. 2017).

Due to the variable nature of renewables and the decreasing amounts of spinning reserve and inertia in power systems and grids, installing and utilizing grid-connected BESS generates the capability of reacting to grid fluctuations on a millisecond timescale (Lawder et al. 2014). In regard to frequency control and primary control reserves, Li-ion-based BESS have been shown to be technically mature and to be relatively economically competitive with conventional power plant dispatch plans and applications for primary reserve control (Stroe et al. 2017).

Giorgio A. et al. (2017) study the utilization of energy storage systems and their provision of an optimal solution for black starts in electricity grids after events resulting in the interruption of the main power supply (Giorgio et al. 2017). Zeh A. et al. (2016) present a sizing optimization for battery energy storage systems such that to maximize the profitability resulting from the utilization of battery storage systems for primary reserve control (Zeh et al. 2016).

Denholm, P. et al. (2017) study the technical and economic performance of grid-connected solar PV and storage systems and find that when comparing such systems with conventional power systems, it is essential to consider the added value presented by the capacity credit of the PV-battery system. Further, the study shows that the decline in capacity value of PV systems as their penetration level increases can be mitigated by grid-connected storage systems (Denholm et al. 2017).

Hale, E. et al. (2018) model the power system of Florida to study the different factors affecting the economic carrying capacity of solar PV under high penetration values. The research done shows that energy shifting resources such as battery storage, different power plant flexibility options, and demand side management solutions are critical when it comes to the economic carrying capacity and the penetration level of solar PV into Florida's power grid (Hale et al. 2018).

Table 7.2 summarizes the main services provided by grid-connected BESS.

Table 7.2 Main grid services and benefits of grid-connected BESS (Hale et al. 2018; Denholm et al. 2017; Giorgio et al. 2017; Zeh et al. 2016; Stroe et al. 2017; Müller et al. 2017)

Service	Benefit or value
Peak shaving and load shifting	Lower peak charges decreased stress on the grid and reduces energy costs
Renewable energy self-consumption	Decreased energy and grid connection costs and increased sustainability
Enhanced demand response	Improves grid stability and supports renewable energy development
Primary control and frequency reserves (ancillary services)	Improves grid stability and reliability and avoids the activation of large energy assets
Renewable energy firming	Avoids renewables curtailment and smoothens out the variable output
Backup power and UPS	Supplies instant power during grid outages and reduces O&M costs
Resource adequacy	Can support the power supply resource in meeting the growing peak demand
Time-of-use bill management	Allows customers with behind the meter storage to manage their consumption profile
Demand charge reduction	Decreases demand charges by supplying power during times of peak demand

As the load demand increases and the transmission and distribution (T&D) network reaches its full operation capacity, utilities and distribution service providers are required to enhance, reinforce, and upgrade the existing T&D network in order to accommodate the increased load. Therefore, reinforcement of the T&D infrastructure mainly depends on peak load increase as well as the aging of the infrastructure. Strategically installed energy storage systems can supply power during peak load times and hence reduce the amount of power needed to be transmitted over the existing transmission lines (Chua et al. 2015). Utilizing battery storage as a distributed energy source by installing it downstream of the T&D infrastructure presents two related value propositions that are (1) deferring the upgrade of the infrastructure and (2) extending the life of that infrastructure by allowing it to operate at lower temperatures and decreasing the occurrence of ground faults.

Drawbacks of Limited BESS Dispatch Models

Distributed grid-connected battery energy storage has multiple and stacked benefits that need to be integrated and employed in order to capture the real value of such systems. Failing to ensure the needed regulatory bases, utility business models and technical standards can render battery storage uneconomical and/or even increase GHG emissions through partial utilization of the system.

Operating and dispatching a battery storage system solely for a single primary application (e.g., energy arbitrage) without re-dispatching it and making use of the multiple services that it can provide (e.g., frequency reserves, enhanced demand response, renewable energy firming, etc.) will result in underutilization of the system. Calculating the actual economic value that can be provided by a battery storage system is a complicated task due to grid-specific factors that vary between different systems and the unavailability of a common and simple methodology to calculate the value and economic benefit that the stacked services of a BESS can provide to the grid, user, or system operator (Fitzgerald et al. 2015).

Under energy arbitrage operation, combining the loss of energy resulting from the roundtrip efficiency of a BESS and the possibility of charging from carbon intensive sources and discharging to replace less carbon intensive sources, battery storage systems can yield a net increase in emissions. If such bulk storage systems are solely utilized for energy arbitrage without employing their stacked services, it is highly likely that they will increase emissions as compared to the base case of having no distributed battery storage.

In the work of Hittinger and Azevedo (2015), the effect on net emissions of a bulk energy storage system providing primarily energy arbitrage services was studied through modeling energy mixes and prices across the United States. It was found that, depending on the location, the operation mode of the storage system, and the renewable energy penetration, bulk energy storage can result in an increase of net emissions mainly by enabling high-emission power generators, such as coal plants, to replace a cleaner generator, such as natural gas (Hittinger and Azevedo 2015, 2017).

3 Methodology

This study aims to model the potential of integrating different renewable energy technologies, BESS, and utilizing demand side management as a means for sustainable transitioning of the Lebanese electricity system. Combining and inputting current and forecasted technical and economic data of existing energy generation and storage technologies under different scenarios enables the optimization of power supply in terms of cost-effectiveness. Including the social cost of carbon (SCC) will give an added perspective to the outcome if and/or when carbon taxes are introduced. Moreover, undertaking sensitivity analysis explores the changes of the outcomes to changes in certain key assumptions.

3.1 Scenario Framework and Sensitivity Variables

Our base case scenario considers the current Lebanese power system with all its available generation, transmission, and distribution assets, having an average LCOE of 16.5 cents per kWh delivered (CoM 2018) and a global warming potential measured by the emittance of greenhouse gases amounting to 1.1 kg of CO_2 equivalent for every 1 kWh of electricity delivered (El-Fadel et al. 2010). Furthermore, a

1450 MW supply deficit is prevalent with the technical losses associated with the transmission and distribution network amounting to 13% of the generated energy.

We then consider an Adapted Base Case scenario which is created by building a hypothetical power system model for Lebanon in the year 2022 with the technical and nontechnical losses reduced to international standards. The 2022 load demand is utilized as the main AC load with hourly resolution; combined cycle gas turbine (CCGT) units running on natural gas are added to replace the current fuel oil and diesel utility grid power generators that meet the base and intermediate demand, and open cycle gas turbine (OCGT) units running on natural gas are added to replace the peaking power plants (see Annex 1 for the detailed parameters used). Grid-connected utility-scale solar PV plants, wind farms, and battery energy storage systems are also added (see Annex 1 for the detailed parameters used). The system is simulated using Homer Pro (Fig. 7.7) to optimize for the ideal configuration under the objective of economic minimization of the overall levelized cost of electricity with percentage of unmet load set to zero.

Under the Adapted Base Case, no social cost of carbon is inputted; the price of natural gas is imported from a study completed by the Sustainable Oil and Gas Development in Lebanon (SODEL) to be 7.4 $/MMBtu and incorporates the cost of infrastructure needed for distribution (Bassil 2018). The minimum loading ratio of the CCGT unit was inputted as 50% of rated capacity with no demand side management strategy integrated. Solar, wind, and temperature resources were imported from the NASA surface meteorology database and scaled to match average performance data collected from local studies and projects. The cost of the converter was incorporated into the costs of the PV system, and the BESS are assumed to be connected in a DC-coupled manner (Denholm et al. 2017). The simulation and financial parameters and constraints used for the overall model and for each conventional, renewable, and battery storage technology are specified in Annex 1.

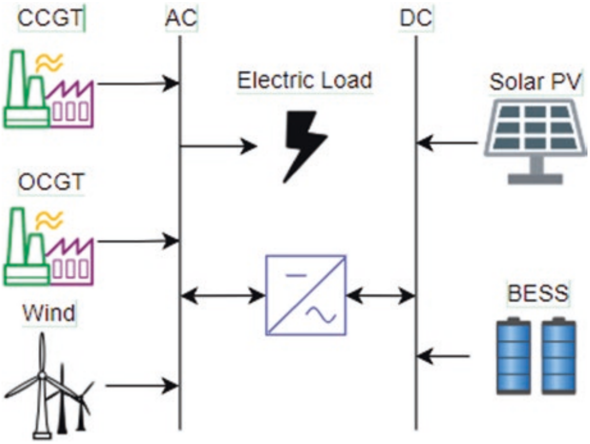

Fig. 7.7 Adapted Base Case scenario configuration in Homer Pro

Six different sensitivity simulations were run based on the price of natural gas and the social cost of carbon. The variability of the price of natural gas was included as a sensitivity by inputting three values to represent the low, median (base case), and high prices which are 5.4 $/MMBtu, 7.4 $/MMBtu, and 9.4 $/MMBtu, respectively. As for the social cost of carbon (SCC), assumptions to estimate its value vary widely in the literature, and therefore there is a wide variation in the SCC. To simplify our objective, only two variables are used to represent the sensitivity of the SCC. The Adapted Base Case variable is \$0/tCO_2 emitted, which can be taken to represent the current environment of not tackling external costs, whereas the second assumption is \$50/tCO_2 emitted, which can be considered conservative (Hale et al. 2018; Nordhaus 2014; Markandya et al. 2016).

In order to study the sensitivity of the flexibility of the CCGT unit and its effects on the cost of electricity and the penetration of renewable energy into the generation mix, we decrease the minimum loading ratio of the CCGT unit from 50% to 40% and then to 30% and rerun the Adapted Base Case scenario simulation to compare the results of the three scenarios with different minimum loading ratios.

The effects of demand side management on system optimal configuration were also modeled by running the Adapted Base Case scenario under a modified yearly load profile. We assumed that under a time-of-use tariff scheme, the system operator is capable of reducing the evening peak demand of the average day load profile by 4% while restructuring the load profile. This is done by limiting the peak demand during the hours of 3 pm–10 pm of the average day load profile to 0.96% of the initial peak demand. The excess demand (above 0.96% of the initial demand) is redistributed by summing all excess demand and then equally distributing it over the load during the 6-hour time period between 9 am and 3 pm. The new average day load profile is used to map and create a new yearly load profile with hourly resolution that has the same total load value as the original load profile, however, with restructured daily load profiles. The hypothetical restructuring is done to simulate the effect of demand side management on the optimal system configuration when it comes to economic minimization.

3.2 *Forecasting the Load Demand in 2022*

The demand data for the year 2022 is forecasted by adopting the collected load data for the year 2015 and adopting an average yearly demand growth of 7% between 2015 and 2020 and 5.81% between 2020 and 2022 as mentioned in the Policy Paper (MEW 2010; LCEC 2016).

The total load demand for 2015 was 21,207 GWh and is forecasted to grow to 33,300 GWh in 2022 with an average demand of 3801 MW having a forecasted average day load profile as shown in Fig. 7.8.

The hourly load data for the year 2022 is inputted into the simulation software in order to represent an accurate model of the total load. Utilizing an accurate load profile in the simulation is critical to correctly model the effects of variable genera-

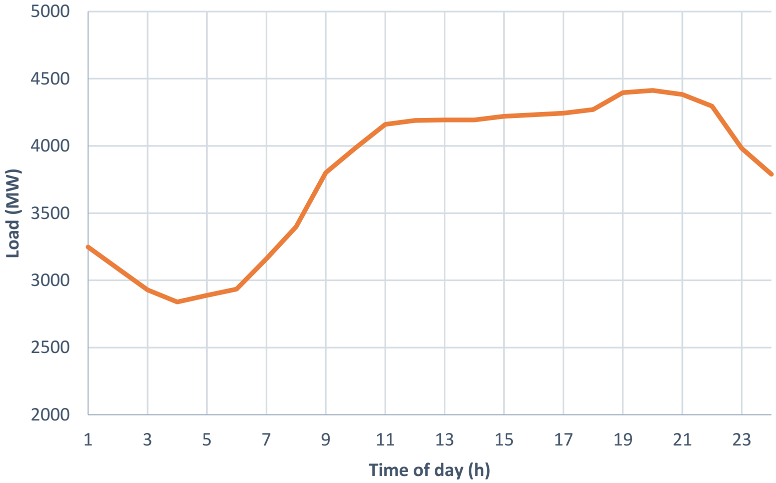

Fig. 7.8 Average day load profile in 2022

tion on the power system and take into account the impacts of the noncoincidence of variable power generation and power consumption. The average peak demand in Lebanon currently occurs between 5 pm and 10 pm.

3.3 Simulation Software

Homer (Hybrid Optimization of Multiple Energy Resources) Pro software is used in order to run the different scenarios and complete the simulations of the power system. The software is originally developed by NREL and is mainly used as an optimization tool to calculate the lowest levelized cost of electricity of a power system given different power generation units, system constraints, and user inputs. The software is also capable of running sensitivity analyses to evaluate different configurations while varying factors that have a large impact on the operation of the system. It incorporates conventional generation units, renewable energy plants, energy storage, load management, and other functionalities (Chua et al. 2015; Lai and McCulloch 2017; Hesse et al. 2017).

Homer Pro is an optimal platform to simulate the developed scenarios and compare them in a controlled manner. It provides the capabilities of (1) inputting hourly load data; (2) defining the operational parameters for conventional power plants, wind farms, solar PV plants, and Li-ion battery storage systems; (3) specifying the dispatch strategy; (4) specifying the financing parameters; (5) running sensitivity analyses; and (6) outputting the technical performance and economic data for each system component separately.

3.4 Flexibility Options and Modeling Limitations

With the increased penetration of variable renewable energy generation, it is expected that conventional power generation units experience increased cycling and increased operation and maintenance costs in order to cater for the variability of the renewable resources and ensure reliability of the power system (Denholm and Hand 2011; Denholm et al. 2016; Hale et al. 2018).

The modeled systems and simulations run are limited with respect to the flexibility options of conventional power generation units. Homer Pro allows the user to input the minimum load ratio, the minimum runtime for power generators, and the minimum spinning reserve requirements. However, generator ramp rate and ramp time limitations and startup and shutdown costs are not included in our model nor the simulations. This is mainly due to the unavailability of sub-hourly load data. Therefore, our model assumes highly flexible power generators as regards the ramp rate and ramp times and does not integrate any additional operational costs when it comes to increased cycling. We accept these assumptions and limitations as our objective is to present the potential limits of economic integration of variable generation and BESS and to study the sensitivity of the economic carrying capacity to several key parameters assumed.

3.5 Capacity Value

Capacity credit or value has been defined in several ways. IEA describes it as the difference between peak demand and peak residual demand, which is the demand met by conventional power generation, as a percentage of variable renewable capacity installed in a system (IEA 2011). NREL defines it as the percentage or fraction of the variable renewable energy source that can be established to reliably meet demand (Kirby et al. 2013). Mills and Wiser state that the capacity value of a solar plant reflects the avoided cost of building traditional power plants to reliably meet peak demand (Mills and Wiser 2012).

Methods to calculate the capacity value of variable renewable energy generation are numerous with a considerable amount of literature available for the different methods. Different utilities in different parts of the world use different models and approximations to calculate the capacity value in order to optimize their capacity expansion models and to calculate the expected loss of load probability. Estimates for “capacity value” are subject to the resolution of data for the demand and supply of power. Two main estimation techniques are used: reliability-based approaches that principally use the loss of load probability (LOLP) as a standard reliability metric and approximation methods that focus on a subset of hours where there is a high risk of the system experiencing a loss of load.

As reliability-based methods require considerable computational effort and generation and consumption data that span over a period of several years and have a sub-hourly resolution, approximation methods are widely used that focus on a subset of hours where the LOLP is high. These approximation methods include the capacity factor-based approximations, Graver approximation-based method, and the Z-method (Madaeni et al. 2012).

NREL's "8760-Based Method for Representing Variable Generation Capacity Value in Capacity Expansion Models" suits the Lebanese case as an approximation method for calculating the capacity credit of variable renewable energy plants. This is the case as it offers a relatively refined and accurate version of capacity value approximations, combining parts of the capacity factor-based approach with the ELCC method. Moreover, it is similar to the method used in the IEA World Energy Model.

The main difference between NREL's method and other approximation methods is that it uses load duration curves to estimate the contribution of the added variable renewable energy source. Load duration curves reflect the total load sorted from hours of highest load to hours of lowest load. Further, the model considers time-synchronous hourly generation and consumption values across the 8760 hours of the year enabling the localization of all high load durations (Denholm et al. 2016). This approximation method, similarly used by Hale et al. (2018), is adopted in our methodology to calculate the capacity value of the renewable energy sources under the Adapted Base Case scenario while utilizing the first 100 hours of the load duration curve as the hours of highest LOLP. We adopt an estimate value of 128 $/kW-year as the annualized cost of installing and operating a peaking power plant operating on natural gas in Lebanon. This cost was verified by running a simulation on Homer Pro having only conventional power generation units to meet the Lebanese electric load and outputting the annualized cost of the OCGT unit.

4 Results and Discussion

4.1 Adapted Base Case Scenario

Simulation results for the optimal configuration of the Adapted Base Case scenario having a price of natural gas of 7.4 $/MMBtu and excluding the social cost of carbon are summarized in Table 7.3.

In the Adapted Base Case scenario, solar PV supplied approximately 9% and wind power supplied approximately 12.5% of the total load. The marginal cost of electricity for the CCGT unit and the OCGT unit is found to be $0.05/kWh and $0.071/kWh, respectively. As for wind and solar energy, the LCOE is found to be $0.055/kWh and $0.04/kWh, respectively. The BESS had an average energy cost of 0.071/kWh. Figure 7.9 shows the monthly generation profile of each resource.

The economic carrying capacity of solar PV and wind energy is limited by a penetration level of 9% and 12.5%, respectively, due to system operational constraints of minimum loading ratios, minimum operating reserves, and the noncoin-

Table 7.3 Main results of the Adapted Base Case scenario simulation

Parameter	Value
CCGT capacity	3.75 GW
OCGT capacity	0.75 GW
Solar PV capacity	1.68 GW
Wind power capacity	1.3 GW
BESS capacity	630 MWh/315 MW
BESS autonomy	9 minutes of average load
Overall levelized cost of energy	7.086 US cents per kWh
Renewable penetration	21.5%

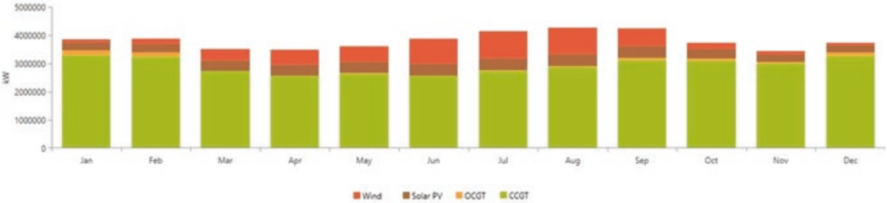

Fig. 7.9 Monthly generation profile of the Adapted Base Case scenario

cidence of the variable generation resource with high load hours. The optimal BESS had a capacity of 9 minutes of average load and had a negligible penetration into the power supply mix, thus mainly providing the functionality of peak shaving in times of maximum load and highest loss of load probability.

The OCGT unit experienced 351 starts per year and mainly operated and supplied power to the peak load hours during the evening time. The CCGT unit is cycled more frequently with increased ramp rates especially during daytime hours when the solar resource is supplying energy. Wind and solar energy experience negligible curtailment with the total excess power of approximately 0.22% of the total electrical load. The optimal dispatch strategy is the cycle charging strategy where a generator operates to serve the primary load. The generator operates at maximum output power and any surplus electrical production goes to charge the battery storage system if needed. Figure 7.10 shows a typical load and generation profile of the modeled system for a week.

Results show that grid-connected utility-scale renewable energy plants and battery energy storage system are technically and economically viable options to consider when it comes to capacity expansion planning. Considering the current cost of utility electricity in Lebanon of approximately $0.165/kWh and an average tariff of $0.096/kWh, it is worth noting that if our modeled Adapted Base Case scenario that achieves a LCOE of approximately $0.071/kWh is adopted by the national utility, the net financial benefits will be approximately $0.094 for each kWh produced. This allows the modeled system, having an initial capital of USD 7.63 billion, to have a simple payback period of approximately 2.5 years.

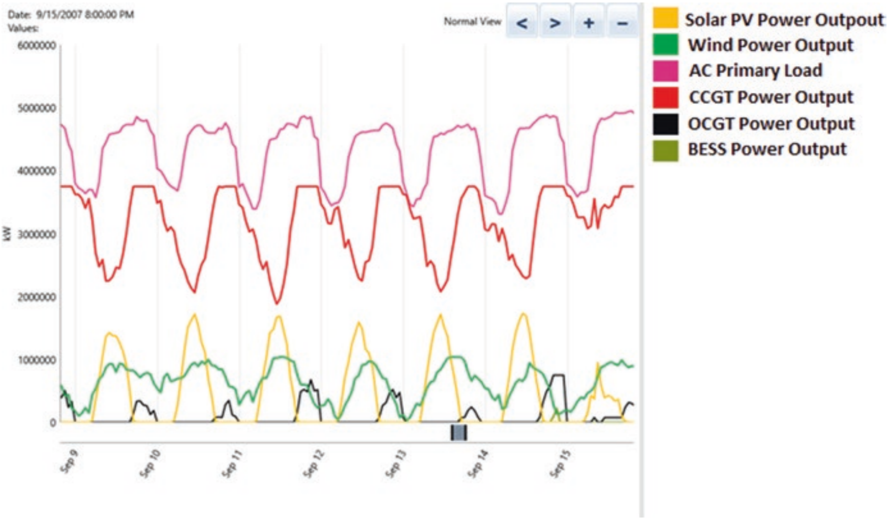

Fig. 7.10 Generation and consumption profile for a week in the Adapted Base Case scenario

4.2 Sensitivity Analysis: SCC and Price of Natural Gas

The simulations are rerun while varying the cost of natural gas and adopting a social cost of carbon of \$50/tCO$_2$. Results show a high level of sensitivity of the optimal system configuration and the economic carrying capacity of renewable energy generation to both inputs. Table 7.4 presents the main results of the six-sensitivity simulations with the Adapted Base Case scenario highlighted in red.

A positive correlation is witnessed between both the price of natural gas and the SCC and the system RE fraction. On the other hand, a negative correlation is witnessed between both the price of natural gas and the cost of carbon and system LCOE.

Sensitivity case (1) excludes CO$_2$ penalties, includes a low price of natural gas (\$5.4/MMBtu), and results in the lowest LCOE of approximately \$0.06/kWh. However, sensitivity case (1) also has the lowest RE penetration at 7.2%. This can be attributed to the low marginal generation costs from the CCGT unit and OCGT unit of \$0.034 and \$0.053/kWh, respectively. Furthermore, the CCGT capacity increased to 4.25 GW as compared to the Adapted Base Case of 3.75 GW. In this case, the economic carrying capacity of the RE sources decreased due to the availability of a power generator having a cheaper marginal generation cost of electricity with no CO$_2$ penalty. Therefore, decreasing the marginal cost of conventional power generation units can result in a decrease in the economic carrying capacity of variable generation units even when decreased technology costs and increased system flexibility are present.

Table 7.4 Simulation results of the sensitivity analysis

Sensitivity case	CO2 penalty ($/t)	NG Price ($/MMBtu)	Solar PV (kW)	Wind (kW)	CCGT (kW)	OCGT (kW)	BESS (kWh)	System LCOE ($/kWh)	RE fraction (%)
1	0	5.4	937,322	228,000	4,250,000	500,000	619,622	0.0597	7.2
2	50	5.4	4,767,575	1,140,000	3,750,000	750,000	1,569,608	0.0744	33.6
Base	0	7.4	1,680,298	1,296,000	3,750,000	750,000	629,637	0.0709	21.5
3	50	7.4	5,337,140	1,572,000	3,750,000	750,000	1,606,902	0.0826	38.9
4	0	9.4	5,526,524	1,383,000	3,750,000	750,000	1,614,582	0.0797	37.9
5	50	9.4	5,316,603	3,060,000	3,750,000	500,000	1,886,945	0.0900	48.4

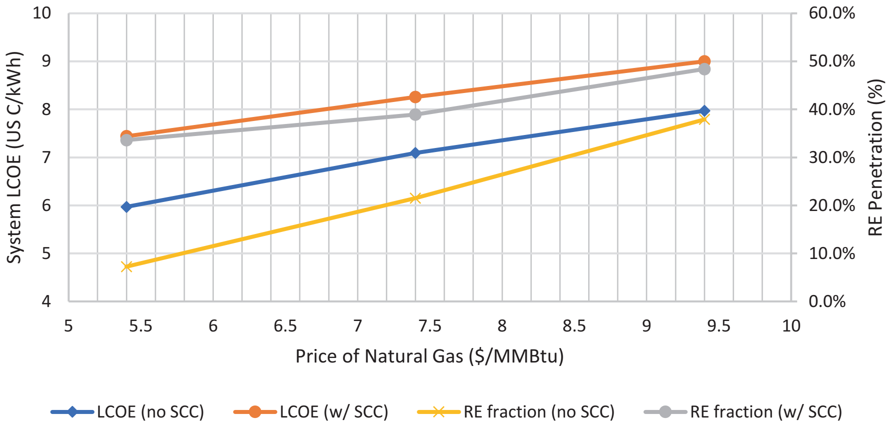

Fig. 7.11 Sensitivity of system LCOE and RE fraction to both the price of natural gas and the cost of carbon

When a cost of carbon is added in sensitivity case (2), a major increase in the RE fraction is witnessed (from 7.2% in sensitivity case (1) to 33.6% in sensitivity case (2)). Even with utilizing the low estimate of the price of natural gas, and mainly due to internalizing the cost of carbon and the subsequent increase in the marginal cost of electricity from conventional power generation units, the economic carrying capacity of RE systems is greatly increased. The LCOE of the system also increased to $0.074/kWh.

Figure 7.11 presents the correlation between the price of natural gas, system LCOE, and the RE fraction under the two cases of excluding or including the SCC.

Sensitivity case (3) utilized the same price of natural gas as the Adapted Base Case ($7.4/MMBtu); however, the SCC is internalized. Results show an increased RE fraction from 21.5% to 38.9% and increased system LCOE from approximately $0.071–$0.083/kWh. The major amendment to the system configuration is the increase of solar PV capacity from 1.6 GW to 5.3 GW and the increase in the BESS capacity from 630 MWh to 1.6 GWh. Excess electricity was calculated at 4.8% of the total yearly demand.

Results of sensitivity case (4) are identical to sensitivity case (3). When the SCC is excluded, the price of natural gas was increased to 9.4 $/MMBtu; the RE fraction and system LCOE are 37.9% and $0.08/kWh, respectively. Furthermore, and when compared to the Adapted Case system configuration, the main adjustments were the increase in the solar PV capacity and the increase in the BESS capacity with excess electricity having a value of 4.95% of the total yearly load.

Sensitivity case (5) considered the internalization of the SCC and a high price for natural gas. The system resulted in the highest system LCOE at $0.09/kWh and the largest RE fraction of 48.4%. Excess energy is approximately 9% of the total yearly load. As compared to the Adapted Base Case, the system configuration witnessed a major increase in both renewable energy sources and the BESS. CCGT capacity remained the same while the OCGT capacity decreased from 750 MW to 500 MW. The decreased OCGT capacity can be mainly attributed to the increased battery storage system capacity which now has a larger role to play in meeting peak demand.

An interesting relationship between the RE fraction and the BESS capacity was found. An increase of the RE fraction from 7.2% in sensitivity case (1) to 21.5% in the Adapted Base Case resulted in a negligible increase of 1.6% in the BESS capacity; however, the increase of RE fraction from 21.5% in the Adapted Base Case to 33.6% in sensitivity case (2) showed a major increase of the BESS capacity from a system having 9 minutes of average load autonomy to a system having 22.3 minutes of average load autonomy, i.e., a 150% increase (see Fig. 7.12). This result shows and verifies the presence of an economic limit, falling between 20% and 25% pen-

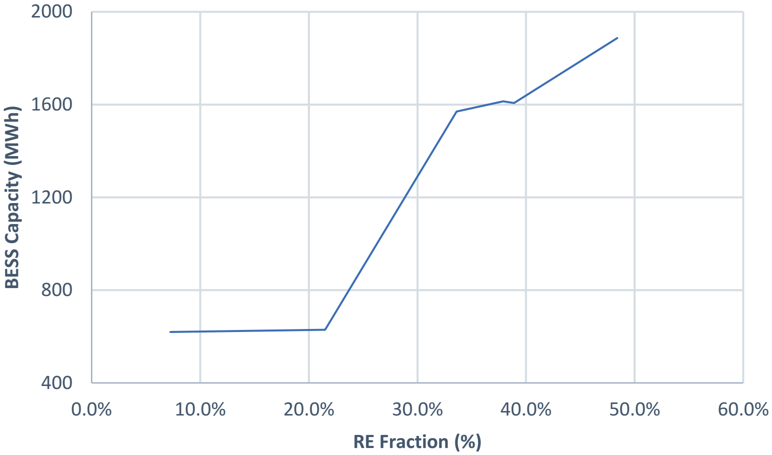

Fig. 7.12 Sensitivity of BESS capacity to system RE fraction

etration, when it comes to the integration of variable renewable energy generation with little to no storage into the Lebanese electricity system. Due to the noncoincidence of renewable supply and the load demand and the variable nature of the renewable energy technology, increasing the penetration beyond the economic limit without adding battery energy storage will only yield excessive curtailment values resulting in an increased overall system LCOE. These findings are in line with findings in Denholm and Hand (2011), Feldman et al. (2016), Denholm and Margolis (2007), and Hale et al. (2018).

The operation of the BESS and its services that enable a larger integration of renewable energy can be witnessed in sensitivity case (5). Figure 7.13 represents the load and generation profile for 1 week from sensitivity case (5) where "inverter power output" represents the output power from the central system inverter which is shared between the PV resource and the BESS and feeds AC power to the load.

The BESS, having a capacity of approximately 30 minutes of average load, mainly charges from the excess renewable resource during the day time, ensuring renewable energy firming and load following, and discharges more frequently during the evening peak times, contributing to peak shaving. It is observed that the OCGT unit, even with its rated capacity decreasing from 750 MW to 500 MW, has now a decreased utilization rate with its capacity factor dropping from 7.8% in the Adapted Base Case to 6.3% in sensitivity case (5). However, both the CCGT unit and OCGT unit experience an increase in the number of starts undergone in a year as compared to the Adapted Base Case scenario.

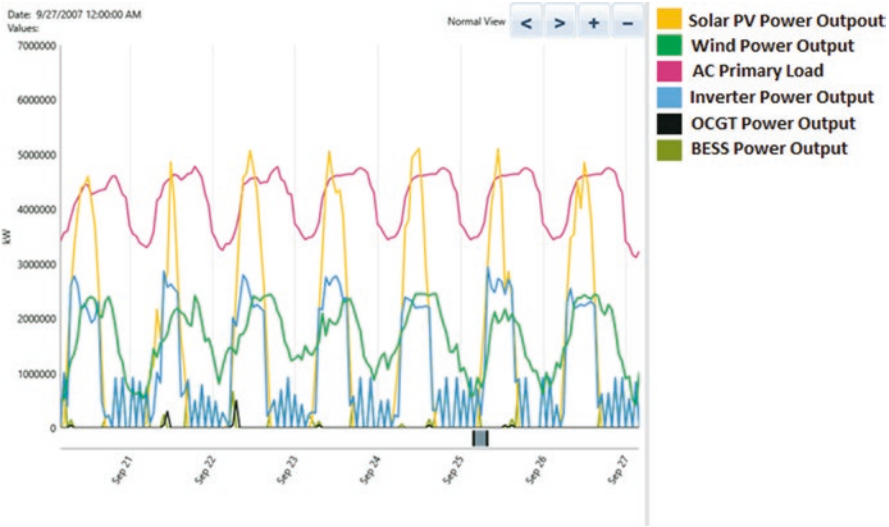

Fig. 7.13 Load and generation profile of sensitivity case (5) for a week

4.3 The Effects of Generation Flexibility on RE Penetration

Our Adapted Base Case model considered a minimum loading ratio for the CCGT unit of 50%. However, in order to assess the effect of increased system flexibility on system configuration and renewable energy penetration, we consider the minimum loading ratio to which the CCGT unit can cycle down to as our main flexibility factor. We simulate two new models based on our Adapted Base Case scenario by decreasing the minimum loading ration to 40% in the first simulation and to 30% in the second simulation. Table 7.5 presents the main results of the two new simulations and the Adapted Base Case model.

Decreasing the minimum loading ratio of the CCGT unit from 50% to 40% resulted in a system with an almost identical LCOE of approximately $0.071/kWh. However, the RE fraction increased from 21.5% to 34.9% when compared to the Adapted Base Case. The large increase in the economic carrying capacity of the solar PV resource is attributed to the provision of greater system flexibility during daytime hours. This is enabled by the combination of allowing the CCGT unit to cycle down to a lower value and increasing the BESS capacity from 630 MWh to approximately 1.53 GWh. Furthermore, decreasing the minimum loading ratio to 30% resulted in a further increase in the solar PV capacity and a slight increase in the battery storage capacity. However, even with a decreased minimum loading ratio (increased CCGT flexibility), a 0.4% decrease in the overall RE fraction is observed with a further decrease of the LCOE to $0.0705/kWh. This slight decrease in the RE fraction between the 40% and 30% minimum loading ratio scenarios is attributed to a considerable decrease in wind power capacity originating from an increased CCGT capacity (to cater for the enhanced economic carrying capacity of solar PV) that has a marginal cost of electricity lower than the LCOE of wind power.

Given that solar power is the most affordable technology in the system (LCOE of $0.04/kWh) and that a lower minimum load ratio of the CCGT unit has a positive impact on the economic carrying capacity of the solar resource, the optimization procedure with the objective of economic minimization will tend to increase the share of solar energy. Other variable generators, such as wind energy, that are not as affected by the decrease in the loading ratio witness a decrease in capacity. This is

Table 7.5 Main results of the sensitivity simulations regarding generation flexibility

CCGT Min. load ratio (%)	Solar PV (kW)	Wind (kW)	CCGT (kW)	OCGT (kW)	BESS (MWh)	System LCOE ($/kWh)	RE fraction (%)
30	5,030,716	993,000	4,000,000	500,000	1,577	0.0705	34.5
40	4,557,387	1,263,000	3,750,000	750,000	1,525	0.0708	34.9
50 (Base)	1,680,298	1,296,000	3,750,000	750,000	630	0.0709	21.5

the main reason behind the increase in the solar PV capacity and the decrease in wind capacity witnessed in both sensitivity simulations.

The penetration of variable generation, especially solar energy, is thus highly sensitive to the flexibility of conventional power generation units and their cycling range. The system LCOE for both sensitivity cases showed only a slight decrease when compared to the less flexible Adapted Base Case scenario assumed.

4.4 The Effects of Demand Side Management on Optimal System Configuration

A hypothetical restructured average load profile under a time of use tariff is adopted into the Adapted Base Case scenario in order to simulate the effect of demand side management on system optimal configuration and LCOE. Figure 7.14 and Table 7.6 present the new average load profile and the main simulation results of the Adapted Base Case scenario with the restructured demand profile, respectively.

When incorporating time-of-use tariffs, the RE fraction decreased from 21.5% to 17.9%, the solar PV capacity increased by approximately 33%, and the wind capacity decreased by approximately 50%. The system LCOE witnessed a slight decrease from \$0.0709/kWh to \$0.0702/kWh. The increase in the solar PV share can be attributed to the low LCOE of solar PV and to the economic minimization objective of the optimization software that is run under a more favorable condition for solar PV energy which can now satisfy more electric load during daytime hours (between

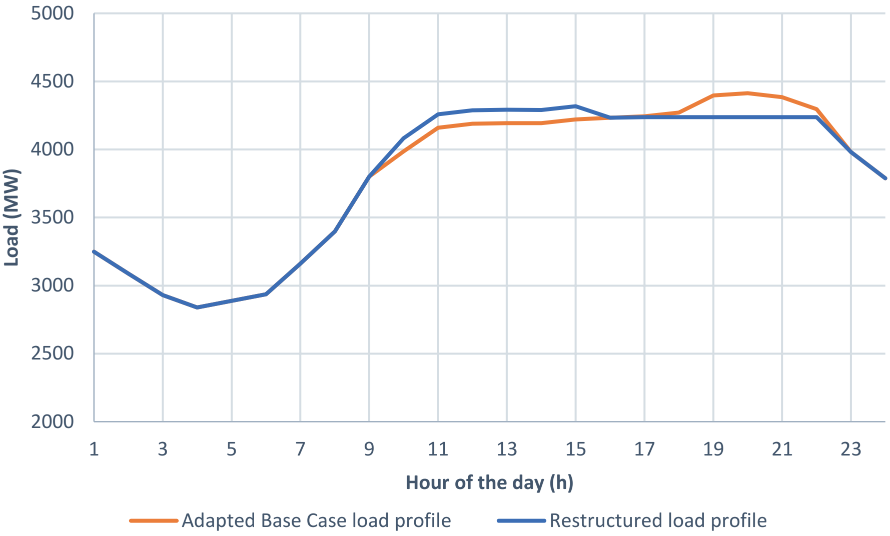

Fig. 7.14 Hypothetical restructured average day load profile under a hypothetical demand side management case

Table 7.6 Main results of the demand side management sensitivity simulation

ToU tariff incorporated	Solar PV (kW)	Wind (kW)	CCGT (kW)	OCGT (kW)	BESS (MWh)	LCOE ($/kWh)	RE fraction (%)
Yes	2,234,763	636,000	4,000,000	500,000	550	0.0702	17.9
No (Base)	1,680,298	1,296,000	3,750,000	750,000	630	0.0709	21.5

9 am and 3 pm). Both the BESS and the OCGT units witnessed a decrease in capacity primarily due to the lower evening peak load. The large dip in wind energy capacity is attributed to a smaller economic carrying capacity under the restructured load profile.

The hypothetical restructured tariff assumes that the peak load between 3 pm and 10 pm of average day load profile is limited to 4.24 GW; a 4% decrease of the original peak load of the average load profile. Furthermore, it is also assumed that all the excess demand above the newly adopted peak load is shifted to the daytime by equally distributing the sum of the excess demand over the 6-hour time period between 9 am and 3 pm. Demand side management strategies can thus lead to the restructuring of the load profile and can have substantial influence on optimal system configuration and the economic carrying capacity of different variable generation sources. Tariff restructuring to influence peak demand must be studied while adopting price elasticity of electricity. In Lebanon this is assumed to be −0.2% (Bjerde et al. 2008), although further research is recommended to validate this value, and to disaggregate it for the various sectors and for the short and long terms.

It is deduced that if the government of Lebanon is not capable of reaching the large wind power installed capacity in the Adapted Base Case of approximately 1.3 GW due to reasons related to social acceptance, land rights, or any other reason, then using time of use tariffs can play a major role in increasing the economic carrying capacity of the solar PV resource and thus help in maintaining a large renewable energy fraction.

4.5 Capacity Value and Other Unquantified Benefits

The modeled scenarios, simulations, and analyses considered only a few of the main operational principles and benefits of grid-connected battery energy storage systems such as renewable energy firming and peak shaving. However, given the current condition of the Lebanese electricity system, its poor grid quality, its inadequacy, its definite loss of load probability, its deteriorating transmission and distribution infrastructure, and its high emissions factor, other benefits of grid-connected BESS may prove to be of substantial added value when it comes to leapfrogging to a sustainable and reliable electricity system. Estimating the price of primary control and the provision of ancillary services in Lebanon is a difficult task due to the unavailability of such services, predominantly in rural areas. Furthermore, calculating and quantifying the benefits of investment deferral regarding upgrades in the transmission and distribution network suffers from a baseline scenario that requires substantial investments in any case. The added benefits of grid-connected BESS, such as the provision of ancillary services and frequency reserves, enhanced demand response and grid reliability, energy arbitrage, increased renewable energy penetration, and transmission and distribution investment deferral, can thus be considered as quintessential for the Lebanese electricity system and its transformation. Incorporating these benefits into our modeled scenarios and simulations are vital areas requiring future research. Only then can the overall value of BESS integration be estimated.

With regard to the benefits of our considered renewable energy systems, our framework incorporates two sources of value: (1) the operational value and (2) the emissions reduction value. A third benefit is the capacity value of the renewable energy systems. To calculate the capacity value of the solar PV and wind energy systems modeled in our Adapted Base Case scenario, we utilize load duration curves to calculate the effective load carrying capacity (ELCC) of the variable generation plants during the "riskiest" hours or the hours of highest loss of load probability, considered as the first 100 hours of the plot. The area between the load duration curve of the existing demand and the load duration curve of the existing demand less the variable generation output during the first 100 hours is calculated as the ELCC (see Figs. 7.15 and 7.16). The achieved value is then divided by the

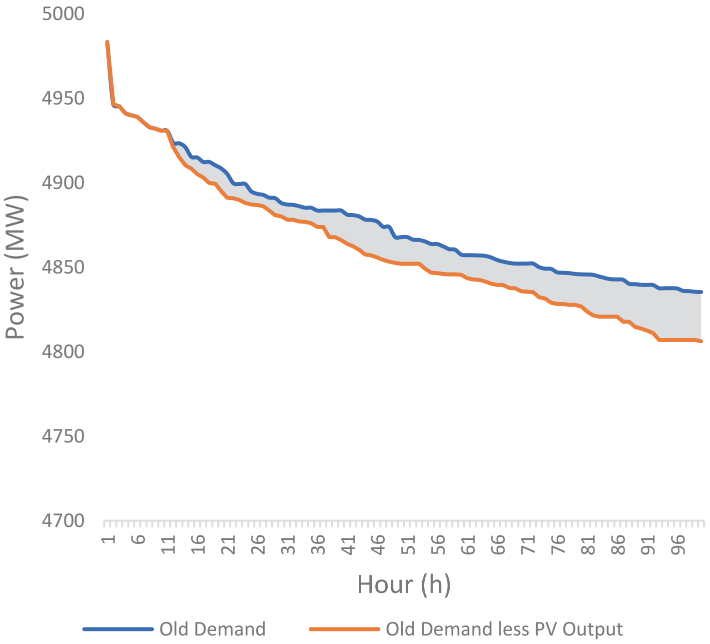

Fig. 7.15 Calculating the ELCC of the solar resource in the Adapted Base Case Model

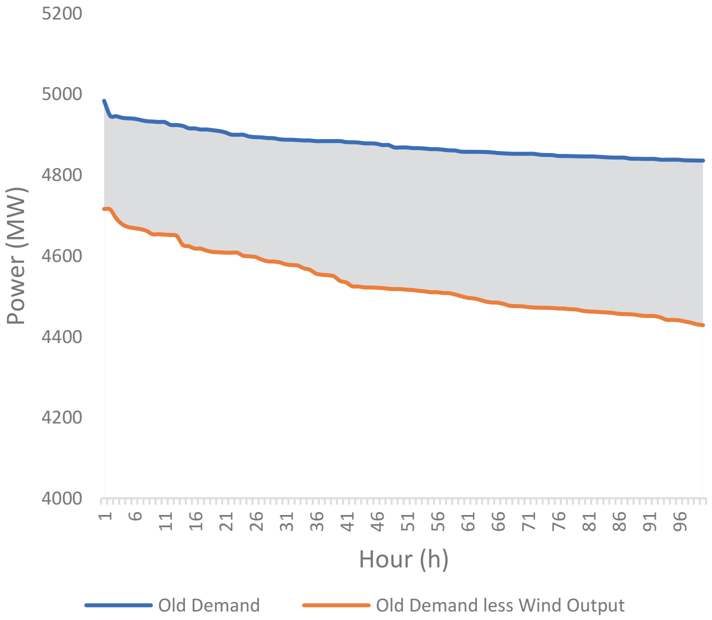

Fig. 7.16 Calculating the ELCC of the wind resource in the Adapted Base Case Model

nominal plant capacity and multiplied by 100 hours to attain the capacity credit of the renewable energy system (as a percentage). Equation (1) presents the calculation procedure:

$$\text{Capacity Credit}(\%) = \frac{\text{ELCC}(Wh)}{100(h) * \text{nomical plant capacity}(W)} \tag{1}$$

Last, the capacity credit is multiplied by the nominal plant capacity and then by the annualized cost of a peaking power (assumed to be \$128/kW) to output the capacity value.

We find the capacity credits of 26.4% and 0.9% for the 1.3 GW wind resource and 1.68 GW solar resource, respectively. The capacity credit for wind power in Lebanon has improved when compared to earlier estimates that calculated wind power capacity credit for Lebanon. An earlier study (Harajli et al. 2011) indicated capacity credits of 36.4%, 32%, and 26%, for 99 MW, 249 MW, and 498 MW of wind power capacity penetration, respectively. Improvements in wind power technology yield higher capacity factors in the same regions.

The estimated capacity values of wind and solar translates to the equivalent of wind power and solar power also operating as a 341 MW and a 14.9 MW peaking power plant, respectively. Utilizing the annualized cost of a peaking power plant of 128\$/kW, we calculate the capacity value of the wind farm to be \$43.6 million and that of the solar PV farm to be \$1.9 million. The large discrepancy in the capacity value of the two renewable energy sources is a result of the larger time coincidence between power generation and peak load hours of the wind resource as compared to the solar resource.

5 Relevance to Power Systems in the Middle East

Energy consumption in the Middle East region is expected to increase by approximately 54% by 2040 (BP 2018). However, considerable room for progress in exploiting the regions renewable resources is present for countries in the Middle East and North Africa region (MENA) as they are endowed with the world's best solar insolation levels, reaching up to 6.5 kWh/m^2/day in some regions, and a substantial wind energy potential, specifically on the Atlantic and Red Sea costs, with wind speeds frequently exceeding 6.9 m/s at a 50-meter hub height in such regions (IRENA 2016a; Poudineh et al. 2018; IRENA 2014). Countries in the Gulf Cooperation Council (GCC) alone were shown to have 59% and 56% of their surface areas suitable for solar and wind deployment, respectively (IRENA 2016b).

As of 2015, the installed power generation capacity in the Arab region consisted of 94% nonrenewable resources, with hydropower taking up 78% of the remaining 6% share of renewable energy (IRENA 2016a). Concurrently, several countries in the Arab region have one of the world's largest carbon footprint per capita (El Hajj et al. 2016).

In the Pan-Arab Strategy for the Development of Renewable Energy, a commitment was established to increase the region's installed renewable energy capacity from 12 GW in 2013 to 75 GW in 2030 (IRENA 2014). In 2015, prior to the twenty-first session of the Conference of Parties (COP 21), all Arab States submitted their intended national determined contributions (INDCs) to the United Nations Framework Convention on Climate Change (UNFCCC), which encompassed national action plans and policies put forward as part of a country's contribution to meeting the global goal of limiting temperature increase to 2 degrees above pre-industrial levels (El Hajj et al. 2016). Countries that are well established in their climate change polices where able to submit their INDCs at an earlier stage with more stringent targets of adaptation. The targets are summarized in Table 7.7 and confirm an overall shift toward solar and wind energy in the region (IRENA 2016a).

A large collection of country-specific literature and studies can be found on countries in the MENA region that deal with deploying various instruments for the introduction of renewable energy, long-term techno-economic optimization models for transitioning to renewable energy, and studies that support the need of an all-encompassing policy framework to promote the adoption of renewable energy. However, there is a shortage of literature and studies that focus on the development of sustainable energy transition strategies through long-term and self-sustainable frameworks for the MENA region (Poudineh et al. 2018). Developing a model framework that incorporates all assets, including high penetration of renewable energy and storage technologies, while studying the sensitivity of the power system

Table 7.7 Renewable energy targets in the Arab region – adopted from (IRENA 2016a)

Country	Target Renewable Fraction (%)	Target Date
Algeria	15	2020
	37 (installed capacity) 27 (electricity generation)	2030
Bahrain	5 (installed capacity)	2030
Djibouti	100 (electricity generation)	2025
Egypt	20 (electricity generation)	2022
Iraq	1 (electricity generation)	2020
Jordan	10 (primary energy)	2020
Kuwait	15 (electricity generation)	2030
Lebanon	12 (electricity generation)	2020
Libya	7 (electricity generation)	2020
	10 (electricity generation)	2025
Mauritania	20 (electricity generation)	2020
Morocco	42 (installed capacity)	2020
	52 (installed capacity)	2030
Palestine	10 (electricity generation)	2020
Qatar	20 (installed capacity)	2030
Saudi Arabia	30 (installed capacity)	2040
Sudan	11 (installed capacity)	2020
	20 (electricity generation)	2030
Syrian Arab Republic	30	2030
Tunisia	30 (installed capacity)	2030
UAE - Abu Dhabi	7 (installed capacity)	2020
UAE - Dubai	25 (electricity generation)	2030
Yemen	15 (installed capacity)	2035

characteristics to key variables (such as price of natural gas, cost of carbon, system flexibility, demand side management) should be considered essential to better inform and guide decarbonization policies in the power sector.

6 Policy Recommendations and Conclusion

The study has shown that utility-scale wind and solar energy systems and grid-connected BESS have an important role to play in the sustainable transitioning of the Lebanese electricity system even when considering the best adaptation scenario of utilizing natural gas CCGT plants. We find that integrating variable renewable energy generation and storage into the power system modeling framework will result in a decreased overall system LCOE and decreased emissions. Choosing to internalize or externalize the cost of carbon and modeling for different estimates of natural gas prices showed a high level of sensitivity as regards the optimal power system configuration, the LCOE, and the penetration and economic carrying capacity of the renewable energy technologies. A positive correlation was found between both the SCC and the price of natural gas and the penetration of variable renewable energy. The scenario that assumes a relatively low price of natural gas and excludes the SCC obtains a system LCOE and a RE fraction of approximately $0.06/kWh and 7.2%, respectively. The scenario with a relatively high price of natural gas and an internalized SCC gives a system LCOE and a RE fraction of $0.09/kWh and 48.4%, respectively. Having a higher system LCOE due to the internalization of the SCC should not be considered as a negative outcome for two reasons. The first is that a higher electricity price induces lower demand, and the second reason is that the government revenue obtained by taxing carbon can be reinjected in sustainable energy provision, including energy efficiency.

Increasing conventional generation flexibility by utilizing the minimum loading ratio as the main flexibility parameter is one effective option observed to decrease system LCOE and increase the economic carrying capacity of variable renewable generation, particularly solar PV. Decreasing the minimum loading ratio of the combined cycle generators from 50% to 40% resulted in approximately a threefold capacity increase of the solar PV resource and a slight decrease of the LCOE from approximately $0.0709/kWh to $0.0708/kWh. Another effective parameter to increase the economic carrying capacity of the solar resource and decrease system LCOE was utilizing demand side management to restructure the load profile and shift the evening peak load to daytime hours. We estimated a new time-of-use tariff scheme to model demand side management and restructure the average load profile which resulted in an increase of the solar resource capacity from 1.6 GW to 2.2 GW and a decrease in system LCOE from 7.09 US cents per kWh to 7.02 US cents per kWh.

An economic limit of approximately 20–25% of wind and solar energy penetration without the addition of substantial energy storage was reached. Furthermore, a positive correlation was found between the penetration of renewable energy above the economic limit and the needed capacity of battery energy storage which is attributed to the variable nature of renewable energy technologies and the increased need for energy shifting.

The provision of renewable energy firming and peak shaving by the BESS and the consequent effects of increasing the economic carrying capacity of solar energy was shown. However, multiple value streams for grid-connected BESS coupled with renewable energy sources were not quantified and integrated into the model. These added benefits include the provision of enhanced demand response and reliability, the provision of ancillary services, and T&D investment deferral. In addition, the unincorporated capacity value of solar PV energy and wind energy in our modeled Adapted Base Case scenario was found to provide peak load support equivalent to a 356 MW peaking power plant.

Given the substantial renewable energy potential that Lebanon has, a more enabling regulatory and overall sector management environment is required to enhance the adoption of large-scale renewable energy solutions, grid-connected battery energy storage, and other innovative technologies to expedite the sustainable energy transitioning. The sector is in need of an independent regulatory authority to compliment the work of the Ministry of Energy and Water and the national utility in order to ensure (1) renewable energy market de-risking, as outlined in (UNDP 2017), (2) secure the required frameworks for public private partnerships, (3) incorporate new business models, and (4) ensure efficient and effective planning and operation of the sector as a whole. Eliminating barriers to multiple value streams for grid-connected storage and utility-scale renewable energy technologies and internalizing externalities such as the SCC should be considered as priorities in policy reform.

The work presented herein is not without its limits. Future work should include utilizing more complex modeling tools in building a stochastic modeling framework while co-optimizing all assets, stacking grid-connected BESS value streams, and internalizing power plant cycling costs and other externalities to achieve more confidence in evaluating sustainable energy transitions.

Adopting a broader view and considering the highly favorable natural conditions that the Arab and MENA region have and the large room for improvement and progress in adopting renewable energy solutions, it can be ascertained that renewable energy has a vital role in the region's sustainable energy transition especially when considering the associated broader contexts of socioeconomic development, the creation of new value-chain activities, industrial diversification and job creation, and enhanced balance of trade. However, the establishment of enabling technical, economic, regulatory, and policy framework is considered imperative (IRENA 2016a). In that regard and considering the recent uptake in the deployment of large-scale renewable energy systems in the region, we highly recommend that countries in the resource-rich Middle East incorporate the multiple value streams of battery energy storage, power system flexibility requirements, the social cost of carbon, and the integrated co-optimization methodology when developing their sustainable energy transition plans in support of policy frameworks.

Annex 1: Key parameters adopted in the Homer Pro model

Conventional generation units' parameters		
Parameter	CCGT	OCGT
Lifetime	25 years	25 years
Capital expenditure	1080 $/kW	835 $/kW
Fixed operation costs	17.7 $/kW-year	11.81 $/kW-year
Variable operation costs	2.6 $/MWh	13.6 $/MWh
Installation time	31.75 months	27 months
Heat rate	6591 BTU/kWh	9697 BTU/kWh
Minimum load	50%, 40%, 30%	10%

Renewable energy generation parameters		
Parameter	Solar PV plant	Wind farms
Lifetime	25 years	25 years
Capital expenditure	565 $/kW	1400 $/kW
Fixed operation costs	11 $/kW	2% of capital cost
Capacity factor	19.40%	37%
Specific yield	1700 kWh/kWp	3241 kWh/kWp
Inverter efficiency	98%	–
Derating factor	88%	–
Overall loss factor (wake effect, availability, electrical, and others)	–	20%
Hub height	–	84 meters

ESS parameters	
Parameter	Value
Lifetime	15 years
Capital expenditure	315 $/kWh
Fixed operation costs	1% of Capex
Replacement cost	145 $/kWh
Minimum state of charge	10%
Rectifier efficiency	98%
Derating limit	30% of initial capacity

Main simulation and financial parameters and constraints	
Parameter	Main inputs
Project lifetime	25 years
Effective interest rate (adjusted for inflation)	12% per year
Inflation rate	2% per year
Percentage of unmet load	0%
Dispatch strategy	Load Following or Cycle Charging
Optimization objective	Economic minimization
Minimum spinning reserve	10% of instantaneous load +10% of instantaneous PV output +10% of instantaneous wind power output

References for above assumptions: (IEA/OECD/NEA 2015; NREL 2012; CEC 2014; eia 2018; Lazard 2017)

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Chapter 8
Climate Change and Energy Dynamics with Solutions: A Case Study in Egypt

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Abstract In general, the normal climate of the Middle East is mainly dry and hot with mild winter and little rain. Due to climate change, the Middle East countries are facing extreme heat, draught, and conditions of aridity. As a result of this, there is a problem of electricity and power generation in the Middle East countries. One way to address this challenge is to increase generation capacity from renewable resources without using conventional way of generation. Renewable resources like solar and wind can easily mitigate the problems related to power generation, as coal will extinct in due course of time and level of water is being highly affected due to climate change. So our goal is to model and simulate a hybrid power system based on renewable energy sources which may solve the problems regarding the power generation due to climate change. Many research works have been done regarding the power generation and how it gets affected by climate change. The use of renewable energy will be able to mitigate climate change if certain aspects are taken into account. The uses of renewable energy predominate in order to tackle the problems regarding power generation due to climate change. Thus in this chapter, we have discussed about the cause for the climate change and the effect of generating power from renewable resource on climate change. We have also modeled, simulated, and optimized a hybrid power system based on renewable energy on a Middle East country. This simulation and optimization will able to know how efficiently the hybrid system will work on those areas and what will be the cost for generation. Moreover, the hybrid power system will be strategically designed in such a way that there will be less emission of carbon, which is one of the main reasons for climate change. In this chapter we have conducted optimization and case studies analysis taking the real-time data in terms of renewable energy, and we assume an average electric load data for our study. Optimization of the hybrid model using those real-time data will give an idea about to what extent there will be the generation of power, the actual cost that will be required to set up the hybrid power plant, and most importantly the per unit cost of energy consumption.

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H. Qudrat-Ullah, A. A. Kayal (eds.), *Climate Change and Energy Dynamics in the Middle East*, Understanding Complex Systems,
https://doi.org/10.1007/978-3-030-11202-8_8

Keywords Optimization · Hybrid power system · Middle East country · Grid · Solar power plant · Wind farm · Egypt · Energy dynamics · Climate change

1 Introduction

The normal climate of the Middle East is mainly dry and hot with mild winter and little rain. The great steppers are the desert of the north, which have an extreme temperature and rain in the winter and spring. The left areas have rainfall in between March and November as well as flood like situation from March to May. One seacoast of northern Iran receives up to 2000 mm of rain in a year, named as Caspian seacoast. On the other hand, there is no rain at all in the desert regions of Iran for many years. Similarly the temperature is not same in all regions. Middle East has a summer temperature of around 85 F but sometimes it rises above 100 F. Middle East countries include Egypt, Iran, Turkey, Iraq, Saudi Arabia, Yemen, Syria, Jordan, United Arab Emirates, Israel, Libya, Lebanon, Oman, Kuwait, Qatar, and Bahrain (List of Middle Eastern countries by population 2018). Presently, the whole world is facing a major problem of global climate and global warming which cause melting of ice caps by rising the temperature in between 3.2 F and 7 F. This cause problem for those persons who lived near coastal areas in the Middle East and force them to move inland and face even more warm summers. It directly affects the economy of Middle East by affecting the oil production, energy consumption, and energy production (Climate of Middle East 2018). The greenhouse effect is the main reason of climate change. When sunlight reaches Earth's surface, then it may absorb by Earth or reflected back to the space. Once absorbed by Earth, then it releases some heat known as infrared radiation. Greenhouse gases like water vapor, carbon dioxide, and methane absorb this heat energy and prevent them to go to space. It is needed to make stable environmental conditions in normal amount but it is dangerous in extreme amount. After the rise of industrial revolution around 1750, a large amount of CO_2 and other heat-trapping gases are added in the atmosphere which rises the temperature. Mainly the burning of fossil fuel for energy production, cooking, vehicles, etc. cause huge climate changes by rising the temperature. Volcanic eruptions released large quantities of CO_2 in the atmosphere, but presently the USGS reports confirm that the human activities emission is more than 135 times as compared to volcanoes each year. Another major greenhouse gas after CO_2 is methane. Natural wetlands, agricultural activities, transport, and fossil fuel extraction are the main causes of methane emission. From the twentieth century, methane concentration rise sharply. Other greenhouse gases like nitrous oxide, water vapor, etc. also contribute a major part in rising temperature (Climate Change Science 2018). For energy generation, coal is a major fuel in the Middle East region which results in the rising demand of the black fuel. A consortium of Saudi Arabia's ACWA Power and China's Harbin Electric began a 2.4 Giga Watt (GW) coal power plant on the site. The energy strategy of UAE in terms of power generation by 2050 is to increase the use of coal for power generation for about 12 percent of the total national electricity generation, which is 11.2 GW. Federal Electricity and Water

Authority (FEWA) in Dubai also planned a 1.8 GW plant in the northern emirates. For industrial use, Egypt imports a large amount of coal since 2014. In addition, the other countries of Middle East with their neighboring countries are also planning to increase the use of coal thermal power plant mainly for the power generation. Middle East region is rich of oil, gas, and solar power but their attraction toward coal power generation is surprising. Countries like China, India, etc. are also planning to reduce their coal power generation and, on the other side, Middle East countries planning to increase it. It is possible that most of the plants are built with advanced pollution control that can reduce the pollution, but still they emit large amount of carbon dioxide which is the main reason of climate change in the Middle East. The use of coal is mainly on the basis of financial viewpoint but not good in terms of nature viewpoint. It is true that the renewable energy usage and the nuclear energy usage are rising in the Middle East, but this rise is very slow as compared to coal usage for power generation (The Strange rise of coal in the Middle East 2018). The city of Dubai over the last 25 years improved a lot in respect to road traffic, urban and industrial development. The increasing use of motor vehicle fleet affects a lot in terms of air quality. Busier roads, expanding airports, new construction, etc. affect the air quality which results in changes observed in climate. Not only this city but many cities of Middle East countries contribute a large amount of pollution mainly from the vehicle and are increasing day by day (Air Pollution in UAE 2018). Middle East countries are located in an area where there is huge possibility of solar power generation. Presently the cost of solar panel is also falling, and so there is huge need to use that possibility not only power generation but for the protection of nature as well as future generation. Solar thermal power plant also possible in these areas as their use not only reduces pollution but also fulfills energy demand. Coastal areas can also be utilized by wind power plant as well as solar wind hybrid power plant for energy generation. It is possible to convert all the huge buildings in Middle East into large-size solar power plant. As well as the use of electric vehicle is needed to be increased for reducing vehicle pollution. These simple advancements not only reduce pollution but control the climate change a lot. In recent past, various studies have been conducted regarding climate change and its impact on Middle East countries. The climate change generally occurs greatly in the atmosphere due to percentage increase of certain gases like carbon dioxide, methane, nitrous oxide, and other gases related to greenhouse effect (McCarthy et al. 2001). According to World Resources Institute (WRI) 2005 report, the total greenhouse gas (GHG) emissions of the world are nearly about 33,000 tetragram in the year 2000, and among them the Middle East countries contribute 4.2% of the world's total GHG emission (UNDP & IIED 2005) which indicates that the Middle East countries face the catastrophic effect of climate change due to their GHG emission. In general most of the GHGs come from the conventional power plant and pollutions from the emission by vehicles. So, this is a high time that we must embrace the use of conventional energy in order to get rid of the ill effects of climate change in Middle East countries.

In Majid et al. (2018), the authors suggest that renewable energy is the only solution to combat climate change and the effects of climate change. The use of the renewable energy must be sustainable in order to congregate the demand for the generation after us. Due to the day by day and fast augmentation of the request of energy around the world, the entire globe is turning into an all-inclusive town though the Earth did not change in its frame. The prerequisite for energy and related organizations to meet human social and fiscal change, flourishing, and prosperity is creating. The entry to maintainable power sources to help mitigate natural change is a mind-blowing approach that must be sensible to meet the energy solicitations of who and what is to come. The examination looked open entryways related with supportable power sources, including security for energy, access toward energy, social and money-related change, easing of ecological change, and diminishing the impact on nature and prosperity. Notwithstanding these openings, there are challenges that hamper the supportability of feasible power sources to mitigate ecological change. These challenges fuse advertised disillusionments, nonappearance of information, access to unrefined materials for the future use of economical resources, and our step-by-step carbon impression. The examination proposed a couple of procedure measures and proposals that, when considered, would help achieve the supportable power source target, in a way diminishing emanations, moderating environmental change, and guaranteeing a perfect domain, and clean energy for who and what is to come.

The world is rapidly transforming into an overall town in view of the step-by-step augment in energy ask for by the entire people of the world, while the earth in its shape can't change. The necessity for energy and related organizations to meet human social and budgetary progression, thriving, and prosperity is creating. All associations require energy organizations to meet basic human needs, for instance, prosperity, lighting, cooking, space comfort, adaptability, and correspondence, and fill in as generative methods (Edenhofer et al. 2011). Securing energy supply and diminishing the dedication of vitality to ecological change are the challenges that energy divisions need to vanquish while in transit to a sensible future (Abbasi & Abbasi 2011). It is overwhelming to know nowadays that 1.4 billion people don't approach control, while 85% of them live in nation locales. Fittingly, it is assessed that the measure of ordinary frameworks in light of the standard utilization of biomass will increment from 2.7 billion today to 2.8 billion out of 2030 (Kaygusuz 2012). From an irrefutable perspective, the basic business coal misuses occurred in 1750, close Richmond, Virginia. Coal is the most upheld fuel for steam motors in light of its higher ability to transport essentialness than the relating measures of biomass-based animates (fuel and coal). It is vital that coal was more reasonable and with a much cleaner fuel in the past numerous years (Abbasi et al. 2011). The transcendence of non-sustainable power source-based vitality creation (coal, oil, and gas) and exponential masses advancement in continuous decades have incited a creating enthusiasm for vitality, which has provoked overall challenges related with a speedy augmentation in outpourings carbon dioxide (Asumadu-Sarkodie & Owusu 2016). Basic natural change has ended up being extraordinary compared to other challenges of the twenty-first century. Its honest to goodness impacts can, in any case, be avoided if attempts are rolled out to improve the present vitality systems. Reasonable power sources have the key potential to move ozone hurting substance transmissions from oil subsidiary-based vitality age and, as needed, to mitigate ecological change. Research on elective vitality sources returns to the 1990s, when the world began to get shock from oil creation to the extent esteem tourism (Abbasi et al. 2011). The written work shows that supplanting fossil vitality sources with supportable power sources, including bio-vitality, organized sun-based vitality, geothermal vitality, and hydropower, wind, and ocean vitality (tides and waves), would gradually achieve the likelihood of reasonability. Vitality is a compulsory asset in our normal everyday presence as a way to deal with upgrade human progression that prompts advancement and productivity. Returning to boundless sources will help diminish natural change anyway ought to be conservative to ensure a viable future for a long time to meet their vitality needs. Data of the association between sensible headway and, particularly, manageable power source is so far limited. The purpose of the paper was to choose on the off chance that it is possible to recuperate vitality sources that are viable and how changing from fossil vitality sources to limitless wellsprings of vitality would add to lessening natural change and its impact. Abstract research has been used to review the articles in the degree of the examination. In any case, the full life cycle of sustainable power sources does not have net discharges as far as possible the future worldwide ozone-depleting substance emanations. Nonetheless, cost, political condition, and economic situations have turned into the obstructions that forestall creating nations, the minimum created and the created ones from making full utilization of their potential. Thus, making an overall open entryway through worldwide coordinated effort to encourage LDCs and making countries to the extent accessibility of practical power sources, vitality capability, clean green developments and research and enthusiasm for vitality establishment will decrease the cost of reasonable power source, remove obstacles to vitality profitability (high refreshing rate) and progress new potential for lightening ecological change. The examination highlighted open entryways for economical power sources, vitality security, access to vitality, social and monetary change, and mitigation and diminishment of natural change impacts on the earth and on prosperity. There are challenges that tend to hamper the reasonability of maintainable power sources and its ability to calm ecological change. These troubles are publicized dissatisfactions, nonattendance of information, access to unrefined materials for the future usage of unlimited resources, and, most importantly, our technique for using vitality inefficiently. In El-Katiri (2014) the author suggests that the Middle East countries have a high advantage of getting solar energy and as a result the renewable energy sources like solar and wind energy potential have been overlooked in those areas, which could have helped those areas to generate electricity easily.

In Meisen and Hunter (2007), the authors also suggest that the Middle East is well blessed with solar energy which is not only renewable and sustainable but also very clean. In countries like Iran, Egypt, UAE, etc., it is not tough to start a renewable energy plant there. If once tapped, the renewable energy will run very far in the near future. Photovoltaic (PV) innovation includes the age of power from light. The key to this procedure is the utilization of a semiconductor material which can be adjusted to discharge electrons, the contrarily charged particles that shape the premise of power. The most well-known semiconductor material utilized as a part of photovoltaic cells is silicon, a component most generally found in sand. All PV cells have no less than two layers of such semiconductors, one emphatically charged and one contrarily charged. At the point when light sparkles on the semiconductor, the electric field over the intersection between these two layers makes power stream. The more noteworthy the force of the light, the more prominent the stream of power. A photovoltaic framework does not, along these lines, require splendid daylight with a specific end goal to work and can create power even on overcast days. At the point when a PV establishment is portrayed as having a limit of 3 kWp (top), this alludes to the yield of the framework under standard testing conditions, permitting correlation between various modules. In focal Europe, a 3 kWp evaluated sun-based power framework, with a surface region of roughly 27 square meters, would create enough capacity to take care of the power demand of an energy cognizant family.

In Nematollahi et al. (2016), the authors suggested that due to increase in economy in the Middle East, there is an increase in demand for the electricity; as a result not only there is an energy crisis but also the amount of pollution is increased. The use of renewable energy can only eliminate these problems. Depending upon the geography, the Middle East has a huge potential for solar, wind, and hydropower energy. The energy security and supplies of energy are the key parts for advancing nations. Sustainable power source assets are quickly being perceived as perfect wellsprings of energy to withstand harms to condition and to maintain a strategic distance from future emergency. In this examination, energy utilization and energy requests in the advancing Center East nations are checked on. In the first place, the development of energy utilization of the area through ongoing years is exhibited which demonstrate the quickly developing energy request in the Center East nations. Second, by utilizing RETScreen programming information, the capability of the primary sustainable power sources of sun-oriented and wind assets are assessed. Results demonstrated that the Center East locale has a decent potential for utilizing sustainable power sources. Results are exhibited as GIS maps of wind speed, wind control thickness, and sunlight-based radiation power. With utilizing the GIS maps, the immense areas for using sun-powered or wind energies are recognized. The displayed GIS maps may encourage improvement of mixture sun-based and twist frameworks inside the Center East district. In this examination, the capability of sustainable power source assets in the Center East district is surveyed. The developing interest of energy utilization for these creating states is examined. With the guide of GIS maps, the capability of sun-powered and wind control is introduced. As per the GIS maps on sun-based power, Yemen, Saudi Arabia, and Egypt have most astounding uncovered zones. Showing that they can well be suggested as more practical and all the more encouraging locales for introducing sunlight-based offices considering GIS guide of wind control, Iran, Turkey, Iraq, Egypt, Yemen, and Oman are among the best nations with high wind possibilities. What's more, in this paper wind energy potential in two statures, 10 m and 50 m are displayed. It is vital to say that little wind turbines can be introduced similarly in the most parts of district. Additionally, a portion of these areas are appropriate for introducing wind turbines to pump water. At the stature of 50 m, extensive wind turbines can be advantageously introduced in the referred to areas.

In this chapter, an optimization case study analysis of solar wind hybrid power plant in an area of Egypt using HOMER Pro software is done. All the Middle East countries face almost the same climate change conditions which indicates that analyzing an area of one Middle East country provides an overall idea of other Middle East countries especially in terms of power generation. This chapter mainly focuses on Egypt. This study uses real-time solar irradiance and wind speed data of selected area of Egypt. Optimization of the hybrid model using these real-time data will give us an idea about to what extent there will be the generation of power, the actual cost that will be required to set up the hybrid power plant, and most importantly the per unit cost of energy consumption. This work contributes toward the dream of making world pollution free using renewable power sources. This chapter also provides an overall power generation analyzing of Egypt which helps us to understand the need of this hybrid system.

2 Reasons Behind the Climate Change in Egypt

The topography of Egypt identifies with two locales: North Africa and Southwest Asia. Egypt has coastlines on the Mediterranean Ocean, the Stream Nile, and the Red Ocean. Egypt fringes Libya toward the west, the Gaza Strip and Israel toward the upper east, and Sudan toward the south. Egypt has a territory of 1,001,449 km^2 (386,662 mi^2). The longest straight-line remove in Egypt from north to south is 1024 km (636 mi), while that from east to west measures 1240 km (771 mi). Egypt is overwhelmingly deserted. 35,000 km^2 – 3.5% – of the aggregate land region is developed and for all time settled. The greater part of the nation exists in the wide band of desert that stretches eastwards from Africa's Atlantic Drift over the landmass and into southwest Asia. Egypt's land history has delivered four noteworthy physical areas:

- Nile Valley and Nile Delta
- Western Desert (from the Nile west to the Libyan fringe)
- Eastern Desert (reaches out from the Nile Valley the distance to the Red Ocean drift)
- Sinai Promontory

Notwithstanding covering just around 6.5% of the aggregate zone of Egypt, the Nile Valley and Nile Delta are the most vital locales, being the nation's solitary cultivable areas and supporting around 99% of the populace. The Nile Valley expands around 800 km from Aswan to the edges of Cairo. The Nile Valley is exceptionally cool and known as Upper Egypt, while the Nile Delta area is known as Lower Egypt. Soak rough precipices ascend along the banks of the Nile in a few stretches, while different regions along the Nile are level, with space for agrarian generation. Previously, flooding of the Nile amid the late spring gave residue and water to make farming conceivable ashore that is generally extremely dry. Since development of the Aswan Dam, agribusiness in the Nile Valley relies upon water system. The Nile Delta comprises of level, low-lying territories. A few sections of the delta are damp and water-logged and subsequently not appropriate for horticulture. Different regions of the delta are utilized for agribusiness. The Nile Valley and Delta, the most broad desert spring on earth, was made by the world's longest waterway and its apparently limitless sources. Without the topographic channel that allows the Nile to stream over the Sahara, Egypt would be altogether desert. The length inside Egypt of the Waterway Nile in its northwards course from three focal African sources – the White Nile, the Blue Nile, and the Atbara – adds up to around 1600 km. The White Nile, which starts at Lake Victoria in Uganda, supplies around 28% of the Nile's Egyptian waters. In its course from Lake Victoria to Juba in South Sudan, the White Nile's channel drops in excess of 600 m. In its 1600-km course from Juba to Khartoum, Sudan's capital, the waterway plunges only 75 m. In South Sudan, the White Nile goes through the Sudd, a wide, level plain secured with overwhelm vegetation and eases back nearly to the point of stagnation. The Blue Nile, which begins at Lake Tana in Ethiopia, gives by and large somewhere in the range of 58% of the Nile's Egyptian waters. This waterway has a more extreme slope and along these lines streams more quickly than the White Nile, which it joins at Khartoum. Dissimilar to the White Nile, the Blue Nile conveys a lot of silt. For a few kilometers north of Khartoum, water nearer toward the eastern bank of the stream, originating from the Blue Nile, is unmistakably sloppy, while that closer toward the western bank, and originating from the White Nile, is clearer. The significantly shorter Atbarah Stream, which additionally begins in Ethiopia, joins the principle Nile north of Khartoum between the fifth and sixth cataracts (areas of soak rapids) and gives around 14% of the Nile's waters in Egypt. During the time of low-water season, which keeps running from January to June, the Atbarah flattens to number of pools. Be that as it may, in pre-fall, when heavy rains fall on the Ethiopian Good countries, the Atbarah gives 22% of the Nile's stream. The Blue Nile has a comparative example. It contributes 17% of the Nile's waters in the low-water season and 68% amid the high-water season. Interestingly, the White Nile gives just 10% of the Nile's waters amid the high-water season however contributes over 80% amid the low-water time frame. Subsequently, before the Aswan High Dam was finished in 1971, the White Nile watered the Egyptian stretch of the stream consistently, while the Blue Nile, conveying occasional rain from Ethiopia, made the Nile flood its banks and store a layer of ripe mud over contiguous fields (Geography of Egypt 2018).

The greenhouse effect is the main reason of climate change. When sunlight reaches Earth's surface, then it may be absorbed by Earth or reflected back to the space. Once absorbed by Earth, then it releases some heat known as infrared radiation. Greenhouse gases like water vapor, carbon dioxide, and methane absorb this heat energy and prevent them to go to space. It is needed to make stable environmental conditions in normal amount, but it is dangerous in extreme amount. After the rise of industrial revolution around 1750, a large amount of CO_2 and other heat-trapping gases are added in the atmosphere which rises the temperature. Mainly the burning of fossil fuel for energy production, cooking, vehicles, etc. cause huge climate changes by rising the temperature. Volcanic eruptions released large quantities of CO_2 in the atmosphere, but presently the USGS reports confirm that the human activities emission is more than 135 times as compared to volcanoes each year. Another major greenhouse gas after CO_2 is methane. Natural wetlands, agricultural activities, transport, and fossil fuel extraction are the main causes of methane emission. From the twentieth century, methane concentration rises sharply. Other greenhouse gases like nitrous oxide, water vapor, etc. also contribute a major part in rising temperature (Climate Change Science 2018). For energy generation, coal is a major fuel in the Middle East region which results in the rising demand of the black fuel. For industrial use, Egypt imports a large amount of coal since 2014. In addition, the other countries of Middle East with their neighboring countries are also planning to increase the use of coal thermal power plant mainly for the power generation. Middle East region is rich of oil, gas, and solar power, but their attraction toward coal power generation is surprising. Countries like China, India, etc. are also planning to reduce their coal power generation and, on the other side, Middle East countries planning to increase it. It is possible that most of the plants are built with advanced pollution control that can reduce the pollution, but still they emit large amount of carbon dioxide which is the main reason of climate change in the Middle East. The use of coal is mainly on the basis of financial viewpoint but not good in terms of nature viewpoint. It is true that the renewable energy usage and the nuclear energy usage are rising in the Middle East, but this rise is very slow as compared to coal usage for power generation (The Strange rise of coal in the Middle East 2018). According to World Resources Institute (WRI) 2005 report, the total greenhouse gas (GHG) emissions of the world are nearly about 33,000 tetragram in the year 2000, and among them the Middle East countries contribute 4.2% of the world's total GHG emission (UNDP & IIED 2005) which indicates that the Middle East countries face the catastrophic effect of climate change due to their GHG emission. In general most of the GHGs come from the conventional power plant and pollutions from the emission by vehicles. So, this is a high time that we must embrace the use of conventional energy in order to get rid of the ill effects of climate change in Middle East countries.

Table 8.1 shows the energy-generated scenario where we can see that till the targeted year 2013/2014 the participation of renewable energy is very low. So this scenario has to be changed in order to combat climate change from high carbon emission and GHG from the conventional power plants. This is the main reason of increasing greenhouse gas emissions in Egypt which result in climate change. In the year 2013, 91% of the power generation mainly depends on oil and gas, and the rest 9% is from renewable sources. It is wanted to expand the sustainable power sources

Table 8.1 Energy-generated scenario in Egypt (Osman 2015)

Generated energy mix (1000 GWH)			
Year	Conventional	Hydro	Renewable energy
Actual 2011/2012	90.53%	8.20%	1.27%
Expected 2012/2013	91%	8%	1%
Targeted 2013/2014	92%	7%	1%

(counting hydro) in the power blend to 20% continuously in 2020. This objective is wanted to be accomplished by depending essentially on wind. Thus, if the use of fossil fuel can be reduced, to generate electricity, the adverse effect of climate change in Egypt can be easily mitigated.

3 Scenario of Climate Change in Egypt

Egypt is one of the countries of Middle East, which has a population of 90 million peoples, and its economy is one of the most diversified in Middle East which mainly depends on agriculture, industry, tourism, and service sectors. Egypt has a 284 billion US dollars gross domestic product (GDP) in 2014. In 1992, Egypt signed the Convention of Climate Change and ratified it in 1994. From the global greenhouse gas emissions, Egypt shares less than 1% percent where the carbon dioxide equivalent for the base year 1990 is 116 million tons to the base year 2000 is 193 million tons recorded by the first national communication record. At the same time, Egypt is one of the most vulnerable countries affected by the risk of climate change in accordance with international and national studies (Egyptian Development & Climate Change 2018). Climate change results warm climate which cause evaporation which will increase average global precipitation. These changes directly impact on weather-related mortality, infected diseases, crops yields, forest composition, geographic range of forest, forest health and productivity, water supply, water quality, competition for water, erosion of beaches, reduction of coastal lands, additional costs of protecting coastal communities, loss of habitat and species, diminishing glaciers, etc. Due to climate change, soil moisture declines in many regions, and intense rainstorms are likely to become more frequent (Climate Change and its possible impact on Egypt 2018). In Egypt, the climate change mainly affects the sectors which include biodiversity, health, food security, water resources, and coastal areas. It affects the biodiversity by providing negative impacts on coral reefs. It affects the health as it increases the vector-borne diseases in Egypt. Climate change increases the surrounding temperature which results people feel uncomfortable in living in Egypt due to hot weather environment. It affects the food security as it affects its productivity. These changes in productivity mainly occur due to the undesirable temperature changes from the normal level, i.e., direct impact of climate change. This is a big issue as it affects the main source of living of human beings in Egypt. It affects the water resources by causing droughts in those areas which are agricultural areas. The water resources of Egypt mainly depend on River Nile almost 95%. The country uses 55.5 billion m^3 of water from the river every year. Due to climate change, the vulnerability is presently facing by the Nile water. IPCC identified Africa as one of the most vulnerable regions to climate change in terms of water resources in its fourth assessment report of 2007. This report mainly tells that the east, central, and west Africa receive heavy rain which increases the risk of flood. Not only that, this report also tells that most of south and northern Africa will be subject to water stress. This is clear impact of climate change which shows unstable environment. It affects the coastal areas by converting them into flooded areas. Due to the climate change, the glaciers are melting. This results rise in the water level of the sea. This increases the risk of flood especially in the north coast of Egypt. According to SNC-2010 and IPCC 4th AR, it is expected that there is a rise of 18–59 cm of global sea level by the end of this century, based on the prevailing scenario. Sea level rise affects the vulnerable areas under two modules. The first module assumed zero levels for lake borders and the second module assumed protecting lake borders. In both cases, the two IPCC assume that up to the year 2100, there is an increment of the sea level with temperature projection depending on long-term tidal measurements in Alexandria and Al-Burullus in Egypt (Egyptian Development & Climate Change 2018). Bearing such a vibrant geography, the country of Egypt is facing tremendous effects of climate change. The natural environment normally adapts the normal climate changes which were occurring over many thousands of years. But the frequent changes occurring due to human activities result in events like sudden shift in ocean currents which cause extinction of species and the collapse of natural ecosystems. There are some examples of impact of frequent and large climate on the natural environment. Firstly, it results in species extinction, lower biodiversity, and changes in the way species interact. That is, it impacts on plant mitigation. Secondly, it affects coral reefs since slightly warmer tropical water may kill the algae which reef animals use for food. Thirdly, it directly affects the insect pests or by changing the mix of plant varieties and their content of nutrient. This may influence food chains and plant survival and also results in the spread of diseases. Fourthly, it affects mangrove swamps which play a crucial role for those animals that live in water as they are important breeding grounds. With the rise of floodwater, these areas may damage by changing the salt amount and the nutrients supply. The effects of climate change on people are different for different places. Many developed societies didn't suffer direct impacts due to their advance technologies as their scientists might develop new crop varieties, construct new water systems, and limit coastal development. Many northern countries might even benefit due to longer seasons and lower heating bills if the climate becomes warmer. Russia and Canada are such countries. Developed countries have less resource for adapting such changes. But those countries which are economically less developed, such as some parts of Africa, Asia, and South America, depend mainly on climate, and they suffered more due to climate change. Climate change may increase the drought in many countries such as Africa to a serious condition if not controlled. Farmers may face problems in adapting new agricultural practices. Climate change affects the human health both directly and indirectly. Illness and death could be the direct impacts due to excessive heat or cold exposure. Respiratory disorders due to air pollution, including spores and pollens, cholera, food productivity, and its relation to nutrition are some of the indirect effects of climate on health. Climate change may results in expanded geographic ranges for many diseases related to mosquito, based on several studies. These indirectly affect the human health. It is estimated that the thermal expansion of the water of the oceans and seas as well as the melting of polar ice caps is the main reason of sea level rise. In the scenario of 2, 3, and 4 meter rise of sea level, 60,000, 80,700 and 100,800 km^2, respectively, of the coastal region of the Arab will be seriously impacted. If the sea level rises up to 5 m, then such impact will be extremely dangerous, and it is estimated that up to 113,000 km^2 of the coastal territory that is 0.8% territory would be inundated by seawater. Egypt, Saudi Arabia, Algeria, and Morocco will suffer more as compared to Sudan, Syria, and Jordan. Egypt suffers the most impact in the Arab world since 12 million Egyptians displaced in the extreme 5 meter sea level rise scenario. It is estimated that the Arab one third population is only impacted by the Egypt alone. This is one of the main reasons of selecting Egypt as the case study area of the proposed hybrid system because Egypt extremely needs to fight against climate change. The low-lying Nile Delta is already retreating of about 100 m per year at an alarming rate. This retreat of about 24,900 km^2 in area accounts for about 65% of Egypt agricultural land alone. This is mainly due to climate change and also a result of human activity of reducing soil sediments due to Aswan High Dam and heavy groundwater extraction. Egypt' s economy will become the most vulnerable if the sea level rises up to 1 m by putting more than 6% of its gross domestic product at risk. With this 1 m rise, more than 12% of the best agricultural land of Egypt goes inside Nile Delta which is a serious thing. Due to the rise of carbon dioxide in the atmosphere, the ocean acidification occurs which destroys the coral reefs. This not only affects an important ecosystem but also the elimination of prime tourist attraction. A major portion of Egypt foreign currency earnings is 20%, that is based on the tourism sector. A large portion of workforce that is 12.6% depends upon the travel industry. Climate change directly affects the economy of Egypt. Due to climate change, temperature is rising which increased evaporation that result in greater water stress. This affects the sectors involving development plans for Egypt. As the sea level rises, salt water affects the fisheries of Egypt, and this forced to import more fish from other nations whose own fisheries will be facing decline. Finally climate change may bring food security problem by the less production of national grain (Climate Change and its possible impact on Egypt, 2018). These are some of the major impacts of climate change on Egypt.

4 Role of Renewable Energy to Combat the Climate Change

These days power is the most required interest for our everyday life. Power is something that individuals can't survive without in the present day. Without it, life will be so much troublesome and moderate. Individuals need to figure out how to deliver power from sustainable power source. With expanding the heap request and the Earth-wide temperature boost issue, many are taking a gander at eco-accommodating kinds of vitality answer to save the earth for the future age, and now the good thing is that there are inexhaustible wellsprings of power that are being found and created. For instance, solar energy which utilizes the warmth from the sun, hydroelectric utilizations intensity of running water that moves turbine and so on. Electricity is a main part of the society, and the availability of electric power led to the development of electric tools in the workplace, which could be smaller, safer, and more reliable. In home, it provided heat to make cooking easier, and electric appliances proved to be time-savers throughout the house. The social and economic development in human history is determined by the energy availability and accessibility. For this reason the solution was searched to supply the energy demand for the need of the society and economic growth. In the present scenario, almost all the countries dependent on thermal power plants for their major portion of energy supply which is a dangerous thing since it rises climate change. There is a need to use renewable energy sources in a large scale to combat climate change. Large scale of using renewable energy sources can increase the security of energy for present and for the future also. The usage of renewable energy has been increasing day by day with the focus on the different renewable energy sources, but this increase in usage is at a very slow speed. Renewable energy technologies can offer the clean and abundant energy which is gathered from self-renewing resources such as sun, water, wind, earth, and plants. It is true that individual renewable energy sources are not able to maintain continuity of power supply, but a hybrid system can. A hybrid energy system is characterized as the blend of at least two energy sources to deliver power. Hybrid systems give an abnormal state of energy security through the blend of nullification technique. The most popular hybrid power system is photovoltaic (PV) and wind turbine with a backup of diesel generator. The utilization of inexhaustible power age innovations decreases the utilization of imported nonrenewable energy sources, taking into account the cleaner age of electrical power and improvement of intensity supply alternatives. The fundamental points of interest of the mixture control framework are:

- Keep the environment clean and away from pollution of the CO2 emissions in the atmosphere.
- Fuel saving (up to 50%).
- Silent system.
- Low maintenance cost.
- Connection to other power supplies (wind turbines, solar panels, etc.).
- Low variability of the system efficiency and more reliable results.
- A long life cycle since it can provide power for more than (20–25) years.

A hybrid power provides a stable form of the power generation. These systems are cost-effective energy solution with high power quality and reliability. And an individual energy system does not generate utilizable energy for a large portion of time during the year as compared to hybrid energy system. It is true that the hybrid system also possesses some disadvantages, but they are still better since they do not support climate change. These drawbacks of hybrid energy system are:

- Large initial project cost: Hybrid system design, installation, construction engineering projects larger than independence.
- Complex systems: Taking energy from two or more different systems, integrating that energy, and using it to power a home is a complex process, and many separate parts have to function in tandem for the system to work reliably. Some systems may have two or more separate control panel overseeing each of the

system. Newer models may combine controls. Maintenance on a system like this and its installation is likely to be costly.
- Independent systems require more maintenance: Use of oil machine requires a lot of maintenance works such as replacing oil filter, spark plugs, fuel filter, etc. and also need to add fuel to the fuel tank.
- Pollution and noise: The PV system is a clean energy system, but because the system uses a hybrid diesel engine parked, so inevitably it produces pollution and noise (Importance of electricity – How it changed people's lives 2018; Marisarla & Kumar 2013; The Impact of Electricity on Society 2018; Vuc et al. 2013; Disadvantages and advantages of hybrid power supply system 2018; Soon 2015; Bhikabhai 2005; Advantages of the Hybrid System, 2018).

In the present scenario, the whole world is facing a serious problem of increasing climate change which is mainly due to greenhouse gases, such as carbon dioxide, which trap the heat in the lower part of the Earth's atmosphere (Climate Change and its possible impact on Egypt 2018). Middle East countries are located in an area where there is huge possibility of solar power generation. Presently the cost of solar panel is also falling, and so there is huge need to use that possibility not only power generation but for the protection of nature as well as future generation. Solar thermal power plant is also possible in these areas as their use not only reduces pollution but also fulfills energy demand. Coastal areas can also be utilized by wind power plant as well as solar wind hybrid power plant for energy generation. It is possible to convert all the huge buildings in Middle East into large-size solar power plant. As well as the use of electric vehicle is needed to be increased for reducing vehicle pollution. These simple advancements not only reduce pollution but control the climate change a lot. In recent past, various studies have been conducted regarding climate change and its impact on Middle East countries. The climate change generally occurs greatly in the atmosphere due to percentage increase of certain gases like carbon dioxide, methane, nitrous oxide, and other gases related to greenhouse effect (McCarthy et al. 2001). These greenhouse gases are mainly generated from thermal power plants and fossil fuel-based vehicles. In other words, climate change is the result of air pollution. With the rise in the number of industrial facilities in Egypt such as plants and factories which emit toxic gases into the atmosphere, air pollution increases, and this results in frequent climate changes (Pollution in Egypt Wikia 2018). In order to combat climate change, renewable energy plays a crucial role since it doesn't emit greenhouse gases so its use not only reduces the pollution but also reduces the climate changes. In Egypt, there is a huge possibility of solar and wind power generation but still its main source is thermal power plants. In this book chapter, we have taken an area of Egypt as our case study. The average temperature of Egypt is about 40 °C and the average wind speed is about 8.0 m/s to 10.0 m/s. Egypt is one of the Middle East countries which face problems due to climate change. The country of Egypt mainly depends on oil, its proved oil reserve in 1984 was 4.0 billion barrels, whereas in 2015 its proved oil barrel is reduced to 3.5 billion barrels (Dubley 2016). The renewable energy potential in Egypt is very high. Figure 8.1 explains the renewable energy availability in Egypt (Jacobson et al. 2017).

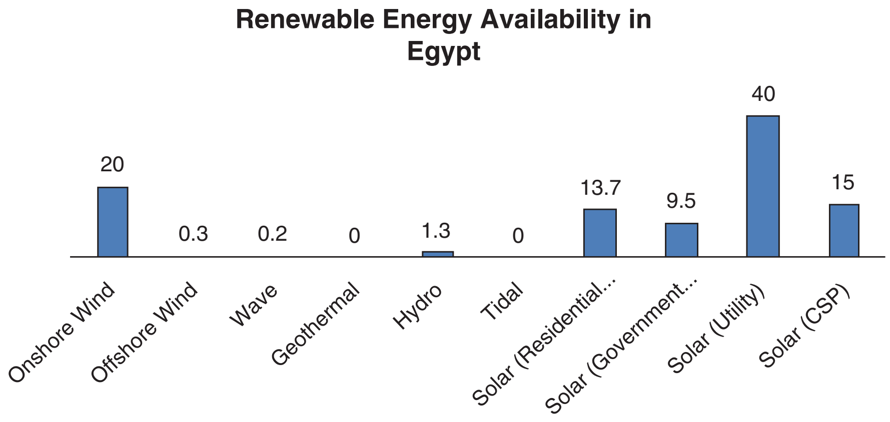


Fig. 8.1 Renewable energy availability in Egypt

It is clearly seen from the above figure that both the solar and the wind energy availability is high in Egypt. The wind energy availability adds up to as high as 20.30%, whereas the solar energy availability is very high, i.e., 78.2%. So setting up of hybrid solar-wind power plant is very profitable in Egypt. The peak demand of Egypt in 2012 was 27,000 MW, and by 2027 the demand would reach as high as 54,200 MW (Osman 2015), and by 2020 it is presumed that the nonconventional source of energy would increase by 20% in Egypt (Osman 2015).

5 System Description of the Proposed Hybrid Power Plant

Figure 8.2 shows the block diagram of the grid-connected hybrid power system which is designed using HOMER Pro software. This hybrid model has been analyzed for 60 M, Qesm Al Wahat Al Khargah, New Valley Governorate, Egypt (26°49.2’N, 30°48.1′E) location. The location of Egypt is shown in Fig. 8.3.

This system consists of two main sources of power, i.e., solar and wind resource. In this hybrid system, grid plays an important role as it purchase extra power as well as to sell power to hybrid system for fulfilling load demand during requirement. These main parts of this block diagram are PV array, windmill, grid, electric load, and converter. This grid-connected hybrid system is designed using HOMER Pro® software for a location of Egypt using real-time solar irradiance and wind speed data of that location.

Sunlight-based energy is brilliant light and warmth from the sun that is bridled utilizing a scope of regularly advancing innovations, for example, sun-oriented warming, photovoltaic, sun-based warm energy, sun-based design, liquid salt power plants, and fake photosynthesis. It is a vital wellspring of sustainable power source, and its advancements are extensively portrayed as either aloof sunlight-based or dynamic sun-based relying upon how they catch and convey sun-based energy or

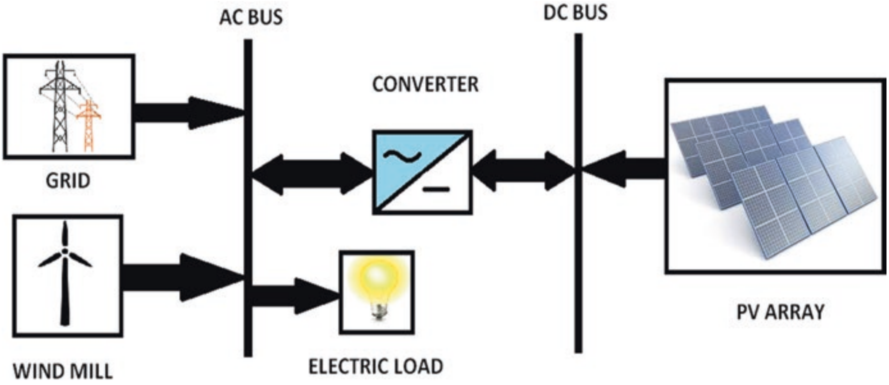


Fig. 8.2 Block diagram of grid-connected hybrid system

Fig. 8.3 Location of 60M, Qesm Al Wahat Al Khargah, New Valley Governorate, Egypt obtained from HOMER Pro software (HOMER Energy 2018)

change over it into sun-based power. Dynamic sunlight-based strategies incorporate the utilization of photovoltaic frameworks, concentrated sun-based power, and sun-oriented water warming to bridle the energy. Inactive sun-based methods incorporate situating a working to the sun, choosing materials with ideal warm mass or light-scattering properties, and planning spaces that normally circle air. The expansive size of sunlight-based energy accessible makes it an exceptionally engaging wellspring of power. The Assembled Countries Improvement Program in its 2000 World Energy Evaluation found that the yearly capability of sun-based energy was 1575– 49,837 exa-joules (EJ). This is a few times bigger than the aggregate world energy utilization, which was 559.8 EJ in 2012. In 2011, the Universal Energy Office said that “the improvement of moderate, unlimited and clean sun powered energy advances will have immense longer-term benefits. It will build nations' energy security through dependence on an indigenous, limitless and generally import-free asset, upgrade manageability, lessen contamination, bring down the expenses of relieving a dangerous atmospheric deviation, and keep petroleum product costs lower than something else. These focal points are worldwide. Subsequently the extra expenses of the motivating forces for early sending ought to be thought about learning ventures; they should be admirably spent and should be broadly shared."

Wind control is the utilization of wind stream through wind turbines to give the mechanical capacity to turn electric generators. Twist control, as a contrasting option to consuming nonrenewable energy sources, is copious, sustainable, generally dispersed, and clean, delivers no ozone-depleting substance outflows amid activity, expends no water, and uses little land. The net consequences for the earth are far less dangerous than those of nonrenewable power sources. Wind ranches comprise of numerous individual wind turbines, which are associated with the electric power transmission arrange. Inland wind is a reasonable wellspring of electric power, aggressive with or in numerous spots less expensive than coal or gas plants. Seaward wind is steadier and more grounded than ashore and seaward homesteads have less visual effect; however development and support costs are impressively higher. Little inland wind homesteads can encourage some vitality into the framework or give electric capacity to disconnected off-network areas. Wind control gives variable power, which is exceptionally reliable from year to year however has huge variety over shorter time scales. It is in this way utilized as a part of conjunction with other electric power sources to give a solid supply. As the extent of twist control in a locale expands, a need to update the lattice and a brought capacity down to supplant regular generation can happen. Power-administration strategies, for example, having abundance limit, topographically appropriated turbines, dispatchable sponsorship sources, adequate hydroelectric power, trading and bringing in capacity to neighboring regions, or decreasing interest when wind creation is low, can much of the time conquer these issues. What's more, climate determining licenses the electric-control system to be prepared for the anticipated varieties underway that happen.

5.1 Load Profile

In this chapter, the average consumption of energy for electric load is assumed as: 30,919 kWh/d. In this analyzing, electric load is assumed to be large to check that the hybrid system is possible to fulfill it or not when the power requirement is high. Figure 8.4 shows the daily average load profile, where the duration for peak demand has been found between 18:00 h and 20:00 h. Figure 8.5 indicates the average load in months where the peak load is found to be 5320 kW (HOMER Energy 2018).

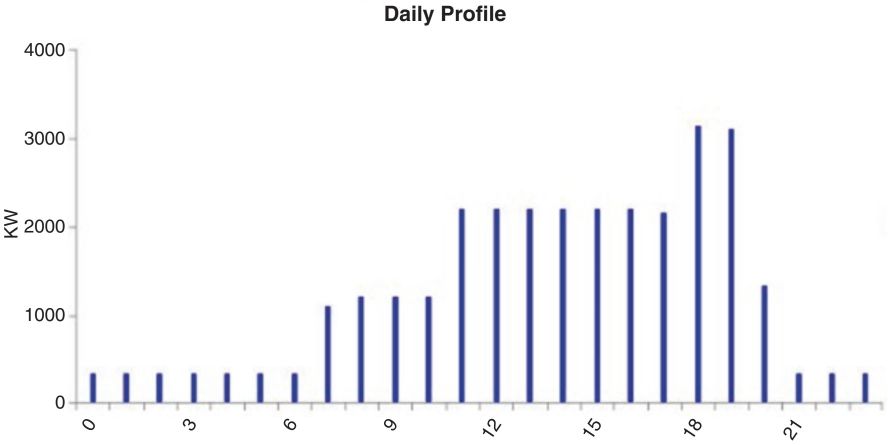


Fig. 8.4 Daily profile for load (average) (HOMER Energy 2018)

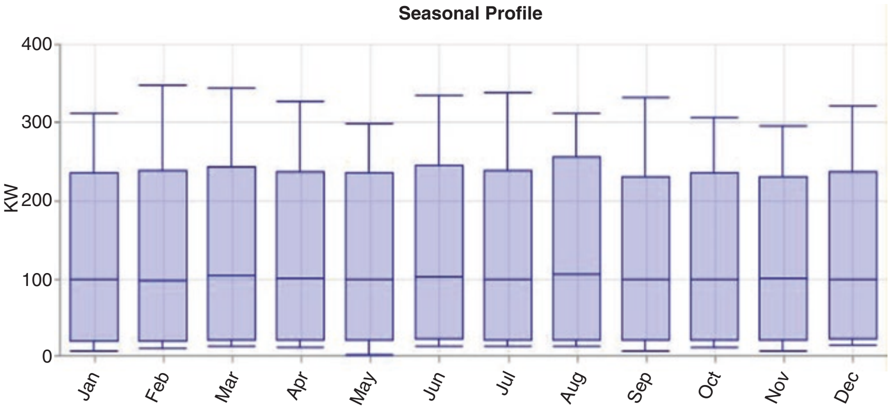


Fig. 8.5 Monthly profile for load (average) (HOMER Energy 2018)

5.2 Solar Radiation and Wind Speed

The latitude and longitude of the assumed location in Egypt are 26°49.2’N and 30°48.1′E. The average annual solar radiation is found to be 6.15 kWh/m^2/day. The monthly average data for solar radiation is shown in Fig. 8.6. The wind speed data is found to be at 50 meters above the surface of the earth. The wind speed data is shown in Fig. 8.7 where the range of the wind speed is from 4.71 meters/seconds to 6.40 meters/seconds. The average annual wind speed is found to be 5.60 meters/ seconds with the speed of the wind highest in June for the selected area.

Figure 8.8 indicates the temperature data of selected area where the range of the temperature is from 13.75 °C to 30.920 °C. The average annual temperature is

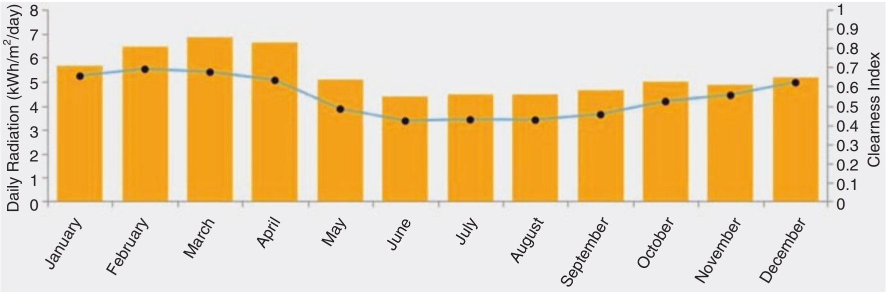


Fig. 8.6 Solar radiation and cleanliness index data (monthly average) (HOMER Energy 2018)

Fig. 8.7 Wind speed data (monthly average) (HOMER Energy 2018)

Fig. 8.8 Temperature data (monthly average) (HOMER Energy 2018)

found to be 23.25 °C with the highest temperature in the month of July of selected area. The data of solar radiation, wind speed, and temperature is obtained from the NASA surface meteorology and solar energy database (NASA Surface meteorology and Solar Energy 2018). These data helps to analyze more accurately especially for cost optimization and power generation.

6 Methodology

HOMER is a free programming application created by the National Renewable Energy Laboratory (NERL) in the United States. This product application is utilized to plan and assess in fact and fiscally the alternatives for off-network and on-lattice control frameworks for remote and remain solitary and circulated age applications. It enables you to consider a substantial number of innovation choices to represent vitality asset accessibility and different factors. HOMER was first created in 1993 for interior DOE (Department of Energy) use to comprehend the tradeoffs between various vitality generation arrangements. A couple of years after, the first outline NREL made an adaptation publically accessible for nothing to serve the developing network of framework planners inspired by sustainable power source. From that point forward, HOMER has remained a free programming application which has developed into an exceptionally powerful apparatus for displaying both customary and sustainable power source advancements (HOMER Energy 2018). The HOMER Pro software follows the following cost optimization methodology:

Net Present Cost The net present cost or NPC consists of installation cost and operating cost of the system throughout its lifetime which is calculated by the following formulae (Nurunnabi & Roy 2015):

$$\mathrm{NPC} = \mathrm{TAC} / \mathrm{CRF}\left(i, \mathrm{Rpr}_j\right) \tag{8.1}$$

Here, TAC indicates total annualized cost in terms of $, CRF indicates capital recovery factor, i indicates the rate of interest in terms of %, and Rpr_j indicates the project lifetime in terms of year.

Total Annualized Cost The total annualized cost comprises of the addition of the cost of all equipment used in power system which comprises of capital cost, operation cost, maintenance cost, replacement cost, and fuel cost calculated annually (Nurunnabi & Roy 2015).

Capital Recovery Factor The capital recovery factor also known as CRF calculates the series of cash flow annually in ratio with respect to the present value (Nurunnabi & Roy 2015).

$$\mathrm{CRF} = \frac{i \times (1+i)^{n}}{(1+i)^{n-1}} \tag{8.2}$$

Here, n indicates the years and i indicates the rate for real interest annually.

Annual Real Interest Rate The annual real interest rate represents the nominal interest rate as a function (Nurunnabi & Roy 2015).

$$i = \frac{i' - \mathrm{F}}{1 + \mathrm{F}} \tag{8.3}$$

Here, i indicates the real interest rate, i' indicates nominal interest rate, and F indicates annual inflation rate.

Cost of Energy The cost of energy also known as COE represents the average cost/kWh of the system producing electrical energy which is useful in practice. The calculative formula for COE is as follows (Geography of Egypt 2018):

$$\mathrm{COE} = \frac{\mathrm{TAC}}{L_{prim,AC} + L_{prim,DC}} \tag{8.4}$$

Here, $\mathrm{L}_{\mathrm{prim,\,AC}}$ indicates primary AC load and $\mathrm{L}_{\mathrm{prim,\,DC}}$ indicates the primary DC load.

7 Simulation Model

The simulation model has been designed by connecting the required components from HOMER Pro® software. The model consists of PV array, windmill, power converter, electric load, and grid. The simulation model of HOMER Pro software is shown in Fig. 8.9.

Photovoltaic (PV) Array The PV array used in solar power plant is generic flat plate PV array which is manufactured by Generic. The rated capacity of this PV array is 250,000 kW and operating temperature is 47 °C. The capital cost of PV array is 500 $/kW and its operation and maintenance (O&M) cost is 10 $/year. The replacement cost of PV array is 500 $/kW. The lifetime of this PV array is 25 years with efficiency of 13%. This system considers real-time temperature effects. It is explicitly modeled with MPPT (maximum power point tracker) with the rated capacity of 260,000 kW. The capital cost of MPPT is 200 $/kW and its operation and maintenance (O&M) cost is 10 $/year. The replacement cost of MPPT is 200 $/kW. The lifetime of this MPPT is 15 years with efficiency of 95%.

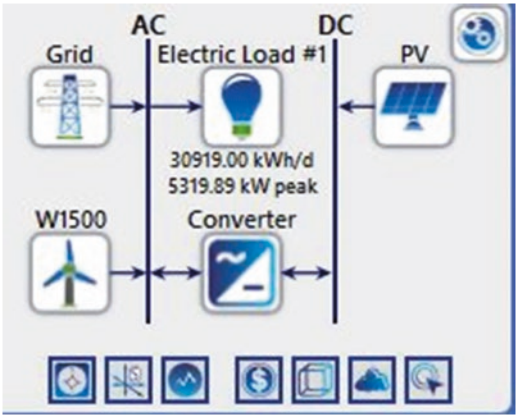


Fig. 8.9 HOMER Pro Model of grid-connected hybrid power system

Wind Turbine The wind turbine used in this windmill of this analyzing is Generic 1.5 MW wind turbine manufactured by Generic. The rated capacity of one windmill is 1500 kW with capital cost $ 2,000,000 and O&M cost 20,000 $/year. The hub height of the turbine is 80 m and its lifetime of 20 years. The replacement cost is $ 2,000,000 for one windmill. The total installed capacity is 750 MW.

Power Converter The name of the power converter is System Converter manufactured by Generic. The lifetime of the power converter is 15 years with efficiency of 95%. The capital cost is 300 $/kW with O&M cost practically zero. The replacement cost is 300 $/kW. The total capacity is 260 MW.

Electric Grid In general grid connection used either to give excess power to the grid or to consume power from the grid. When after satisfying the load demand of an area, there is an excess of power, then that excess power can be sale to the grid. On the other hand, when there is shortage of power from the renewable energy sources, then power can be consumed from the grid. Grid power purchasing price is 0.12 $/kWh and sellback price is 0.06 $/kWh.

8 Optimization Results of the System

Table 8.2 represents the net present costs of hybrid system. Table 8.3 represents the annualized costs of hybrid system. The levelized cost of energy is 0.00417 $/kWh and the total net present cost is $106,890,700. Table 8.4 shows the data for production summary where it can be seen that the total renewable energy generated per year is 2,000,771,345 kWh/year. Table 8.5 shows the data for consumption summary where it is seen that the AC primary load consumed is 11,285,435 kWh/year. Thus, the hybrid model easily satisfies the load demand and can generate quiet excess of the load demand. Table 8.6 shows the grid purchase (kW) per month and

Table 8.2 Net present costs of hybrid system

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Grid	$1.70	−$1.53B	$0.00	$0.00	$0.00	−$1.53B
PV dedicated converter	$52.0 M	$33.6 M	$22.1 M	−$4.15 M	$0.00	$104 M
Solar power plant	$125 M	$32.3 M	$0.00	$0.00	$0.00	$157 M
System Converter	$78.0 M	$0.00	$33.1 M	−$6.23 M	$0.00	$105 M
Wind farm	$1.00B	$129 M	$319 M	−$180 M	$0.00	$1.27B
System	$1.26B	−$1.33B	$374 M	−$190 M	$0.00	$107 M

Table 8.3 Annualized costs of hybrid system

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Grid	$0.132	-$118 M	$0.00	$0.00	$0.00	−$118 M
PV dedicated converter	$4.02 M	$2.60 M	$1.71 M	−$321,201	$0.00	$8.01 M
Solar power plant	$9.67 M	$2.50 M	$0.00	$0.00	$0.00	$12.2 M
System Converter	$6.03 M	$0.00	$2.56 M	−$481,802	$0.00	$8.11 M
Wind farm	$77.4 M	$10.0 M	$24.7 M	−$13.9 M	$0.00	$98.1 M
System	$97.1 M	-$103 M	$28.9 M	−$14.7 M	$0.00	$8.27 M

Table 8.4 Grid purchase (kW) per month and grid sales (kW) per month of hybrid system

Month	Energy purchased (kWh)	Energy sold (kWh)	Net energy purchased (kWh)	Peak demand (kW)	Energy charge	Demand charge
January	158,914	123,433,458	−123,274,544	4596	−$7.40 M	$0.00
February	122,952	126,122,378	−125,999,426	4289	−$7.56 M	$0.00
March	103,408	168,104,718	−168,001,309	4834	−$10.1 M	$0.00
April	94,562	177,726,482	−177,631,921	4108	−$10.7 M	$0.00
May	83,079	185,326,799	−185,243,719	3861	−$11.1 M	$0.00
June	56,666	201,194,475	−201,137,809	5033	−$12.1 M	$0.00
July	62,167	193,897,398	−193,835,231	4116	−$11.6 M	$0.00
August	84,890	191,845,579	−191,760,689	4040	−$11.5 M	$0.00
September	88,826	185,856,768	−185,767,942	4638	−$11.1 M	$0.00
October	94,980	175,497,955	−175,402,975	4545	−$10.5 M	$0.00
November	109,132	124,431,934	−124,322,802	4278	−$7.46 M	$0.00
December	174,883	116,760,002	−116,585,119	4914	−$7.00 M	$0.00
Annual	1,234,459	1,970,197,945	−1,968,963,487	5033	−$118 M	$0.00

Table 8.5 Production summary of hybrid system

Component	Production (kWh/yr)	Percent
Solar power plant	410,448,455	20.5
Wind farm	1,590,322,890	79.4
Grid purchases	1,234,459	0.0617
Total	2,002,005,803	100

Table 8.6 Consumption Summary of Hybrid System

Component	Consumption (kWh/yr)	Percent
AC primary load	11,285,435	0.570
DC primary load	0	0
Grid sales	1,970,197,945	99.4
Total	1,981,483,380	100

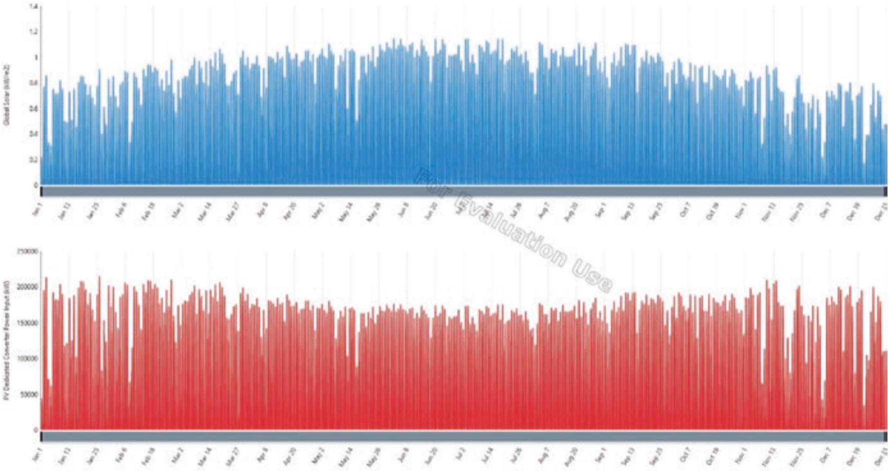


Fig. 8.10 Plot between global solar irradiance (kW/m^2) per month and solar power plant output (kV) per month of hybrid system

grid sales (kW) per month which indicates that the hybrid plant sells huge power than what it buys from the grid. Figure 8.10 shows the plot between the solar irradiance in kW/m^{2}per month and solar power plant output in kV per month. In Fig. 8.10, the solar power plant output is represented by PV dedicated converter power input. Figure 8.11 shows the plot between wind speed in m/s per month and wind farm power output in kW per month. Table 1.7 shows the emission from the hybrid power plant which indicates that minimum pollutants are being emitted. From Table 8.5, 8.6, and 1.7, it is clear that the hybrid system provides a profitable business if implemented as their grid purchase is only 0.0617% and also they sell almost 99.4% of generated power to grid after fulfilling the load demand. As well as this result shows that the hybrid system is safe for the environment.

Figure 8.12 shows the plot between grid purchase power output (kW) per month and grid sales power output (kW) per month of hybrid system which helps us to understand power fulfillment using grid all over the year. Figure 8.13 shows the electrical power summary of the hybrid system. This shows that the overall power generation in every month individually is very good. Figure 8.14 shows the plot

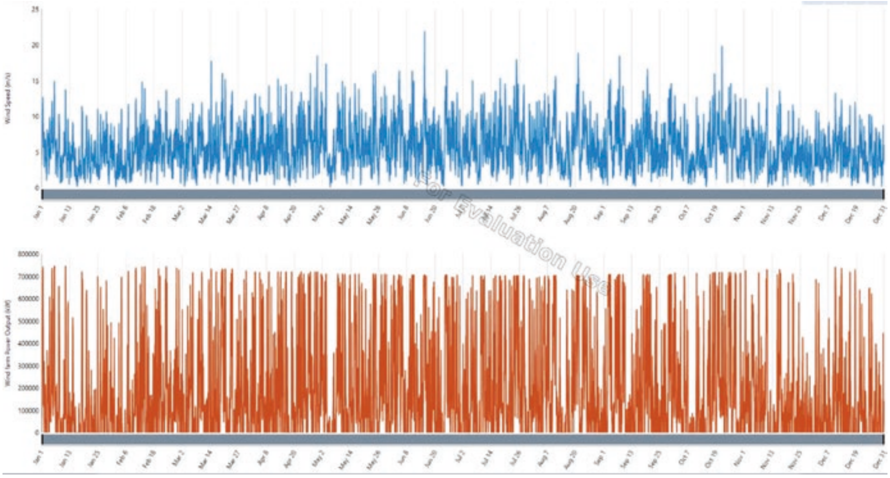


Fig. 8.11 Plot between wind speed (m/s) per month and wind farm power output (kW) per month of hybrid system

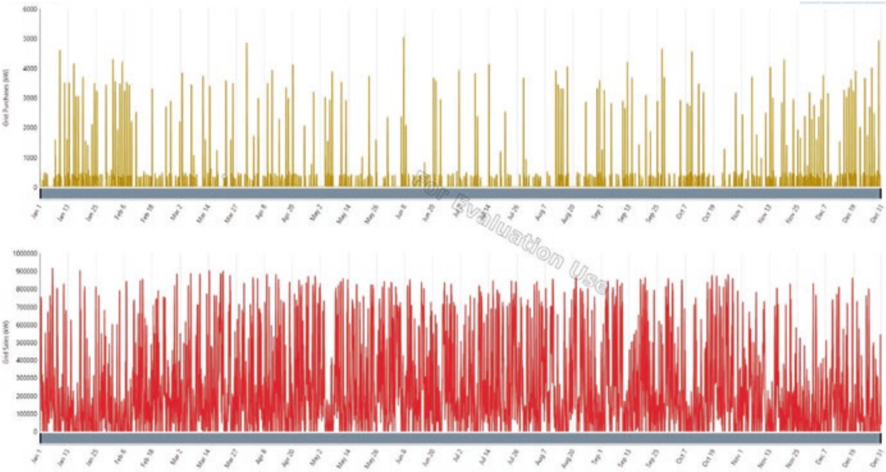
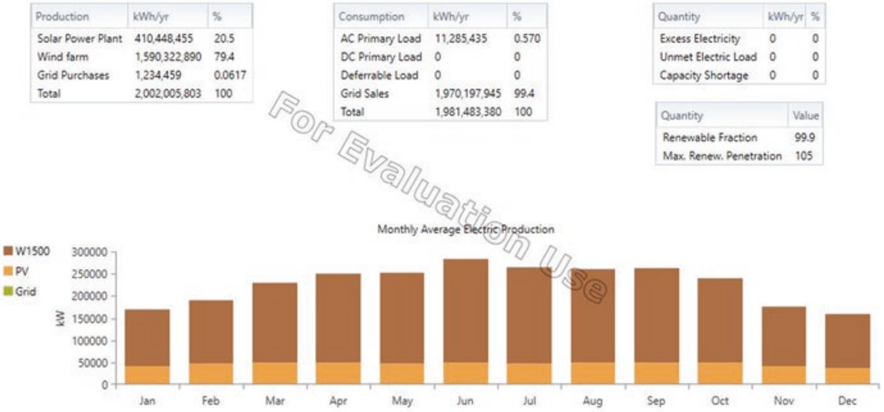


Fig. 8.12 Plot between grid purchase power output (kW) per month and grid sales power output (kW) per month of hybrid system



Production	kWh/yr	%
Solar Power Plant	410,448,455	20.5
Wind farm	1,590,322,890	79.4
Grid Purchases	1,234,459	0.0617
Total	2,002,005,803	100

Consumption	kWh/yr	%
AC Primary Load	11,285,435	0.570
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sales	1,970,197,945	99.4
Total	1,981,483,380	100

Quantity	kWh/yr	%
Excess Electricity	0	0
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value
Renewable Fraction	99.9
Max. Renew. Penetration	105

Fig. 8.13 Electrical power summary per month of hybrid system

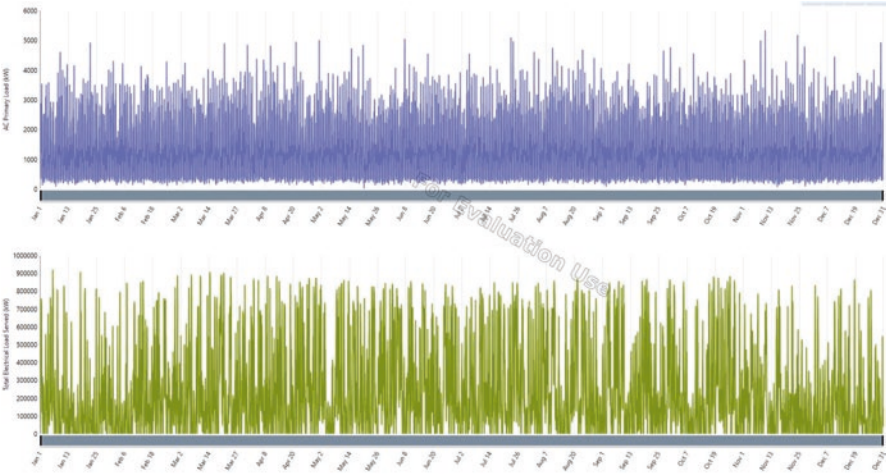


Fig. 8.14 Plot between AC primary load (kW) per month and total electric load served (kW) per month of hybrid system

between AC primary load output (kW) per month and total electrical load served (kW) per month of hybrid system. Figure 8.15 shows the plot between the total renewable power output (kW) per month and renewable penetration (kW) per month of hybrid system. These optimization results of the hybrid system help to understand the generation of power, the actual cost that will be required to set up the hybrid power plant, and most importantly the per unit cost of energy consumption on the basis of the real-time data of renewable energy sources available in the selected location of Egypt.

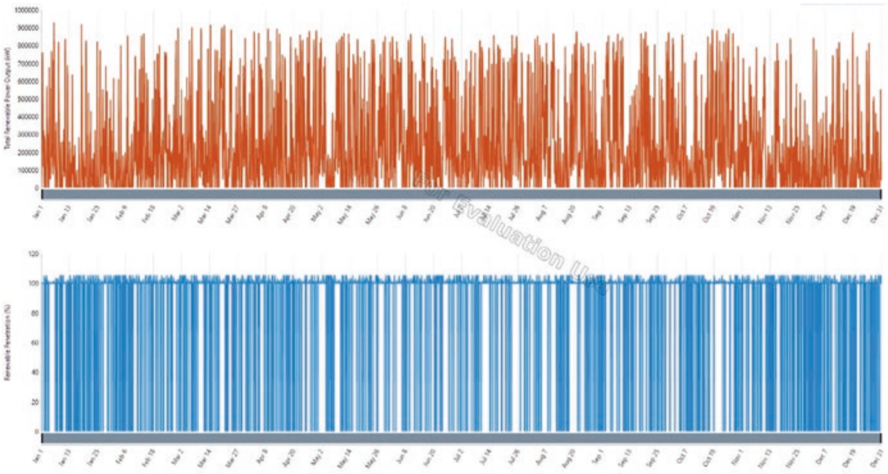


Fig. 8.15 Plot between total renewable power output (kW) per month and renewable penetration (kW) per month of hybrid system

9 Case Study Analysis of Hybrid System

This case study analysis is mainly based on 24 hours duration to understand all the different situations. On the basis of data obtained from the optimization of the hybrid system in HOMER Pro software, these case studies are done. During the daytime, the solar power is there, but it is confirmed that the solar power will not be present at night and it is also possible that the wind power may not be there at the same time. At this condition, grid power is used as backup power to fulfill the load demand. If the grid power is not present at that time, then load shedding will occur.

Figure 8.16 shows the hourly solar and wind power generation in kW. Figure 8.17 shows the hourly grid power purchase in kW. Figure 8.18 shows the hourly grid power sale in kW. All these figures are based on the 24-hour real-time data of January month. With the help of the Figs. 8.16, 8.17 and 8.18, it is easy to understand three main situations. In the first situation, i.e., from 6:00 AM to 5:00 PM time duration, both the solar and wind power are there so grid purchase is zero at that time and grid sale is very high. In the second situation, i.e., from 5:00 PM to 11:00 PM time duration, solar power is not there, but wind power is there so grid purchase is zero at that time, and grid sale is still high but lower to first situation. In the third situation, i.e., from 12:00 AM to 4:00 AM time duration, both the solar and wind power generation are zero which results that grid purchase is there and grid sale is zero. The time duration from 4:00 AM to 6:00 AM again represents the second situation. In addition to it, one more situation, i.e., fourth situation, is there where solar power is present but wind power is zero. At that time, grid purchase is zero and grid sale is medium good. All these situations are based on the proposed solar wind hybrid system. With the help of case study, it is easy to understand that

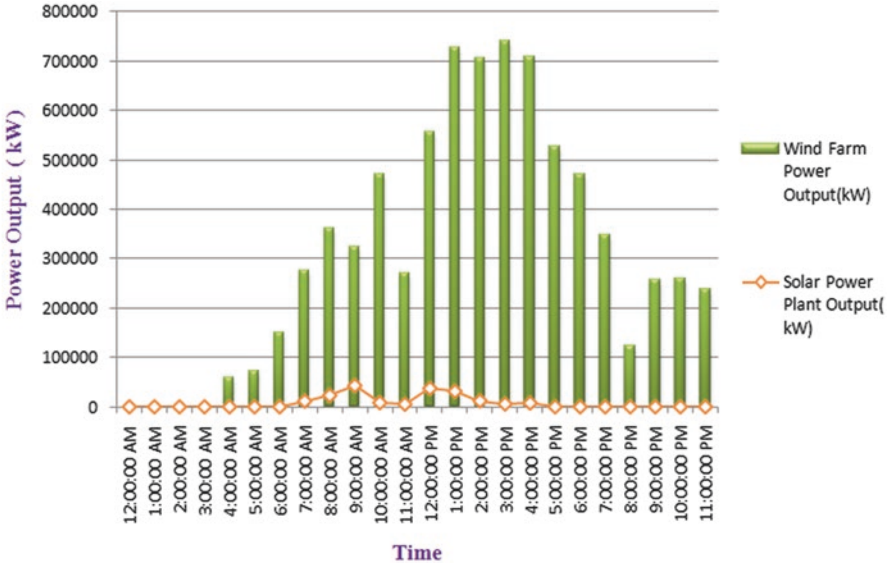


Fig. 8.16 Hourly solar and wind power in kW

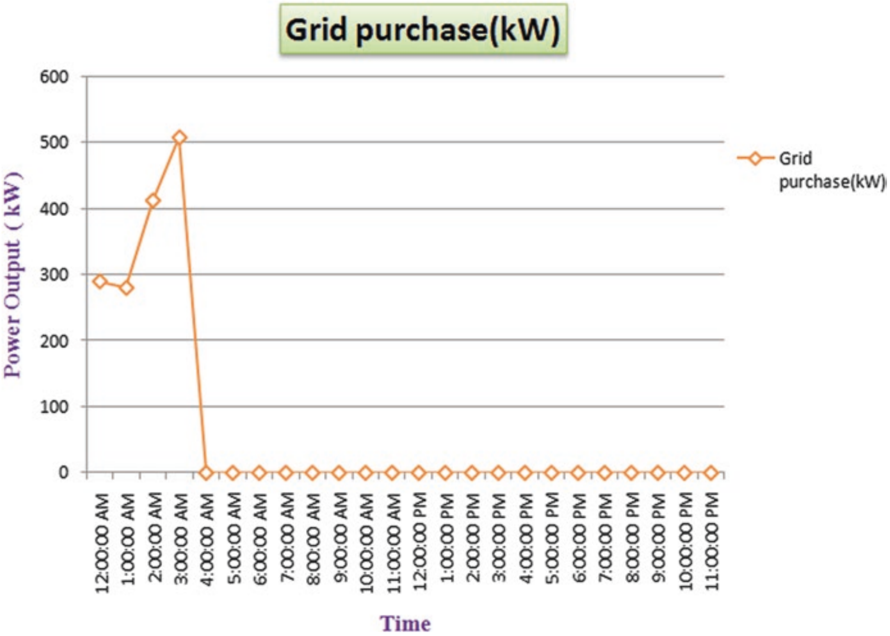


Fig. 8.17 Hourly grid power purchase in kW

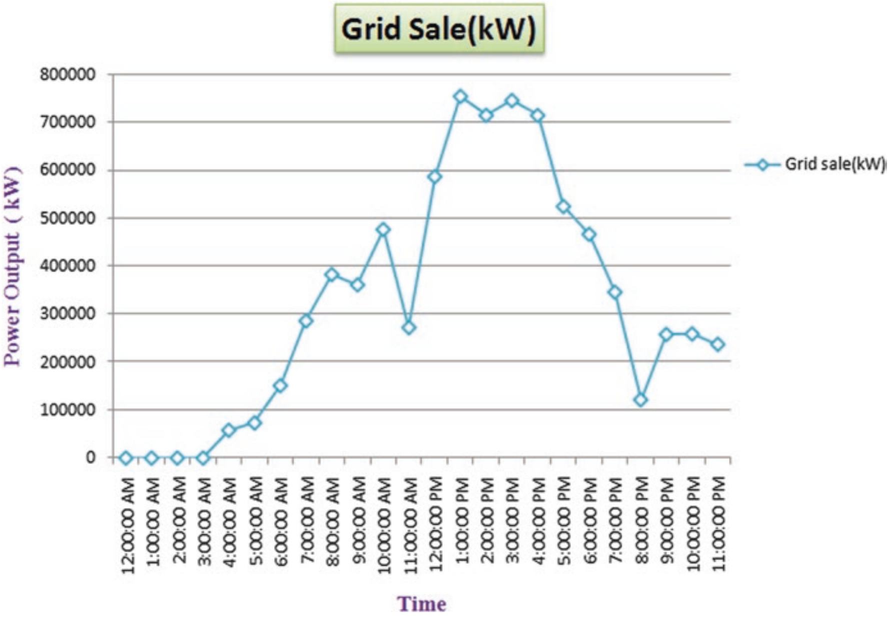


Fig. 8.18 Hourly grid power sale in kW

the proposed location of Egypt possesses huge scope of wind power generation which is needed to be used. Solar power generation is possible at a larger extent as well as the scope of wind power generation is very high which is proved by the case study analysis.

10 Discussion and Implication

The normal climate of the Middle East is mainly dry and hot with mild winter and little rain. Due to the climate change, the Middle East countries are facing extreme heat, draught, and conditions of aridity; as a result of this, there is a problem of electricity and power generation in the Middle East countries. This chapter mainly addresses the challenge of fulfilling increasing generation capacity from renewable resources without using conventional way of generation. Renewable resources like solar and wind can easily mitigate the problems related to power generation, as coal will extinct in due course of time and level of water is being highly affected due to climate change. In this chapter, the grid-connected hybrid system is strategically designed in such a way that there will be less emission of carbon as well as to show the scope of large wind power generation which is not being utilized as much. In this chapter, the optimization analysis of hybrid system using real-time data is mainly focussed. The optimization results of the hybrid model using the real-time data provide an idea about to what extent there will be the generation of power, the actual cost that will be required to set up the hybrid power plant, and most importantly the per unit cost of energy consumption. In this chapter, a 24-hour case study is also done to explain all different situations which the hybrid system mainly faces during its operation. From this case study, one limitation of this study is carried out that the solar power will not be present at night and it is also possible that the wind power may not be there at the same time. At this condition, grid power is used as backup power to fulfill the load demand. If the grid power is not present at that time, then load shedding will occur. To avoid this load shedding, it is better to use battery backup or backup biogas generator.

11 Conclusion

Renewable energy is the only option for saving the future of the whole world. Nature provides us a wide variety of sources which are abandoned. But the resource capability varies throughout the day based on time and also varies with season along a year. This drawback can be resolved by combining two or more sources together in the form of hybrid energy system based upon the location condition. In this book chapter, a hybrid energy system which includes PV array and windmill connected to electric grid has been presented. The system components are connected using AC and DC buses in order to improve the system efficiency and system reliability. This system is used to fulfill a certain load demand by reducing the use of grid as much as possible. The research toward the proposed system illustrates its results using these points:

- The average annual solar radiation is found to be 6.15 kWh/m^2/day. The average annual wind speed is found to be 5.60 meters/seconds. The average annual temperature is found to be 23.25 °C. These indicate that the proposed location is a suitable place for solar and wind power generation.
- The total production of solar energy is 410,448,455 kWh/yr, which is 20.5% of the total energy production per year.
- The total production of wind energy is 1,590,322,890 kWh/yr, which is 79.4% of the total energy production per year.
- The total renewable energy generated per year is 2,000,771,345 kWh/year.
- The total energy which is required to be purchased from grid is 1,234,459 kWh/yr, which is 0.0617% of the total energy production per year.
- The electric load consumed is 11,285,435 kWh/yr, which is 0.570% of the total energy consumption per year.
- The total energy sell to grid is 1,970,197,945 kWh/yr, which is 99.4% of the total energy consumption per year.
- The levelized cost of energy is 0.00417 $/kWh and the total net present cost is $106,890,700.

These points simply indicate that the selected location is rich of the possibility of solar and wind power production as well as the total renewable power production of the proposed hybrid system indicates that the system successfully utilizing these possibilities. With the optimization results, it is clear that the grid-connected hybrid system successfully fulfills the load demand all over the year by using renewable energy sources mainly. Its grid purchases are very low, and grid sales are very good which is needed for profitable business, and there are no emissions so environmentally friendly. The levelized cost of energy is low which shows the overall system is profitable. The overall conclusion of this chapter is that the grid-connected hybrid system is profitable, economic, environmentally friendly, and effective in maintaining continuity of power supply. So, we can finally conclude that if these kinds of hybrid power plant are set up in other parts of Egypt and also in Middle East counties, energy dynamics problem due to climate change can easily be mitigated. In order to expand this research in terms of future research, the research on the intelligent controller of hybrid system plays a crucial role as it helps to utilize more accurately each unit of electrical energy. It also includes research toward lowering voltage fluctuation, voltage drops, and transmission line losses.

12 Open Research Directions

In order to reduce the impact of climate change, this chapter proposes an idea of installing the renewable energy source-based hybrid energy system in those areas where its power generation possibilities are good. This opens various new research directions which include searching of all those places where the possibility of renewable power generation is good. It also includes new research directions for searching and analyzing various combinations of different renewable energy sources based upon the location. If these hybrid systems are placed all over the Middle East and if they are connected, then it fulfills the desired load demand by using only renewable energy sources very easily. Also with an additional battery backup, the objective of continuity of power supply can be fulfilled using renewable sources only. This is a broad level research direction which helps to combat climate change using renewable energy sources. Some places of Egypt or say Middle East are rich in some other renewable energy sources like hydro, etc., which can be used as a main component of such kind of hybrid system. Hydroelectric power plants are the most efficient plants as compared to nuclear and thermal power plants. If the use of high-efficiency power plant increases for supplying the base load, then it reduces the energy generation cost. Biofuel-based power plants may also contribute in reducing the impact of climate change by using it as an additional energy source in the hybrid system. Solar thermal power plants can also be connected as a part of this hybrid system as well as rooftop solar panels may also help in maintaining continuity of power supply. With the increase in use of electric vehicle, climate change is also possible to reduce. If the solar energy system is placed on big water sources like canal, river, etc., based upon the solar irradiance and energy requirement, then it also helps to reduce the impact of climate change and also saves water from evaporating especially in Middle East countries. This idea also reduces the land area requirement. Small renewable energy system with battery bank-based microgrid in islands and hilly areas also helps in reducing climate change of the world. These are some directions of research where it is possible to do research and reduce the impact of climate change. If these ideas are implemented in practice, climate change problem reduces to a very low extent, especially in the Middle East, which is the major requirement of the present situation. These ideas also provides a profitable business if implemented with proper planning.

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Chapter 9
Greenhouse Gases Emissions and Alternative Energy in the Middle East

Erginbay Uğurlu

Abstract This chapter follows the relationship between GDP per capita and renewable energy use and CO_2 emissions in ten Middle East countries, namely, Algeria, Iran, Iraq, Israel, Jordan, Lebanon, Libya, Saudi Arabia, Turkey, and the UAE. Before the empirical application investigated the outlook of the economy, greenhouse gases emission and renewable energy use of the Middle East countries are discussed. A panel Granger causality test is used in the empirical application section, and the preliminary tests are done before the model. The period used in the analysis is 2000–2014. The results show that the GDP per capita has positive and renewable energy use has a negative effect on carbon dioxide emission. Also, the variables have a cointegration relationship, and there is one-way Granger causality from GDP per capita to carbon dioxide emissions.

Keywords Energy policy · Energy consumption · Economic growth · GDP per capita · Oil production · Oil reserves · Carbon dioxide emissions · Renewable energy · Climate change · Global warming · The Middle East countries · Panel data models · Panel Granger causality · Panel VAR approach

1 Introduction

The 1973 Arab oil embargo is to draw attention to the strategic importance of Persian Gulf oil to the world economy (Mason and Mor 2009). Many countries have concerns to reach affordable energy supplies, because of International Energy Agency's (IEA 2008) forecasts suggest an increase in global demand. Therefore

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H. Qudrat-Ullah, A. A. Kayal (eds.), *Climate Change and Energy Dynamics in the Middle East*, Understanding Complex Systems,
https://doi.org/10.1007/978-3-030-11202-8_9

these concerns have been invoked to support military moves to protect and maintain strategic nonrenewable energy sources (Russell and Moran 2008).

Climate change is one of the most important challenges for the world. During the past 100 years, the average temperature on earth has increased. Intergovernmental Panel on Climate Change announced the observations of the most dramatic historical events of the last few centuries in 2007. The water in the oceans expands, and the sea level rises because more and more Arctic sea ice and the permanent ice of the glaciers also melt. Consequently, climate change, global warming, and renewable energy use – as one of the solutions to these problems – have increasing concerns all over the world.

Energy consumption, environmental degradation, and climate change are closely related together. Also, renewable energy is related to them as one of the solutions to climate change mitigation. Renewable energy usage not only mitigates climate change but also makes countries having independence in energy supply. Nowadays, technological development of renewable energy is rapidly increasing.

In the context of energy consumption, the source of consumed energy is mostly from the Middle East countries. In 2014 four of the top eight oil-producing countries in the world are from the Middle East. About 30% of world oil production refrains from the Middle East. Unfortunately, the Middle East countries are world's top CO_2 emitters, based on the Energy Information Administration (EIA), and the CO_2 emission increased by over 200% during the period 1990–2009 in the region. One of the reasons for this high-level increase is a fast-growing population of these countries and their increasing economic growth; therefore, environmental problems occur in the Middle East similar to other countries in the world.

Although the Middle East is the oil-producing heart of the world, the renewable energy sources (RES) have grown in importance; it is expected to diversify more and more of their energy sources to renewable energy. One of the reasons for the interests of RES is climate change which is the main pillar of the developed countries of the world, and the other is sustainable development. Although the countries have fundamental differences in economic structure, geographical features, cultural heritage, language, and abundance of natural sources such as oil and gas from country to country, the Middle East countries are taken together in this research and many other types of research.

In this chapter, greenhouse gases emission and renewable energy use in the Middle East countries will be discussed. The chapter will use an empirical application to analyze the relationship between the investigated variables.

The rest of the chapter is organized as follows. Section 2 gives brief economic information about the Middle East. Sections 3 and 4 contain an overview of greenhouse gas emission and renewable energy use of the Middle East countries, respectively. Section 4 gives a brief discussion of the data, applies an econometric model, and then discusses the findings. Section 5 presents some concluding remarks.

2 Economic Outlook for the Middle East

Angrist (2013) states that the Middle East region comprises 20 countries. These countries are Turkey, Iran, Egypt, Saudi Arabia, Yemen, Oman, the United Arab Emirates (UAE), Qatar, Bahrain, Kuwait, Israel, Palestine, Jordan, Iraq, Syria, Lebanon, Morocco, Algeria, Tunisia, and Libya. These countries are from different regions of the world such as North Africa, West Asia, the Arabian Peninsula, and Central Asia. Also except for three of these countries which are Turkey, Iran, and Israel, the Middle East countries are Arab. These countries are members of different groups. For example, Saudi Arabia, the United Arab Emirates (UAE), Kuwait, Oman, Qatar, and Bahrain are in the Gulf Cooperation Council (GCC); Algeria, Iran, Iraq, Kuwait, Libya, Qatar, Saudi Arabia, and the UAE are members of the Organization of the Petroleum Exporting Countries (OPEC).

The Middle East is a major region for oil production. Also, it is the world's fastest-growing regional consumer of oil (Narayan and Smyth 2009). From 1990 to 2006, real GDP in the Middle East grew at an average annual rate of 4.3%, and it is higher than the rates in the other emerging regions of the world (Sadorsky 2011). The total proportion of petroleum and other liquids production is 36% within all oil producer counties (EIA 2017). The Middle East region is an important region for the world of natural gas production too. The natural gas production was 22% (781 billion cubic meters) of global production of natural gas (Zhang et al. 2017).

According to 2017 data, Table 9.1 shows total petroleum and other liquids production of the oil producer countries of the Middle East. Saudi Arabia is the leading producer of the region and the second of the world. Iran is second and Iraq is the third producer of the region and the sixth and the seventh of the world, respectively. Yemen is the last biggest oil producer of the region. It is seen that the oil producer countries of the Middle East are among the top 28 countries globally in 2017.

El-Katiri (2014) emphasizes that in the Middle East, the per capita income of the countries varies in the broad range. The author states that at the top are

Table 9.1 Total petroleum and other liquids production 2017

World ranking	Country	Value	Percent
2	Saudi Arabia	12090	12
6	Iran	4669	5
7	Iraq	4462	5
8	UAE	3721	4
10	Kuwait	2928	3
13	Qatar	2068	2
18	Algeria	1641	2
21	Oman	980	1
24	Libya	852	1
28	Egypt	653	1

Source: EIA (2017)

Table 9.2 Middle East countries[a] by per capita income (2017)

Low income (GNI per capita $995 or less)	Lower middle-income between (GNI per capita $996 and $3895)	Upper middle-income (GNI per capita $3896 and $12,055)	High-income (GNI per capita $12,056 or more)
Syria Yemen	Egypt Morocco Tunisia	Turkey Algeria Iran Iraq Jordan Lebanon Libya	Bahrain Israel Kuwait Oman Qatar Saudi Arabia UAE

Notes: [a] In the World Bank listings, Turkey is in the Europe and Central Asia region. Data are taken from the World Bank list of economies (June 2018)

the high-income countries such as Qatar and some other GCC countries. Then upper-middle-income countries and middle-income countries are following them, such as Iran, Saudi Arabia, Libya, and Algeria, and then at the bottom are low-income countries such as Morocco, Jordan, Syria, Tunisia, Egypt, and Yemen.

World Bank (2018a) calculated GNI per capita using the World Bank Atlas[1] method. According to the World Bank, countries are divided into four income categories: low income, lower-middle-income, upper-middle-income, and high-income economies. Table 9.2 shows the income groups of the Middle East countries.

The gross domestic product (GDP) of these countries lies in a broad range too. Figure 9.1 shows the GDP of 18 countries[2] from 2000 to 2014. As seen in Fig. 9.1, the trend of the GDP is increasing in the overall period.

Devlin (2010) discusses the Middle East and North Africa (MENA) countries and states that the countries are diverse in natural resource wealth, economic structures, population, culture, religion, and distinctive historical and social continuity. Also, the author summarizes these diversifications into three categories according to the World Bank (2003), Richards and Waterbury (1998), and Drysdale and Blake (1985). World Bank (2003) categorizes the countries according to their economy; thus Egypt, Jordan, Morocco, Tunisia, and Lebanon are in the resource-poor economies; Algeria, Iran, Iraq, Syria, and Yemen are in the resource-rich and labor-abundant economies; and Bahrain, Kuwait, Libya, Oman, Qatar, Saudi Arabia, and the UAE are resource-rich and labor importer economies. Richards and Waterbury (1998) categorize the countries based on their political economy, and they state that Yemen is agro-poor; Israel, Jordan, Tunisia, and Syria are watchmakers; Egypt and Morocco are newly industrialized countries (NICs); Iran, Iraq, Saudi Arabia, and Algeria are oil industrializers; and Libya, Kuwait, Oman, Bahrain, Qatar, and the UAE are coupon clippers. Finally Drysdale and Blake (1985) make their groups

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[1] https://datahelpdesk.worldbank.org/knowledgebase/articles/378832-what-is-the-world-bank-atlas-method.

[2] Data for Palestine is not published by the World Bank web site, and Syria data is not available for the period of 2000–2014.

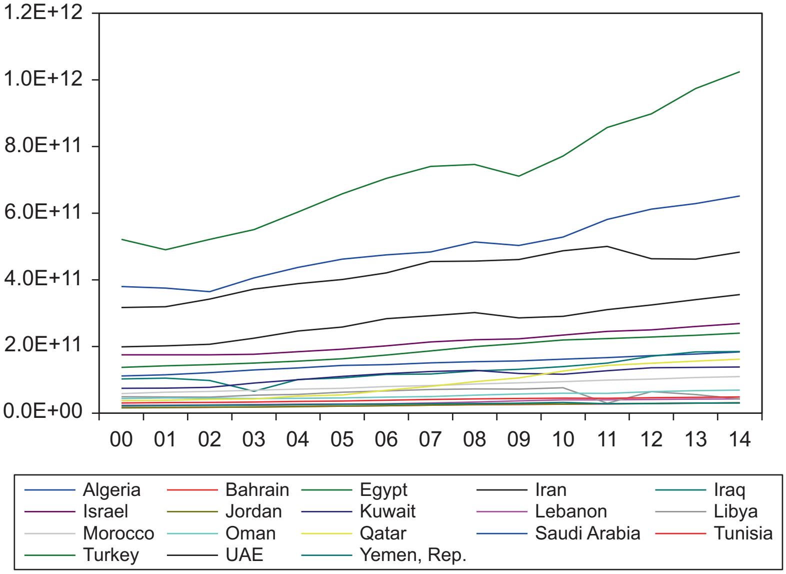

Fig. 9.1 GDP (constant 2010 US$) of the countries. (Source: World Bank)

according to social topics: Morocco, Algeria, and Iran are categorized as linguistically diverse, religiously cohesive; Egypt, Yemen, Kuwait, Oman, the UAE, Bahrain, Saudi Arabia, Syria, and Lebanon are religiously diverse, linguistically cohesive; and Turkey and Iraq are linguistically diverse and religiously diverse.

To understand the income level trend of the countries, I present (Fig. 9.2) values of the years of 2000, 2005, 2010, and 2014. Moreover, I split the full sample into two subsamples (from 2000 to 2005 and 2006 to 2014). The mean GDP of the countries for these subsamples and full sample are calculated and presented in Table 9.3.

For all the years, Turkey has the highest GDP value among other countries, and Iran is the second largest economy among the investigated countries. Jordan, Libya, and Lebanon are the three smallest economies according to GDP size in the Middle East. Also thanks to the bar graph, it can be seen that there are significant differences among the GDP values of the countries. Also, the GDP level of the countries is changing both positively and negatively through the years.

Table 9.3 shows the mean GDP of investigated countries for the full sample and two subsamples. For all periods, Turkey has the highest mean GDP, and Saudi Arabia is the second. Despite political instabilities in Iraq that resulted from the two Gulf Wars, Iraq is continuously the eighth economy in the region. Jordan is the 17th country for full-sample and 2006–2014 period but 18th for the 2000–2005 period. Bahrain is the last country except for the 2000–2005 period when it is the 17th. Jordan is the 17th country except for 2000–2005 when it is the last country in the period.

An issue that is directly related to CO_2 emissions and renewable energy is energy consumption. Energy consumption plays a vital role in greenhouse gases emissions,

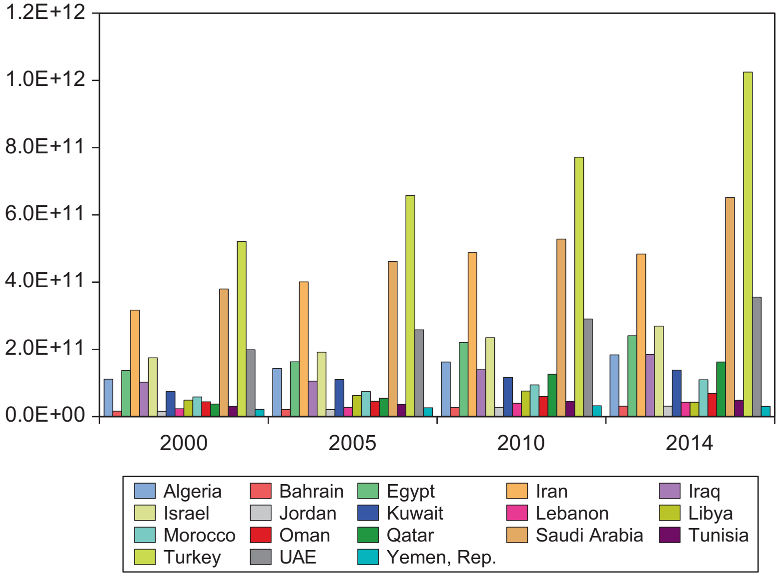

Fig. 9.2 GDP for the selected years. (Source: World Bank)

Table 9.3 Mean GDP for selected periods

	2000–2014		2000–2005		2006–2014	
Periods	Mean GDP	Rank	Mean GDP	Rank	Mean GDP	Rank
ARE	2.74E + 11	4	2.22×10^{11}	4	3.09×10^{11}	4
BHR	2.21E + 10	18	1.70×10^{10}	17	2.55×10^{10}	18
DZA	1.47E + 11	7	1.25×10^{11}	7	1.62×10^{11}	7
EGY	1.86E + 11	6	1.48×10^{11}	6	2.12×10^{11}	6
IRN	4.22E + 11	3	3.56×10^{11}	3	4.65×10^{11}	5
IRQ	1.25E + 11	8	9.52×10^{10}	8	1.46×10^{11}	8
ISR	2.12E + 11	5	1.79×10^{11}	5	2.34×10^{11}	5
JOR	2.22E + 10	17	1.66×10^{10}	18	2.60×10^{10}	17
KWT	1.11E + 11	9	8.68×10^{10}	9	1.26×10^{11}	9
LBN	3.12E + 10	15	2.40×10^{10}	15	3.60×10^{10}	15
LBY	5.69E + 10	12	5.19×10^{10}	11	6.01×10^{10}	11
MAR	8.24E + 10	11	6.57×10^{10}	10	9.36×10^{10}	12
OMN	5.19E + 10	13	4.34×10^{10}	12	5.76×10^{10}	13
QAT	8.90E + 10	10	4.30×10^{10}	13	1.20×10^{11}	10
SAU	4.93E + 11	2	4.04×10^{11}	2	5.53×10^{11}	2
TUN	3.85E + 10	14	3.19×10^{10}	14	4.30×10^{10}	14
TUR	7.18E + 11	1	5.57×10^{11}	1	8.26×10^{11}	1
YEM	2.58E + 10	16	2.25×10^{10}	16	2.80×10^{10}	16

DZA Algeria, *BHR* Bahrain, *EGY* Egypt, *IRN* Iran, *IRQ* Iraq, *ISR* Israel, *JOR* Jordan, *KWT* Kuwait, *LBN* Lebanon, *LBY* Libya, *MLT* Malta, *MAR* Morocco, *OMN* Oman, *QAT* Qatar, *SAU* Saudi Arabia, *SYR* Syrian, *TUN* Tunisia, *ARE* United Arab Emirates, *YEM* Yemen, Rep

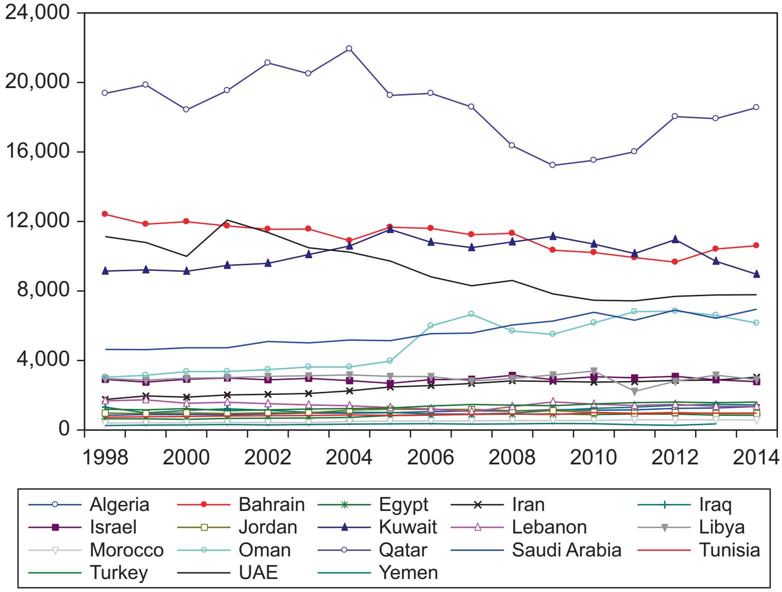

Fig. 9.3 Energy use of the countries. (Source: World Bank 2018a)

and increasing energy consumptions canalize the countries to alternative energy sources. It can be seen from the figures and Table 9.3 that the region had a rapid increase in GDP. Therefore remarkable boost in energy consumption occurred in the region (Al-Mulali and Ozturk 2015; World Bank 2014).

Figure 9.3 shows energy use[3] (kg of oil equivalent per capita) of the countries for the overall sample. The graph shows the trend of the countries. To understand the values better, Fig. 9.3 was adopted for the bar graph in Fig. 9.4 for the selected years as used in Fig. 9.2.

In Table 9.4 the mean energy uses of the countries are presented for selected time periods. Qatar always has the highest energy use than second in Bahrain for 2000, 2005, and 2014; the third is Kuwait for 2000 and 2010. Lowest energy users are Morocco, Yemen, and Egypt. Compared over 14 years, none of the countries shows a pattern. Generally, the figure shows increases from 2000 to 2014, but in 2010 a small decrease can be seen in countries' energy consumption which may be caused by the 2008 financial crises.

Both the literature and the data show that there are wide variations within the Middle East countries. Since these variations disrupt the homogeneity of the data, it is better to omit some countries before the model estimated. However several studies about the Middle East countries use a different number of countries to analyze.

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[3] Energy use refers to use of primary energy before transformation to other.

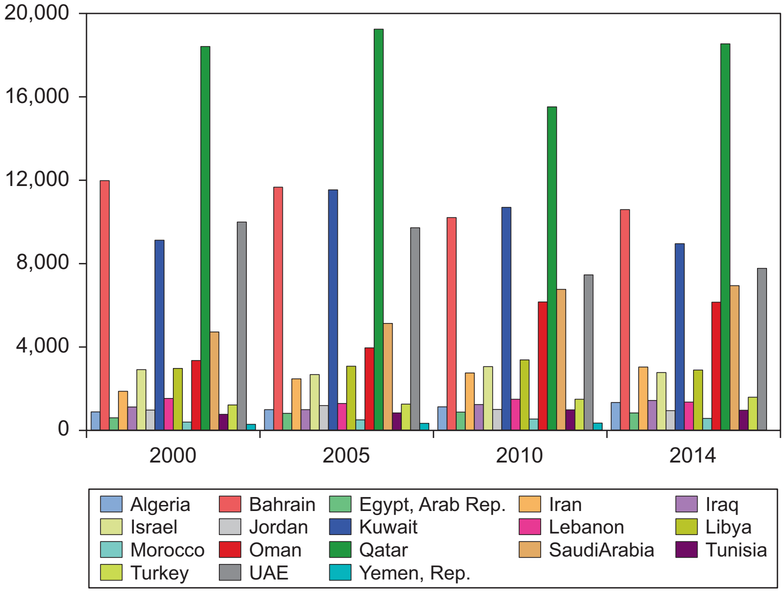

Fig. 9.4 Energy use of the countries. (Source: World Bank 2018a)

Table 9.4 Mean energy use (ENU) for selected periods

	2000–2014 Mean ENU	2000–2005 Mean ENU	2006–2014 Mean ENU
ARE	9034.46	10647.81	7.96×10^3
BHR	10979.81	11568.71	1.06×10^4
DZA	1056.60	916.21	1.15×10^3
EGY	787.64	671.45	8.65×10^2
IRN	2507.75	2106.72	2.78×10^3
IRQ	1132.55	1060.91	1.18×10^3
ISR	2911.63	2861.33	2.95×10^3
JOR	1022.71	1014.71	1.03×10^3
KWT	10274.93	10067.27	1.04×10^4
LBN	1381.93	1435.50	1.35×10^3
LBY	2977.51	3056.73	2.92×10^3
MAR	486.28	421.94	5.29×10^2
OMN	5172.48	3549.08	6.25×10^3
QAT	18440.24	20149	1.73×10^4
SAU	5764.13	4963.49	6.30×10^3
TUN	868.61	801.46	9.13×10^2
TUR	1356.58	1176.33	1.48×10^3
YEM	302.64	290.26	3.12×10^2

Notes: 2014 data is not available for Yemen. When the mean was calculating 2014, data is not used in the formula. *DZA* Algeria, *BHR* Bahrain, *EGY* Egypt, *IRN* Iran, *IRQ* Iraq, *ISR* Israel, *JOR* Jordan, *KWT* Kuwait, *LBN* Lebanon, *LBY* Libya, *MLT* Malta, *MAR* Morocco, *OMN* Oman, *QAT* Qatar, *SAU* Saudi Arabia, *SYR* Syrian, *TUN* Tunisia, *ARE* United Arab Emirates, *YEM* Yemen, Rep

Table 9.5 Summary of the researches about the Middle East

Author	Countries	Topic
Narayan and Smyth (2007)	Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Oman, Qatar, Saudi Arabia, Syria, the UAE, Yemen	Demand for oil
Narayan and Smyth (2009)	Iran, Israel, Kuwait, Oman, Saudi Arabia, Syria	Multivariate Granger causality between electricity consumption, exports, and GDP
Sadorsky (2011)	Bahrain, Iran, Jordan, Oman, Qatar, Saudi Arabia, Syria, the UAE	Trade and energy consumption
Al-Mulali (2012)	Bahrain, Egypt, Iran, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, the UAE, and Yemen	Factors affecting CO_2 emission
Ozcan (2013)	Bahrain, the UAE, Iran, Israel, Egypt, Syria, Saudi Arabia, Turkey, Oman, Jordan, Lebanon, Yemen	The nexus between carbon emissions, energy consumption, and economic growth
Al-Mulali and Ozturk (2015)	Algeria, Egypt, Iran, Jordan, Kuwait, Lebanon, Libya, Oman, Saudi Arabia, Syria, Tunisia, the UAE, Yemen	Effect of energy consumption and some macroeconomic variables on the environmental degradation
Nematollahi et al. (2016)	Iran, Jordan, Saudi Arabia, the UAE, Egypt, Bahrain, Kuwait, Oman, Syria	Energy demands and renewable energy resources in the Middle East
Magazzino (2016)	Six GCC countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, the UAE) and four non-GCC countries (the author did not give a list of the countries)	CO_2 emissions, economic growth, and energy use

Table 9.5 presents the countries which are used as the Middle East countries in recent studies about greenhouse gases emissions, energy, and renewable energy.

In the literature mainly 12 countries (Table 9.5) are commonly used to represent the Middle East. These are Bahrain, Egypt, Iran, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, the UAE, and Yemen. In this chapter we focus on these countries; however, in the empirical application because of the lack of data of some countries, the countries investigated are Algeria, Iran, Iraq, Israel, Jordan, Lebanon, Libya, Saudi Arabia, Turkey, and the UAE.

3 Greenhouse Gases Emissions in the Middle East

Reducing greenhouse gases emissions is a major international debate over the world in recent years. To understand the importance of reducing greenhouse gases, it is necessary to understand global warming and climate change in the first place.

During the past 100 years, the average temperature on earth has increased by 0.7 °C. Although it seems reasonable, the warming is not leading to the same level of increase in every region also not constant for every year. In some regions of the world, the temperature is already higher by 2 °C as an annual average. The atmosphere has a protective influence on earth. Without the atmosphere's protective effect, the earth's temperature would be around −18 °C. This means we would be living on an ice-bound planet without the atmosphere's protective influence (Quaschning 2008).

In 1824 the first research by Joseph Fourier showed that gases in the atmosphere could increase the surface temperature of the earth. After his study in 1859, John Tyndall showed that several gases were able to trap and hold heat. The most important gases were water vapor (H_2O) and CO_2 in Tyndall research. After these studies, researchers determined that the gases in the atmosphere let the sunlight in the earth trap enough solar energy to keep the global average temperature of earth in a habitable range. This effect is named as the greenhouse effect. However, many human activities such as the burning of fossil fuels and deforestation increase the atmospheric concentration of greenhouse gases, and these activities are warming the earth by emitting these gases. Thus this process causes climate change. The Intergovernmental Panel on Climate Change (IPCC) (2013) stated that the greenhouse gases warm the atmosphere and the ocean and change the global water cycle, raise the global sea level, and change some climate extremes. This definition can be considered as a summary of climate change. Besides these, IPCC predictions showed that fossil fuels would remain dominant in the global energy mix to 2030 and beyond. IEA (2007) notes that the trend for both CO_2 emissions and energy security is worsening.

Elliott and Cook (2018) state that global energy consumption comes from the combustion of fossil fuels such as coals, oil, and gas, the proportion of which is around 80%. The authors also state that to decrease the effect of global warming, release of carbon dioxide gas has to stop. Their suggestions to stop global warming are switching to use non-fossil energy sources, increasing energy efficiency in energy consumption, and using nuclear power. Whereas all these ways have pros and cons, nuclear energy has much more problems such as security and safety. Despite these problems, nuclear contribution in global electricity production is at around 11%; in addition, renewables are expanding rapidly with decreasing cost of production. In fact, some countries can get nearly 100% of their total energy from renewables by 2050 (Jacobson et al. 2017).

The first conference about environmental degradation was the United Nations Conference on the Human Environment which was held in Stockholm in 1972 (Schirnding et al. 2002). The carbon market of the United Nations' Kyoto Protocol was voted by 165 nations in Kyoto. The objective of the 1997 Kyoto Protocol was to reduce greenhouse gases (GHG) to the 1990 level during the period from 2008 to 2012 (Chichilnisky 2010). The Protocol was adopted at the third session of the Conference of the Parties to the 1992 UNFCCC held at Kyoto (Japan) from 1 to 11 December 1997. The 21st Conference of the Parties (COP 21) of the United Nations Framework Convention on Climate Change (UNFCCC) adopted an agreement in Paris in 2015 which is called the Paris Agreement (Jayaraman 2015). Before the COP 21 several events took place. In 2007 in Bali conference (COP 13) and then in

Table 9.6 Signature date of Kyoto

Country	Signature	Accession
Algeria		16 Feb 2005
Iran		22 Aug 2005
Iraq		28 Jul 2009
Israel	16 Dec 1998	15 Mar 2004
Jordan		17 Jan 2003
Lebanon		13 Nov 2006
Libya		24 Aug 2006
Saudi Arabia		31 Jan 2005
Turkey		28 May 2009
UAE		26 Jan 2005

Source: United Nations. https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-a&chapter=27&clang=_en#bottom

2009 in Copenhagen, 15th Conference of the Parties (COP 15) of the UNFCCC was held. Many other agreements were signed for the other environmental problems: the Montreal Protocol on Protection of the Ozone Layer (1987), the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (1989), the Convention on Biological Diversity in 1992, the Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade (1998), and the Stockholm Convention on Persistent Organic Pollutants (2001) (Schirnding et al. 2002). The Kyoto Protocol has primary importance for the earth. Table 9.6 shows the signature day and accession date of the ten Middle East countries of Kyoto Protocol.

World Bank data shows that the Middle East countries are major countries in carbon dioxide emissions. According to World Bank (2018b) data of 2014 on total carbon dioxide emissions (metric tons per capita), Qatar is ranked the first, Kuwait the fourth, Bahrain the fifth, the UAE the sixth, Saudi Arabia the eighth, and Oman the 15th among countries in the top 15 CO_2 emitters. They were in the top 15 in 2009 too (Atalay et al. 2016). Although these data show that these countries are the highest CO_2 per capita emitters between 2009 and 2014, we will see in the next section that they have been trying to diversify their energy sources to renewable energy.

The Middle East countries have different landscapes, different climate conditions, and different economic categories.

Algeria landscape consists mainly of deserted areas; this feature reduces the possibilities of carbon capture (INDC 2015). Also, Algeria is in a "hot spot" of climate change area (Sahnoune et al. 2013). Moreover, it was one of the countries which first submitted the Intended Nationally Determined Contribution (INDC) to the UN Framework Convention on Climate Change (Bouznit and Romero 2016). According to CIA World Factbook (2015), Algeria's oil export share was 97% of its total exports in 2013. As one of the developing countries, Algeria has tried to industrialize and modernize the economy and growth of the country has been increasing steadily. Therefore the country tends to increase their CO_2 emissions (Omri 2013 and Amrouche et al. 2010). Algeria ratified in the UNFCCC in April 1993 moreover adhering to the Kyoto Protocol in 2005 (Sahnoune et al. 2013). Algeria has developed a national strategy based primarily on four areas. These areas are institutional strengthening, adaptation to climate change, mitigation of emissions of GHG, and human capacity building (Sahnoune et al. 2013).

Iran has joined the Basel Convention in 1993, the UNFCCC in 1996, the London Convention in 1997, and the Kyoto Protocol in 1998. Also, Iran has the second largest natural gas reserves and is the fourth owner of conventional oil reservoirs in the world. (Banan and Malekib 2013). Moshiri et al. (2012) state that in 2011 the fossil fuels energy consumption was 99.52% according to the World Bank data, and in 2011 and 2012, the emissions of Iran were 480 million tons CO_2-equivalent emissions. Also, the authors calculated that it would be doubled in 2030.

Israel has some special circumstances based on its varied topography. The shape of the land is long and narrow; thus the land compromises arid zones, plains and valleys, mountain ranges, the Jordan Rift Valley, and coastal strip. Among these features the biggest area is arid zones with 45% shares, and the smallest is the coastal strip with 5% shares. The special circumstances are related to population density, limited freshwater sources and their dependency on seasonal rainfall, and additional advantages of greenhouse gas-reducing technologies (UNFCCC 2000). At the Copenhagen Conference in 2009, Israel has stated that to reduce 20% of greenhouse gas emissions by 2020. Indeed, in November 2010 the government approved the National Program for Greenhouse Gas Emissions Reduction in Israel (Government Resolution No. 2508).

Jordan is one of the non-oil producer countries in the Middle East. Urbanization, industrialization, and economic and social developments increase the energy demands of Jordan. In 1991, the first environmental strategy of Jordan and at the same time first of its kind in West Asia which is entitled The National Environmental Strategy (NES) was prepared in Jordan. In 1996 a Global Environment Facility (GEF) funded project (Building Capacity for GHG Inventory and Action Plans in the Hashemite Kingdom of Jordan in Response to UNFCCC Communications Obligations) was started then Kyoto Protocol entered into force in January 2003 (Jordan National Report 2010).

Before the civil war in 2011, Libya's GHG emissions grew at an average of 2.4% per year from 1990 to 2010. The data show that it continues to increase parallel to oil production. Although Libya had funding from the GEF to apply a national communication to the UNFCCC, the project ended in 2005 because of immeasurable results (WRI 2017).

In Lebanon, the transportation sector is the main source of air pollution; according to MOE/EU/NEAP (2011), NOx emissions are one of the largest contributors with 59% share in urban air pollution. In terms of the CO_2 emissions, largest emitters are energy industries (thermal power plants) with 39% of national CO_2 emissions in 2005, also 68% of national SO_2 emissions in 2005 caused by energy industries.

Being the wealthiest country in the Arab world, Saudi Arabia was the world's largest producer of oil in 2012 (Alshehry and Belloumi 2015), also one of the largest CO_2 emitters (WDI 2012). Saudi Arabia had strong economic and industrial growth during the 1971–2013 period, consistent with the growth of total oil consumption which increased sharply in the same period. Moreover comparing with other industrialized countries such as Germany and Japan, Saudi Arabia consumes more than 3 million barrels of oil per day than those countries. While the consumption of Saudi Arabia is much higher than these industrialized countries, German economy is six times larger than Saudi Arabia, and the Japanese economy is nearly nine times as large as Saudi Arabian economy (Alkhathlan and Javid 2015). The data show a big asymmetry between the size of the economy and the amount of oil consumption in Saudi Arabia.

Turkey is heavily dependent on imported energy sources, and in 2015 its total primary energy consumption increased more than doubled compared the consumption of 1995 (Uğurlu 2018). The share of fossil fuels in total electricity generation has increased during 1990–2013 period; in 2013 their share within total energy generation was 71.15%. Ozcan (2016) discusses the targets of Turkey regarding energy generation, environment and climate change. The aims of these targets are to make reform in the electricity sector, strategic planning in the electricity energy market, supply security in the energy market and energy efficiency.

The United Arab Emirates (UAE) is a federation of seven Emirates that spans approximately 83,600 km^2. In the UAE climate is very dry with accompanying humidity; thus temperature is rising to about 48 °C in coastal cities and reaches as high as 90% with humidity levels and in southern regions rising to about 50 °C (Radhi 2009). In the UAE main source of GHG emissions is energy consumption; in 2006 95% of CO_2 emissions was caused by energy-related CO_2 emissions from fossil fuel production and combustion (Kazim 2007). Same as the other countries, the UAE CO_2 emission is increasing too; CO_2 emissions from fuel combustion are 175.4 million tonnes of CO_2, while it was 79.8 million tonnes of CO_2 in 2000 (IEA 2016).

In this research, World Bank WDI[4] data are used to analyze greenhouse gases emission in the region. World Bank greenhouse gases series includes other greenhouse gas emissions (HFC, PFC, and SF_6), PFC gas emissions, total greenhouse gas emissions, and methane emissions. However, due to the lack of data for some countries, I use four greenhouse gases which are available for all investigated countries for all years. Table 9.7 presents and defines the data.

Table 9.7 Greenhouse gases variables and their definition

CO2KT	CO_2 emissions (kt)
CO2P	CO_2 emissions (metric tons per capita)
MET	Methane emissions (kt of CO_2 equivalent)
NIT	Nitrous oxide emissions (1000 metric tons of CO_2 equivalent)

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[4] http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators.

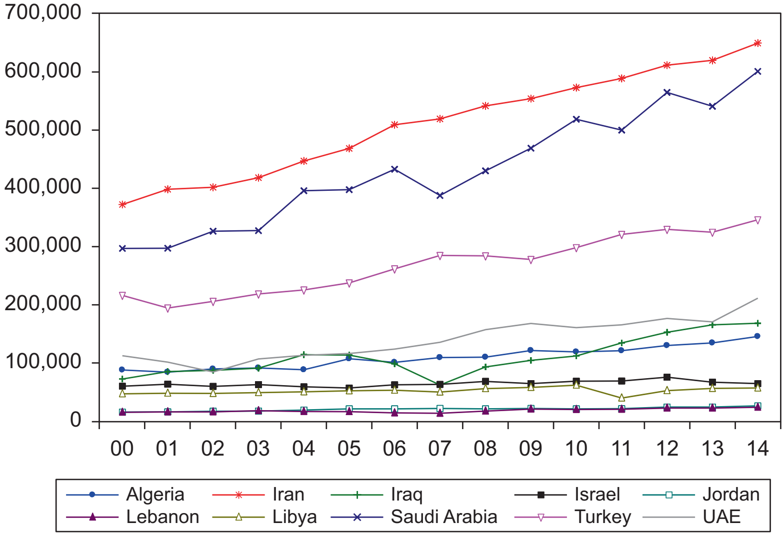

Fig. 9.5 CO_2 emissions (kt) of the countries

Figure 9.5 shows that Iran has the highest level of CO_2 emissions among the countries. Iran is followed by Saudi Arabia, Turkey, the UAE, Algeria, and Libya. Nearly all the countries show growth in their CO_2 emissions.

Although Iran is the leading country in the Middle East countries considering CO_2 emission, it is the fifth country according to CO_2 emissions per capita. Figure 9.6 shows the UAE has the highest CO_2 per capita between 2000 and 2014 and then followed by Saudi Arabia. Libya and Israel have close values, and they are third and fourth countries, respectively.

If methane emissions take into consideration, there is a considerable gap between the countries. The figure shows (Fig. 9.7) that Turkey and Iran are three times larger than their nearest followers by means of methane emissions. The sources of methane (CH_4) are fossil fuels, rice paddies, and waste dumps. The size of the rice cultivation in these two countries may be the cause of this high methane emission. Rice is the second important agricultural crop in Iran with approximately 647000 hectares of paddy fields. Its share in the world's cultivation area is 4% (Sharifi and Taki 2016). It is also an important cereal crop in Turkey (Dengiz 2013).

Iran has the highest nitrous oxide emission among the countries (Fig. 9.8). Second, third, and fourth countries are Turkey, Saudi Arabia, and Algeria, respectively, but they have close emission levels. Agricultural systems cause nitrous oxide (N_2O) emissions including direct emissions of N_2O from agricultural fields, direct emissions of N_2O in animal production systems, and some of the indirect emission of N_2O (Mosier et al. 1998). Differentiation of the emission levels of the nitrous oxide of the countries can be dependent on their agricultural production and agricultural land size.

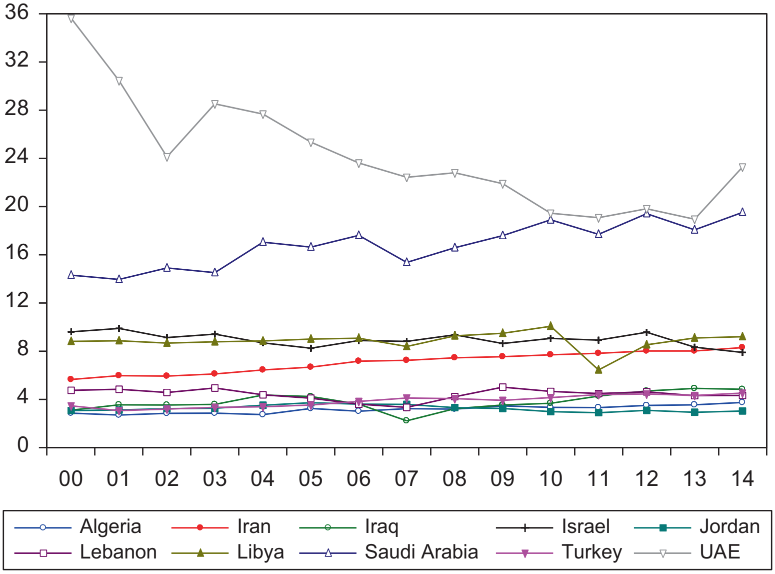

Fig. 9.6 CO_2 emissions metric tons per capita

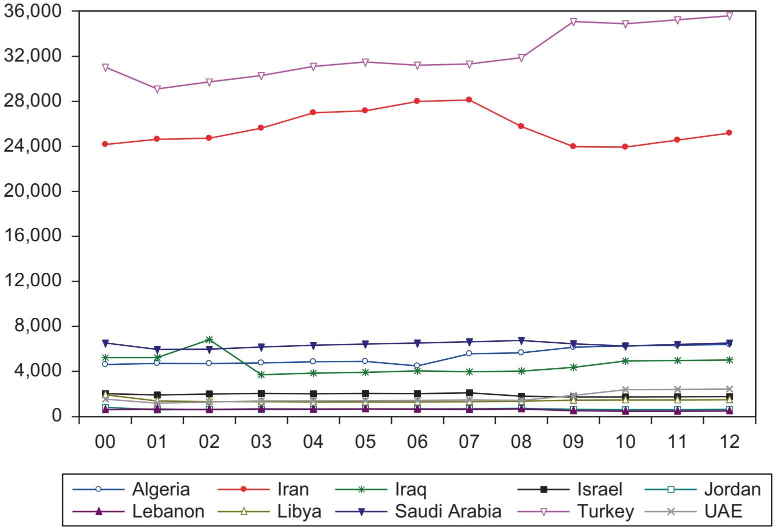

Fig. 9.7 Methane emissions (kt of CO_2 equivalent)

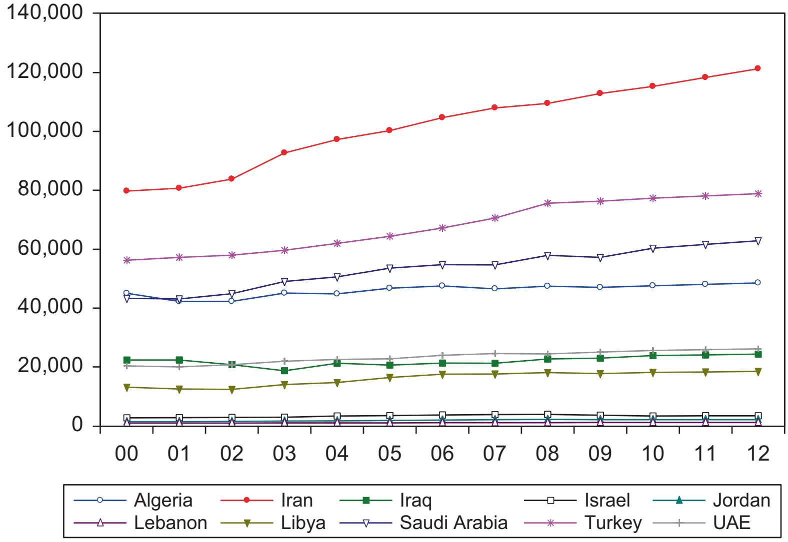

Fig. 9.8 Nitrous oxide emissions (1000 metric tons of CO_2 equivalent)

4 Renewable Energy in the Middle East

4.1 Renewable Energy

Renewable energy (RE) has been defined, somewhat strictly, as "energy flows that occur naturally and repeatedly in the environment and can be harnessed for human benefit" (Moore and Smith 2007).

Renewable energy is obtained from solar, geophysical, or biological sources and includes resources such as biomass, solar energy, wind energy, hydropower, tide and waves and ocean thermal energy, and geothermal heat. In 2010 renewable energy sector provided more than 450,000 jobs and had an annual turnover exceeding €45 billion (EREC 2010). Moreover Roy and Das (2018) deal with six types of energy (Fig. 9.9); the authors state that most of the renewable energies rely on the sunlight directly or indirectly.

Roy and Das (2018) define these energy types. According to authors wind power is generated by the conversion of the kinetic energy; the solar energy is generated from the power of the sun using photovoltaic (PV) cell or concentrating solar power (CSP) method. Hydropower is generated from water using its potential energy; bioenergy is generated from forest woods and wastes. Geothermal energy is generated from geothermal power plants (GPPs) using the hot vapor or steam powers and electric generator. Marine energy is generated from energy by six distinct systems as are waves, tidal ranges, tidal currents, ocean currents, and ocean thermal energy conversion (OTC) and salinity gradients.

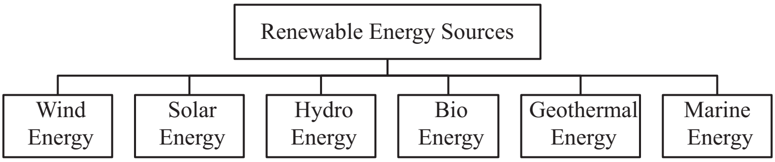

Fig. 9.9 Classification of renewable energy. (Source: Roy and Das 2018)

In 2014, the share of global investment new renewable energy capacity was 59% of net additions to global power capacity. In investment in renewable energy, leading source is solar power with the share of 55% among other non-hydro-renewable energy (Griffiths and Mills 2016).

Global final energy consumptions consist of fossil fuels, all renewables, and nuclear power; their shares are 78.3%, 19.2%, and 2.5%, respectively. All renewables are modern renewables and traditional biomass at 10.3% and 8.9%, respectively. Also, modern renewables can be split into four groups that are biomass/geothermal/solar heat, hydropower, wind/solar/biomass/geothermal power, and biofuels with shares of 4.2%, 3.9%, 1.4%, and 0.8%, respectively (REN21 2016).

According to REN21 (2016), data for the 2015 bioenergy production were increased, but there was a challenge globally. In geothermal power and heat, the market was led by Turkey, and Turkey has nearly have half of new global capacity additions in the world. Hydropower capacity was increasing in 2015 too. Ocean energy had faced a constrained financial landscape and mostly used tidal power. Solar market power was nearly the one-fourth of total renewable energy in 2014. Turkey is the leader of the capacity added of solar water heating collectors with 10% increases in 2015. Concentrating Solar Thermal Power (CSP) rose approximately 10% in 2015, and this increases mostly in developing regions. On the other hand, in Europe wind power was the leading source of renewable energy.

4.2 Potential of the Renewable Energy in the Middle East

As it is noted above, some of the Middle East countries are the GCC countries; these countries have some of the highest solar potential in the world (Alnaser and Alnaser 2009). Also, it is stated below the majority of the land in the GCC area is desert; thus this land characteristic can be used to develop large-scale solar power plants. Also because of their coastal and gulf areas, they have important potential for wind energy. Moreover, based on the strong animal population of the GCC, biogas can be generated using animal manure (Abdmouleh et al. 2015). In the Middle East and North Africa (MENA) region, leading source is solar PV (Griffiths and Mills 2016).

Table 9.8 shows the number of sources in renewable electricity generation in 2015 for the Middle East countries. Turkey is the most developed country regarding renewable energy use in the electricity sector. While Turkey generated renewable

Table 9.8 Amount of sources in renewable electricity generation (GWh) in 2015

Country	Industrial waste	Biogases	Geothermal	Solar thermal	Hydro	Solar PV	Wind
Algeria	0	0	0	0	145	58	19
Iran	0	14	0	0	14090	1	221
Iraq	0	0	0	0	2572	0	0
Israel	0	68	0	0	24	1115	7
Jordan	0	6	0	0	53	2	123
Lebanon	0	0	0	0	479	0	0
S. Arabia	0	0	0	0	0	1	0
Turkey	109	1208	3425	0	67146	194	11652
UAE	0	0	0	243	0	53	0

Notes: Libya data is not available
Source: IEA Renewables Information 2017 – https://webstore.iea.org/renewables-information

energy for electricity from six sources out of seven sources, Iraq and Saudi Arabia used only one source in 2015. Moreover, the differences between Turkey and the other countries are very wide. According to REN21[5](2016), Turkey is the first among the top five countries based on geothermal power capacity, and followers were the United States, Mexico, Kenya, and Germany/Japan, respectively, in 2015.

Because electricity is a vital source for the industries, renewable energy sources (RES) for electricity generation is one of the crucial topics for countries. Thus renewable energy in electricity consumption has significant growth and significant development (Fig. 9.10). Furthermore, electricity consumption is used as a proxy for the level of development.

The main renewable energy source is hydro in Turkey, and then it is followed by wind, geothermal, biogases, solar PV, and industrial waste, respectively. Although Turkey is the most significant renewable energy producer in the Middle East, Israel is the biggest solar energy producer, and the UAE is the biggest solar thermal energy producer.

International Renewable Energy Agency (IRENA) publishes final renewable energy consumption by sector. The data[6] show that Turkey is the biggest renewable energy consumer among the countries (Table 9.9), and major sectors in renewable energy consumption are industry sector and residential sector for the Middle East countries (Fig. 9.11).

Beginning with the country-specific renewable energy potential, Algeria has an excellent solar energy source with average daily sunshine in the range of 7–9 h and also has excellent daily solar radiation. Thus the photovoltaic pumping is an advantageous way for Algeria (Amrouche et al. 2010; Himri et al. 2009). In 2016, except Algeria, a major share of sectoral final renewable energy consumptions is made from residential sector in all the countries investigated in Fig. 9.11. In Algeria, the

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[5] Renewable Energy Policy Network for the 21st Century

[6] http://resourceirena.irena.org/gateway/dashboard/?topic=18&subTopic=47.

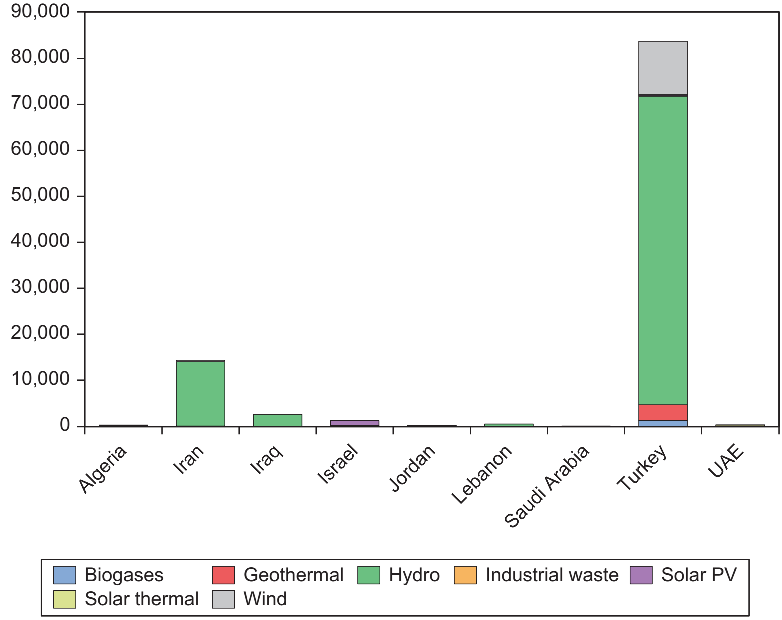

Fig. 9.10 The share of sources in renewable electricity generation in 2015

Table 9.9 Final renewable energy consumption[a] (terajoule)

Country	Total
Algeria	1494.2
Iran	49911
Iraq	8589
Jordan	10312
Saudi Arabia	5488
Turkey	499770
UAE	4939

Notes: [a] Israel, Lebanon, and Libya data are not published in IRENA

Source: http://resourceirena.irena.org/gateway/dashboard/?topic=18&subTopic=47

biggest share is from industry sector, whereas the sector has very low shares in other countries. The sector energy consumptions change based on the countries distinctive characteristics. In Algeria, the Electricity Law of 5th of February 2002 was set. This law is also about the financial source of the RES, and they are feed-in tariffs or directly by the state. After the law same year in July, government-owned company SONATRACH formed to exploit the hydrocarbon resources of the country, SONELGAZ (National Society for Electricity and Gas) became a legal monopoly

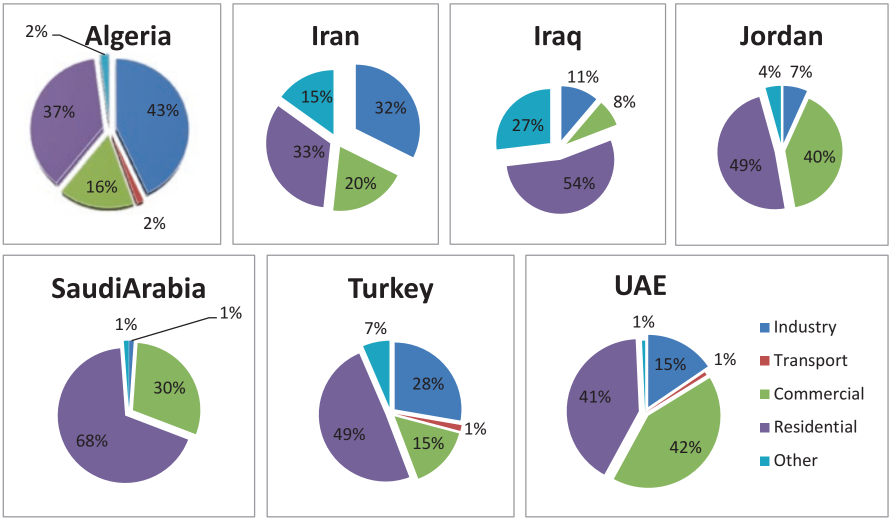

Fig. 9.11 Final renewable energy consumption by sector in 2016

over power production, and Algerian private company SIM formed a new renewable energy joint venture company called New Energy Algeria (NEAL) (Tsikalakis et al. 2011).

Whereas large parts of the Middle East have high solar irradiation and strong winds, the use of those potentials is low in the Middle East countries. However, some countries such as Turkey, Morocco, and Syria have a significant level of initiative to use renewable sources (Dees and Auktory 2018). Although the Middle East is prosperous regarding hydrocarbon, in the region around 20 million people live without access to even basic levels of electricity (El-Katiri 2014).

The main authorities of Egypt renewable energy strategies are the Ministry of Electricity and Energy and the New & Renewable Energy Authority (NREA). Egypt aims to produce 20% of the generated electricity using renewable energy sources by 2020 (Tsikalakis et al. 2011).

Mor et al. (2009) state that there was no data about renewable energy in Israel's statistics before 2006. However, the Ministry of National Infrastructures (MNI) announced policies and rules of Israel to develop RE in 2004, and then the Israel Public Utilities Authority – Electricity (PUA) made some regulations for renewable electricity generators.

The government of Jordan has shown an interest in various types of renewable energy since the 1980s such as wind, solar, bio, and other renewable sources. Jordan's interest in wind energy has started since the late 1980s. In these years Jordan established a plant in the northeast corner of the country and another plant in nearby Hofa; therefore in 2006 these plants' energy production reached MWh in electricity (Jaber et al. 2004; MEMR 2007). As for the solar energy, the first solar thermal plant in the Al-Qweira area and some other pilot projects are aimed to establish the National Energy Research Center that was created in 1998 with a mandate. Although biomass energy has little potential in Jordan (Jaber et al. 2004), the government has an interest in bioenergy. Therefore they started a project in 1998, which was funded from United Nations Global Environment Facility and the Danish Government. The aim of the project is to generate bioenergy from burning municipal solid waste and organic waste. Nevertheless, in 2006, the Bio-Gas Company's plant (Rusaifa plant) had reached a voltage capacity of 3.5 MW (Mason et al. 2009). Jordan aims to increase its share of renewables to 10% by 2020; moreover, after the European Investment Bank (EIB) and the French Development Agency have approved financing, Jordan will apply Green Corridor project to increase its power transmission capabilities (MESIA 2017).

Quaschning (2008) argues about the energy supply of the world, and the author splits the development of energy supply into four different periods starting from the French Revolution. After the revolution, the periods are the era of Black Gold, usage of natural gas, the invention of nuclear power, and fossil energy century. As it is stated in Quaschning (2008), renewable energies are also referred to as "regenerative" or "alternative" energies, and they consist of hydropower, wind power, biomass, the natural heat of the earth, and solar energy.

In 2013 the UAE installed the first utility-scale solar power facility in the GCC (Griffiths and Mills 2016). In some of the Middle East countries, which are located in the North Africa region, there is a potential for the expansion of stagnation in the economy. Therefore, these countries considered wind and solar technologies for electricity from Renewable Energy Sources (RES-E) (Brand and Zingerle 2011). The government of the UAE strategy has focused on the diversification of the national economy, and in its Vision 2021, the UAE aims to increase clean energy to 24% of the total energy mix by 2021 (Decision 24/CP.18).

5 Empirical Analysis

5.1 Data

The data cover the period of 2000–2014 for panel ten Middle East countries. CO_2 emissions are measured in kg per 2010 US$ of GDP, GDP per capita is in constant 2010 US$, renewable energy consumption is % of total final energy consumption. Data are collected from WDI. The data period is selected to use a common number of observations for the investigated countries depending on available data.

Table 9.10 presents some descriptive statistics of the variables used in the analysis. The descriptive statistics are the values of the variables before they are in natural logarithms. The highest level of GDP per capita is in the UAE while the lowest value in Iraq. Turkey is the biggest consumer of renewable energy by means of percentage of total energy consumption, and the smallest consumer is Saudi Arabia.

Table 9.10 Descriptive statistics of the variables

	GDPP	CO2P	REN
Mean	14175.92	8.416926	3.368730
Median	8055.591	5.309191	1.718659
Maximum	62833.25	35.67826	18.11179
Minimum	2526.043	2.189317	0.006009
Std. Dev.	14221.38	6.826632	4.453681
Skewness	1.774506	1.626201	1.729161
Kurtosis	5.575276	5.126049	5.163184
Jarque-Bera	120.1721	94.36374	103.9960
Probability	0.000000	0.000000	0.000000
Observations	150	150	150

This chapter aims to investigate the long-run relationship between CO_2 emissions and independent variables. Therefore this chapter uses the methodology proposed by many researchers (Ang 2007; Apergis and Payne 2009, 2010; Al-Mulali 2012 and Al-Mulali and Sab 2018) to estimate long-run relationship for panel data. The methodology is to propose Panel Granger Causality test. The causality between variables is very important for the policy makers. For instance, if causality runs from energy consumption to economic growth, decreasing energy consumption will have a negative effect on economic growth and vice versa. The root of the method relies on Engle and Granger (1987), Holtz-Eakin et al. (1988), and Toda and Yamamoto (1995). In the methodology direction of Granger causality, the variables are defined in both the long run and the short run using a panel error correction model. Holtz-Eakin et al. (1988) proposed the error correction model that estimates dynamic error correction terms with the one-period lagged residuals. Toda and Yamamoto (1995) developed a procedure to test the Granger non-causality for the level VARS.

In the analysis, all variables are used in their logarithm (the letter L then represents logarithm in the abbreviation of series) form. Figure 9.12 shows the graph of the variables in the logarithm form.

Also, correlation coefficients among the variables are calculated for the logarithm form of the variables (Table 9.11). The correlation coefficients show that all coefficients are statistically significant at 1% level significance. CO_2 emissions are positively correlated with GDP and negatively correlated with renewable energy consumption. While the correlation between GDP and CO_2 emission is high, the correlation between GDP and renewable energy consumption is moderate.

5.2 Panel Unit Root Tests

The empirical application of the chapter started with unit root tests of the variables. In the time series econometrics, it is expected that the variables have a unit root process. Therefore, it is necessary to test variables for the presence of a unit, in other

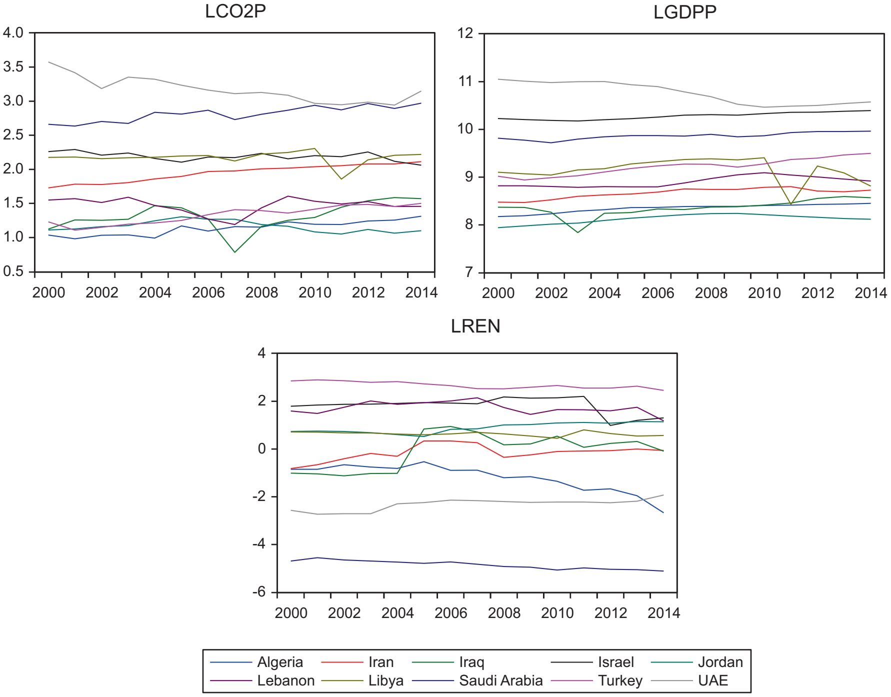

Fig. 9.12 Graphs of the variables

Table 9.11 Correlation coefficients

Probability		LCO2P	LGDPP	LREN
LCO2P	r	1		
	p			
LGDPP	r	0.858944	1	
	p	0.0000		
LREN	r	−0.594427	−0.287021	1
	p	0.0000	0.0004	

words, for the integration order of variable (Uğurlu 2009). It is known that panel data has both cross-sectional and time series features, various unit root tests were developed to deal with time series side of panel data structures. Panel unit root tests are more powerful than the normal unit root tests (Al-Mulali 2011, 2012).

Campbell and Perron (1991) state that if the time series is short, standard unit root and cointegration tests in time series have low statistical power. Panel-based tests increase the statistical power adding cross-sectional dimension (Belke et al. 2011).

Panel unit root tests are divided into two groups based on their assumptions. The first group assumes a common unit root process across the cross sections, and second group assumes an individual unit root process across the cross sections (Jebli et al. 2016). The Breitung (2000) and LLC's test (Levin et al. 2002) are in the first

Table 9.12 Panel unit root tests results

Variable	*Levin, Lin, and Chu (LLC)*		*Im, Pesaran, and Shin (IPS)*	
	Level	*First difference*	*Level*	*First difference*
LGDPP	−2.99229***	−7.62202***	−0.21436	−5.97473***
LCO2P	−2.00796**	−9.91696***	−0.77015	−8.45945***
LREN	0.56356	−8.84831***	1.31266	−7.31653***
Variable	*ADF – Fisher Chi-square*		*PP – Fisher Chi-square*	
	Level	*First difference*	*Level*	*First difference*
LGDPP	24.3371	64.4046***	24.2128	81.1930***
LCO2	25.9971	95.6366***	31.4492	137.018***
LREN	17.4657	83.5956***	17.5405	98.868***

Notes: Automatic selection based on the Schwarz is used to choose the optimal lag length. ** and *** denote statistical significance at the 5% and 1% levels, respectively

group, and Im, Pesaran, and Shin W-stat (Im and Pesaran 2003), ADF-Fisher Chi-square (Dickey and Fuller 1979), and PP-Fisher Chi-square (Phillips and Perron 1988) are in the second group. The null hypothesis of these tests is that there is a unit root in the series.

In this study, the LLC, the IPS, the Fisher-ADF, and the PP tests are employed. Table 9.12 shows the results of both of the panel unit root tests. Except for LLC test for LGDPP and LCO2P, all the test results clearly show that all the variables cannot reject the null hypothesis at levels. In LLC test for these two variables, the results show that the variables are stationary at the level. Although these two results have a different conclusion, a majority of the tests conclude that all the variables are stationary at the first difference. Taken together, the three tests suggest that all variables contain a panel unit root, and empirical application can proceed with panel cointegration test.

5.3 *Cointegration Tests*

Another time series feature of the variables is cointegration. If the time series data are considered, long-run parameters are conventionally expected to exhibit cointegrating relationships among a set of same order integrated variables (Uğurlu 2009). Although there are several estimations of cointegration relations, generally two of them are used: the Johansen test (Johansen 1988) and Engle and Granger (Engle and Granger 1987) two-step procedure.

Similarly, in panel data, it is tested whether there is the existence of a long-run equilibrium relationship between the same order integrated variables. The Pedroni test (Pedroni 1999, 2004) and Kao test (1999) will be employed in this study to examine whether the long-run relationship exists between the variables.

Table 9.13 Panel cointegration test

Pedroni panel cointegration test		
	Statistic	*Prob.*
Panel v-statistic	0.450861	0.326
Panel rho-statistic	−0.04359	0.4826
Panel PP-statistic	−1.68314**	0.0462
Panel ADF-statistic	−1.71903**	0.0428
Group rho-statistic	0.83358	0.7977
Group PP-statistic	−2.51803***	0.0059
Group ADF-statistic	−3.01875***	0.0013
Kao panel cointegration test		
	Statistic	*Prob.*
ADF	−2.54186 0***	0.0055
	Residual variance	0.007833
	HAC variance	0.00481

Notes: Automatic selection based on the Schwarz is used to choose the optimal lag length. ** and *** denote statistical significance at the 5% and 1% levels, respectively

Table 9.13 shows the Pedroni and Kao cointegration test results. This study used only one trend assumption, similar to the previous unit root test's assumption, namely, no deterministic trend. The results of Pedroni test show that four statistics out of seven statistics cannot reject the null hypothesis of no cointegration. Also, Kao cointegration test gives the same decision. Thus, the panel cointegration tests conclude that GDP per capita and renewable energy consumption have a long-run relationship with CO_2 emission in the Middle East countries.

5.4 *Panel Granger Causality*

Since the variables are cointegrated, the Granger causality based on the VECM can be performed. In panel VEC model, three types of causality tests are used. The tests are based on the study by Ang (2008) and the study by Pao and Tsai (2010), which were a short-run Granger non-causality test, a weak exogeneity test (long-running non-causality test), and a strong exogeneity test, respectively.

In this research short-run and long-run tests are used. In the short-run test, lagged dynamic terms are tested by using the F test; in the short run, the error correction term (ECT) is tested.

Before the VEC model is estimated, the long-running panel model must be estimated. In Eq. 9.1 the general model can be seen:

$$\mathrm{LCO2}_{\mathrm{it}} = \alpha_{0i} + \alpha_{1i}\mathrm{LGDPP}_{\mathrm{it}} + \alpha_{2i}\mathrm{LREN}_{\mathrm{it}} + \mathrm{u}_{\mathrm{it}} \tag{9.1}$$

Table 9.14 FMOLS estimation results

Dependent variable: LCO2	
Variable	Coefficient
LGDPP	0.522742***
LREN	−0.08561***
R-squared 0.981997	

Notes: *** denotes statistical significance at the 1% levels

Table 9.15 Country FMOLS estimation results

Dependent variable: LCO2		
	LGDPP	LREN
Algeria	0.780378***	−0.05887**
	(0.140762)	(0.018134
Iran	1.037625***	0.000119
	(0.182627)	(0.061811)
Iraq	0.792175*	−0.08337
	(0.374231)	(0.095312)
Israel	−0.38173*	0.003762
	(0.183122)	(0.03661)
Jordan	0.57537***	−0.39424***
	(0.137427)	(0.053707)
Lebanon	−0.04274	−0.30882**
	(0.317236)	(0.134708)
Libya	0.159351***	−0.62279***
	(0.063944)	(0.196861)
Saudi Arabia	0.420056*	−0.37081***
	(0.226437)	(0.091062)
Turkey	0.464537***	−0.40431***
	(0.100564)	(0.12264)
UAE	0.587194***	−0.03037
	(0.12275)	(0.113883)

Notes: Standard errors in parenthesis.*, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively

The error correction terms are derived from the long-running co-integrated relationships using FMOLS model.

Table 9.14 introduces the pooled fully modified OLS test results and shows that an increase in LGDPP will increase CO_2 emission and that the increase in renewable energy consumption will decrease CO_2 emission. The technique can show us country-specific results which are presented in Table 9.15.

Beginning with the country-specific results, LGDPP has a positive and statistically significant impact on LCO2 in all countries except Israel and Lebanon. The coefficients of LGDPP range from 0.15 in the case of Libya to 1.03 in the case of Iran. However, for Israel and Lebanon, the coefficients are negative and statistically significant.

The coefficient of LREN which shows the effect of renewable energy consumption of the countries is significant in Algeria, Jordan, Lebanon, Libya, Saudi Arabia, Turkey, and the UAE. In all countries which have a significant coefficient, the effect is negative means that if the renewable energy use increases, CO_2 emission will decrease which is expected.

The main aim of the estimation of FMOLS is to obtain the residuals. The first-lagged residuals are used in the VEC model as the error correction term.

The VEC model is specified as follows:

$$\begin{aligned}\Delta LCO2_{it} &= \alpha_{1i} + \sum_{p_{11}}^{j=1} \beta_{11ij} \Delta LCO2_{it-j} + \sum_{p_{12}}^{j=1} \beta_{12ij} \Delta \mathrm{LGDPP}_{it-j} \\ &+ \sum_{p_{13}}^{j=1} \beta_{13ij} \Delta \mathrm{LREN}_{it-j} + \theta_{1i} \mathrm{ECT}_{it-1} + \varepsilon_{1it}\end{aligned} \tag{9.2}$$

$$\begin{aligned}\Delta \mathrm{LGDPP}_{\mathrm{it}} &= \alpha_{2i} + \sum_{p_{21}}^{j=1} \beta_{21ij} \Delta LCO2_{it-j} + \sum_{p_{22}}^{j=1} \beta_{22ij} \Delta \mathrm{LGDPP}_{it-j} \\ &+ \sum_{p_{23}}^{j=1} \beta_{23ij} \Delta \mathrm{LREN}_{it-j} + \theta_{2i} \mathrm{ECT}_{it-1} + \varepsilon_{2it}\end{aligned} \tag{9.3}$$

$$\begin{aligned}\Delta \mathrm{LREN}_{it} &= \alpha_{3i} + \sum_{p_{31}}^{j=1} \beta_{31ij} \Delta LCO2_{it-j} + \sum_{p_{32}}^{j=1} \beta_{22ij} \Delta \mathrm{LGDPP}_{it-j} \\ &+ \sum_{p_{33}}^{j=1} \beta_{23ij} \Delta \mathrm{LREN}_{it-j} + \theta_{3i} \mathrm{ECT}_{it-1} + \varepsilon_{3it}\end{aligned} \tag{9.4}$$

where $\mathrm{ECT}_{it} = \mathrm{LCO2}_{it} - \alpha_{0i} - \alpha_{1i}\mathrm{LGDPP}_{it} - \alpha_{2i}\mathrm{LREN}_{it}$

In the Eqs. (9.2), (9.3), and (9.4), the term Δ denotes the first j, m is the lag length, and ECT is error correction term.

After the VEC model is estimated, the Wald test will be used to test the short-run and long-run causalities. Table 9.16 summarizes the Wald test hypothesis for panel Granger causality technique (Muratoğlu and Uğurlu 2014; Uğurlu 2014).

In Table 9.16, each column shows an investigated independent variable. For any of the independent variable, if the null hypothesis, which shows equality of the coefficients of the lagged terms of the independent variable, is rejected, it means causality runs from the independent variable to the dependent variable. For exam-

Table 9.16 Representation summary of the panel causality tests

	Independent variables			
	Short run			Long run
Dependent variables	ΔLCO2P	ΔLDGPP	ΔLREN	ECT
ΔLCO2P	–	$\beta_{12\mathrm{ip}} = 0\ \forall\ \mathrm{ip}$	$\beta_{13\mathrm{ip}} = 0\ \forall\ \mathrm{ip}$	$\theta_{1i}=0\ \forall \mathrm{ip}$
ΔLGDPP	$\beta_{21\mathrm{ip}} = 0\ \forall\ \mathrm{ip}$	–	$\beta_{23\mathrm{ip}} = 0\ \forall\ \mathrm{ip}$	$\theta_{2i}=0\ \forall \mathrm{ip}$
ΔLREN	$\beta_{31\mathrm{ip}} = 0\ \forall\ \mathrm{ip}$	$\beta_{32\mathrm{ip}} = 0\ \forall\ \mathrm{ip}$	–	$\theta_{3i}=0\ \forall \mathrm{ip}$

Table 9.17 Panel granger causa1lity test results

	Independent variables			
	Short run			Long run
Dependent variables	ΔLCO2P	ΔLDGPP	ΔLREN	ECT
ΔLCO2P	–	4.9999**	0.3706	−0.71637***
ΔLGDPP	0.59658	–	0.19756	0.15004
ΔLREN	0.24009	1.2994	–	0.66223

Notes: ECT represents the error correction term lagged one period. χ^2 statistics is used for the short run, and t-statistic is for the long run. ** and *** denote significance at 5% level and 1% level, respectively

ple, if the null hypothesis $\beta_{21ip} = 0 \ \forall$ ip is rejected, causality runs from ΔLCO2P to ΔLGDPP.

As shown in Table 9.17, in the short run, there is a unidirectional Granger causality running from ΔLGDPP to LCO2P. The absence of a short-run causality running from renewable energy consumption to GDP per capita indicates that renewable energy consumption does not have enough effect on carbon dioxide emissions. According to the long-run results, only one unidirectional panel Granger causality is running from gross domestic product per capita and renewable energy consumption to CO_2 emission per capita, in line with the results of the FMOLS model.

6 Conclusion

Climate change is one of the crucial problems for the countries, and the countries aim to have low-emission GHG and to reduce dependence on fossil fuels. It is clear that renewable energy use is the main solution to this problem, but it still has some challenges regarding cost and installed capacity and energy produced by each technology.

In this chapter GSH emission, renewable energy use, and growth of the countries are investigated for the Middle East countries that have a trend of growing energy demand and growing GHS emissions. In the empirical side, we investigate the relationship between GDP per capita, renewable energy use, and CO_2 emissions in ten Middle East countries over the period 2000–2014. The empirical strategy uses a recent panel cointegration approach. At first, descriptive statistics are investigated, then correlation coefficients are interpreted. The correlation coefficients among these three variables are significant, but magnitudes of between each group of two countries are different. Further, the cointegration test was done, and the pooled fully modified OLS model was estimated. For the overall sample the model shows that GDP per capita has a positive effect, and renewable energy use has an adverse effect on carbon dioxide emission in the Middle East countries. For the eight countries, the effect of economic growth on CO_2 emissions is positive and significant, and for six countries, the effect of renewable energy use on CO_2 emissions is adverse and significant. Because the cointegration test results showed cointegration among variables, panel Granger test was done for the variables. These findings represent empirical support for expectations. The empirical results also show that there is a unidirectional causal relationship from GDP per capita to carbon dioxide emissions without feedback. The causal relationship implies that the high production levels put pressure on the CO_2 emissions.

The findings of this study give inspiration to future research to study CO_2 emission, growth, and renewable energy relationship. Future studies could be to examine the relationship for different economic sectors. Further studies could use models with more independent variables, such as industrial production index, energy prices, and oil production. Also, different greenhouse gases could be used to discuss the climate mitigation potential.

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Chapter 10
Quantitative Analysis Methods Used in Modeling Power Systems and Climate Change for Saudi Arabia

Aymen A. Kayal and Mohammad A. Al-Khars

Abstract The relationship between energy consumption and economic growth and emission reduction is considered sustainable development, and it has been the subject of intense research in the last couple of decades. The authors believed that balancing emission reduction while satisfying growing energy demand is an important issue for both policy makers and researchers alike in the Kingdom of Saudi Arabia (KSA). This seriousness in sustainable development in KSA should be clearly evident in the literature through the increasing number of articles found in top journals related to the area. In order to ascertain our assumptions, the authors of this chapter conducted a sample review of publications that focused on quantitative modeling of the dynamics of both power and environment aspects in Saudi Arabia. Analysis of the sample of articles under study clearly revealed an exponential increase in the use of quantitative models for analyzing the integration of power generation and emission reduction dimensions in KSA. This growth indicates an increase in the propensity of research to evolve from descriptive energy studies to systems modeling that focuses more on KSA's energy mix and emission reduction.

Keywords Quantitative analysis · Quantitative models · Power systems · Climate change · Saudi Arabia · Sustainable development

1 Introduction

The Kingdom of Saudi Arabia (KSA) is rich in oil and natural gas reserves. However, industrialization, population growth, and increasing water desalination have led to high energy demand growth, affecting its ability to maintain energy export levels in the future. To support its growing economy, the country is increasingly consuming a large amount of energy domestically. For example, in 2014, KSA consumed nearly a third of its oil production making it the seventh largest

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H. Qudrat-Ullah, A. A. Kayal (eds.), *Climate Change and Energy Dynamics in the Middle East*, Understanding Complex Systems,
https://doi.org/10.1007/978-3-030-11202-8_10

consumer of oil in the world (IRENA 2016). Energy consumption in KSA has grown about seventy-four percent (74%) since year 2000 (Kinninmont 2010). For the same reasons, electricity consumption has also increased at a fast rate of around 3.15% per year and much higher than the world average of 2.5% (Kinninmont 2010). In the last few years, together the Golf Cooperation Countries (GCC) have overtaken major consumers such as China, India, and Brazil in terms of energy consumption growth, thereby reducing the share of production that can be exported (Bekhet et al. 2017; IRENA 2016).

The relationship between energy consumption and economic growth, as well as economic growth and environmental pollution, has been the subject of intense research and controversy in the last couple of decades. This storm has recently dawned on developing but oil-rich countries because of its relatively large consumption of fossil fuels for the generation of power and water. KSA is currently facing a dual challenge; one involves having to maintain a rapidly increasing domestic energy demand, and the other involves controlling emissions. In essence, there is an urgent need to plan renewable energy technologies which can address these future challenges (Bekhet et al. 2017).

To address environmental issues on the international, national, and regional levels, KSA have recently adopted policies, regulations, and plans that should reduce CO2 emissions while addressing its growing demand for energy. The combined approach of increasing energy efficiency, and the introduction of renewables in the energy mix, should result in a dual benefit of reducing CO2 emissions while maintaining the increasing energy demand needed by its rapidly growing economy (IRENA, IEA and REN21 2018). The recent activation of the Clean Development Mechanism Designated National Authority, Saudi Energy Efficiency Center, and King Abdullah City for Atomic and Renewable Energy were all mechanisms designed to address sustainable development in KSA.

The authors believed that the emerging need of balancing emission reduction while satisfying the growing energy and power demand is now an important issue for both policy makers and researchers alike in KSA, and this seriousness should be clearly evident in the literature by the increasing number of articles found in top journals that focus on energy and emissions. Furthermore, the use of country-specific quantitative energy models that incorporate power generation, renewable energy sources, and environmental concerns like reduction of CO2 emissions should also indicate an advanced level of propensity and readiness of the country toward sustainable development. The importance of these models lays in the fact that they capture, synthesize, and test the most important decision variables related to the country, as well as reveal the relations between these variables. The types of quantitative models that might emerge vary from optimization (linear and no-linear programing), system dynamics, econometric, simulation, regression, etc. It is the authors' notion that sustainable development in KSA has reached this level of seriousness and that any methodical review of research publications should find an exponential growth in the number of articles that offer quantitative models that integrate energy (power generation) with environmental and climate change dimensions. In order to ascertain our argument, the authors of this chapter conducted a sample review of publications that focused on quantitative models describing the dynamics of both power and environment aspects specifically related to Saudi Arabia.

2 Literature Review

Energy systems models have been around in various forms since the 1940s and were initially focused more on energy security and costs. The twenty-first century climate change policy has since emerged as a powerful factor driving many studies and models, with a focus on pathways to achieve the significant reductions in greenhouse gas emissions.

Although there are various ways to group, or classify, energy systems models, Pfenninger et al. focused on four paradigms of models and discuss representative examples to illustrate their salient features (Pfenninger et al. 2014):

1. *Energy systems optimization models*: models covering the entire energy system, primarily using optimization methods, with the primary aim of providing scenarios of how the system could evolve.
2. *Energy systems simulation models*: models covering the entire energy system, primarily using simulation techniques, with the primary purpose of providing forecasts of how the system may evolve.
3. *Power systems and electricity market models*: models focused exclusively on the electricity system, ranging in methods and intentions from optimization/scenarios to simulation/prediction.
4. *Qualitative and mixed-method scenarios*: Scenarios relying on more qualitative or mixed methods rather than detailed mathematical models.

Connolly et al. (2010) reviewed a large number of computer-based energy models which integrate renewable energy in the energy system. Although they found discrepancies between the models in terms of its ability to simulate 100% renewable energy systems, they did manage to provide a neat classification for all the 37 models they studied. The classification systems they used to distinguish between the different types of energy were (Connolly et al. 2010):

1. A *simulation* tool simulates the operation of a given energy system to supply a given set of energy demands. Typically, a simulation tool is operated in hourly time-steps over a 1-year time period.
2. A *scenario* tool usually combines a series of years into a long-term scenario. Typically, scenario tools function in time-steps of 1 year and combine such annual results into a scenario of typically 20–50 years.
3. An *equilibrium* tool seeks to explain the behavior of supply, demand, and prices in a whole economy or part of an economy (general or partial) with several or

many markets. It is often assumed that agents are price takers and that equilibrium can be identified.

4. A *top-down* tool is a macroeconomic tool using general macroeconomic data to determine growth in energy prices and demands. Typically, top-down tools are also equilibrium tools (see 3).
5. A *bottom-up* tool identifies and analyzes the specific energy technologies and thereby identifies investment options and alternatives.
6. *Operation optimization* tools optimize the operation of a given energy system. Typically, operation optimization tools are also simulation tools optimizing the operation of a given system.
7. *Investment optimization* tools optimize the investments in an energy system. Typically, optimization tools are also scenario tools optimizing investments in new energy stations and technologies.

Another large attempt to review and classify energy systems models was made by Jebaraj and Iniyan who classified energy models under six general types (Jebaraj and Iniyan 2006):

1. Energy planning models
2. Energy supply-demand models
3. Forecasting models
    - 3.1. Commercial energy models
    - 3.2. Renewable energy models
        - 3.2.1. Solar energy models
        - 3.2.2. Wind energy models
        - 3.2.3. Biomass and bioenergy models
4. Optimization models
5. Energy models based on neural networks
6. Emission reduction models

2.1 Modeling Energy and Environment in KSA

The energy remodeling strategies adopted by Saudi Arabia, and other GCC countries, require a long-term equilibrium relationship between economic growth and environmental protection. In essence, balancing key variables that include CO2 emissions, GDP per capita, energy consumption, and financial development is essential to achieve a long-term energy remodeling strategy. The empirical analyses and results found in the literature so far proved the existence of a long-term equilibrium relationship among CO2 and real GDP per capita, energy consumption, and financial development in KSA and all GCC countries (Osman et al. 2016; Reiche 2010). However, policy implications drawn from such analyses will be limited unless it addresses the very dynamic nature of the system. Systems modeling methods lend themselves as one of the best management science tools that can be used to properly represent the complexity of interactions and multiple layers of energy across a modern economy.

While energy models were initially focused more on energy security and costs, climate change policy has since emerged as a powerful factor driving many studies, with a focus on pathways to achieve the significant reductions in greenhouse gas emissions called for by climate science (Pfenninger et al. 2014). The following sections provide a literature review of objective information related to power energy production, consumption, and emission reduction related to KSA.

2.2 *The Realities of Energy and Electricity Production and Consumption in KSA*

This section briefly describes the increasing energy demand situation of Saudi Arabia as described by credible secondary data sources. Half of all energy consumption in the KSA (50%) goes to the industrial sector which is highly energy intensive in nature and includes the power and water sectors, refining, petrochemicals, and fertilizer industries. The transport sector accounts for the second largest share (32%), followed by residential (10%), commercial (5%), and other sectors (2%) (IRENA 2016).

In terms of *electricity* production and consumption, KSA produces and consumes all electricity within its national borders. Current production capacities barely exceed consumption and need expansions to meet future supply plans. The residential sector accounts for most of the electricity demand (IRENA 2016). A

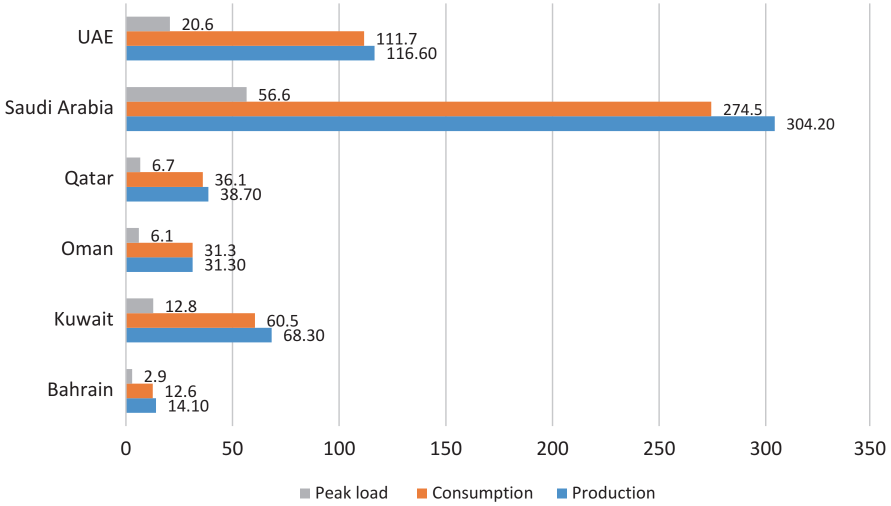

Fig. 10.1 Electricity production (TWh), consumption (TWh), and peak load (GW) in the GCC

Table 10.1 Estimated fuel consumption by power and water sectors (TBtu)

Country	Crude oil	Natural gas	Diesel	HFO	Total
Saudi Arabia	865.1	670.3	469.8	275.0	*2280.1*

Source: KAPSARC (2017)

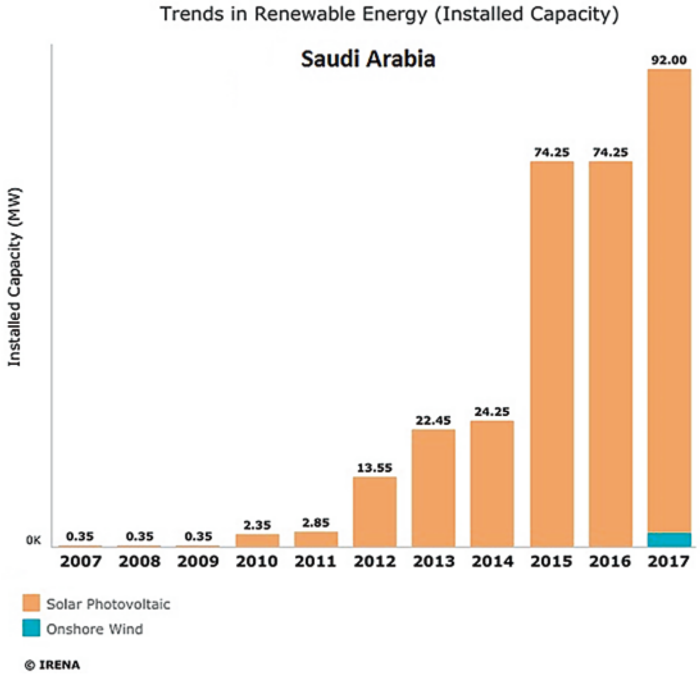

Fig. 10.2 Installed electricity capacity in KSA generated from renewable energy

comparison of electricity production, consumption, and peak loads of KSA compared with other GCC countries is shown in Fig. 10.1.

The main energy fuels used for generating electricity and desalinating seawater in this desert environment are natural gas, crude oil, HFO, and diesel. Table 10.1 presents the magnitude of consumption of each fuel type for the generation of electricity power and desalinated water.

2.3 *Realities of Energy and Emission Reduction in KSA*

According to the International Renewable Energy Agency (IRENA), the actual installed electricity capacity in KSA, which was generated from renewable energy sources (mainly solar), has grown exponentially in the last few years (see Fig. 10.2 and Table 10.2).

Table 10.2 Renewable energy capacity and generation in KSA

Country/area	Technology	Indicator	2014	2015	2016	2017
Saudi Arabia	Total renewable energy	Electricity capacity (MW)	24	74	74	92
		Electricity generation (GWh)	42	129	129	

Source: IRENA (2018)

Table 10.3 CO2 emissions in KSA

Saudi Arabia	Elec. cons. (TWh)	CO2 emissions (Kt of CO2)	Elect cons/pop. (kWh/capita)	CO2/ population	CO2/GDP 2010 USD
	316.9	527,200	9818	16.34	0.76

Source: Birol (2018)

With regard to CO2 emissions in KSA, Table 10.3 presents data from the latest International Energy Agency (IEA) report which estimated it to be 527.2 Mt of CO2. The CO2/population indicator was estimated to be 16.34 Mt/capita. To get a perspective of magnitude of CO2 emissions, Figs. 10.3 and 10.4 present the growth of CO2 emissions in KSA in time series from 1990 to 2014. The figures show a clear trend that corresponds with the growing energy consumption of the country.

3 Methodology

The authors believed that KSA has reached a relatively high level of seriousness in sustainable development and that this aspect is now convoluted with the existence of many quantitative models that attempt to assist researchers and policy makers in striking the right balance between energy and emission reduction. For this purpose, a review of research publications (articles) in related top tier journals was conducted. The authors identified a number of journals and conducted a database query to identify all the articles that fit the scope of the investigation. The focus of the query used to identify the articles was on quantitative models describing the dynamics of electricity power (demand or supply) and environmental dimensions (climate change, emission reduction, CO2, or renewables) in Saudi Arabia. To assure the quality of the research publications being queried, the authors used convenience sampling of SCImago Journal & Country Rank (SJR) and randomly selected five of the Q1 journals that focused on quantitative analysis of energy and environment (climate change and renewables). The five journals selected were all published by Elsevier, and they are listed in Table 10.4. The query limited the search to quantitative models related to Saudi Arabia from 1988 to 2017.

The SCImago Journal & Country Rank is a publicly available portal that includes the journals and country scientific indicators developed from the information contained in the Scopus® database (Elsevier B.V.). These indicators can be used to assess and analyze scientific domains. Journals can be compared or analyzed separately. Country rankings may also be compared or analyzed separately. Journals can

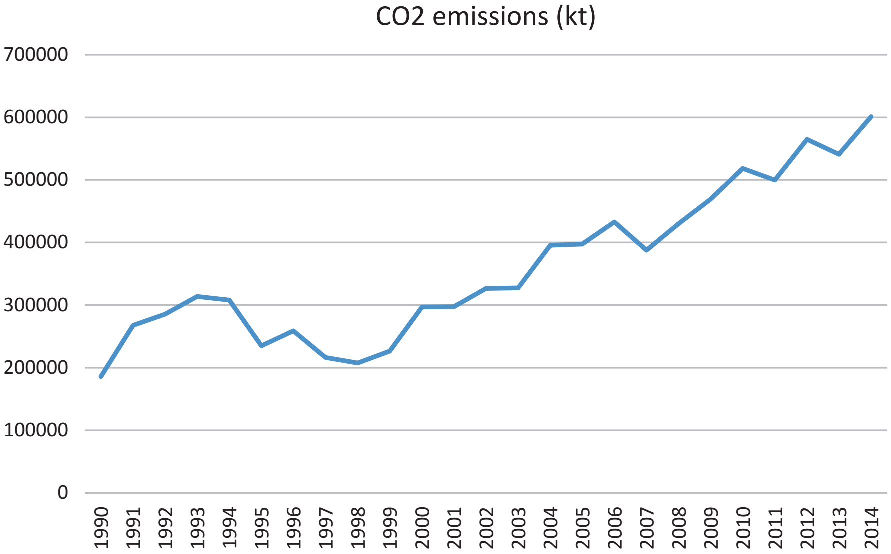

Fig. 10.3 CO2 emissions in KSA (Source: World Bank Data)

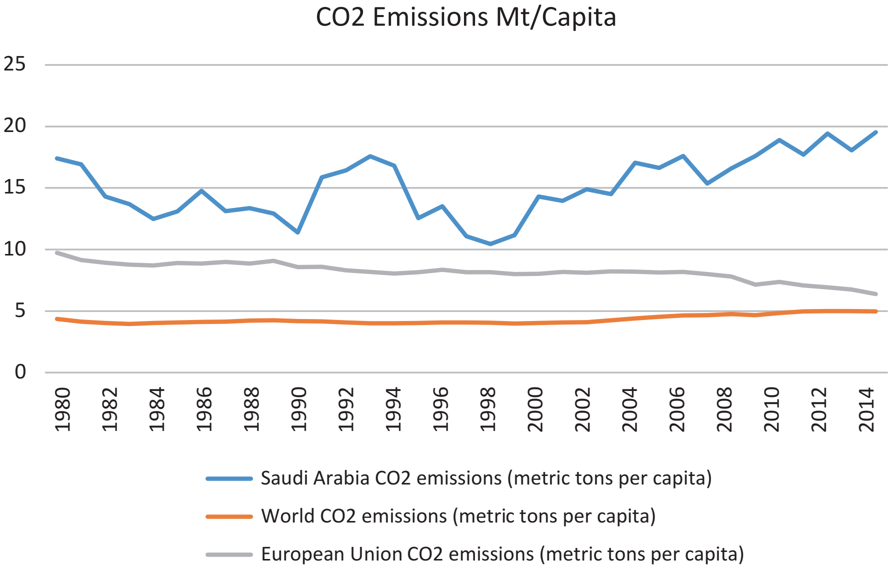

Fig. 10.4 CO2 emissions Mt/population in KSA (Source: World Bank Data)

Table 10.4 List of journal selected in this review

Journal name	Impact indicators		
Applied Energy	Q1	H index 140	SJR 3.162
Energy	Q1	H index 146	SJR 1.99
Energy Economics	Q1	H index 109	SJR 1.916
Energy Policy	Q1	H index 159	SJR 1.994
Renewable and Sustainable Energy Reviews	Q 1	H index 193	SJR 3.036

be grouped by subject area (27 major thematic areas), by subject category (313 specific subject categories), or by country.

The research query conducted resulted in a large number of articles, which were further examined and filtered to eliminate descriptive studies and to make sure that only relevant articles were included. The resulting final number of articles identified were 58 articles. These articles focused on modeling power (either demand or supply) and environmental issues (renewable energy, climate change, CO2, or emission reduction).

After analyzing each of the 58 articles in terms of the quantitative methods used in them, the authors then classified them into three general methods that they subjectively believed best fit these articles: 1) econometric, 2) optimization, and 3) simulation. The following section will provide details of the review analysis.

4 Analysis

The authors found 58 research publications that quantitatively described, modeled, or simulated the dynamics of energy and emission reduction in KSA. Table 10.5 presents the number of research articles found in the query in each year. Figure 10.5 shows the growth in the number of research publications identified, and it is clearly evident that the growth during the last 5 years was exponential.

The articles were then classified according to the three quantitative modeling methods that they have used: (1) econometric, (2) optimization, and (3) simulation. Table 10.6 and Fig. 10.6 show the distribution of the 58 articles based on the quantitative method. The number of articles identified was relatively small, but the authors believed that this is probably due to the fact that energy modeling for KSA is still relatively new and that many studies are still needed to describe the evolving dimensions of the system before it can be captured in quantitative models.

Table 10.5 The number of research articles found in the query

No	Year	No. of papers	No	Year	No. of papers
1	1988	2	16	2003	0
2	1989	0	17	2004	0
3	1990	0	18	2005	1
4	1991	0	19	2006	0
5	1992	0	20	2007	0
6	1993	0	21	2008	2
7	1994	1	22	2009	1
8	1995	0	23	2010	1
9	1996	0	24	2011	3
10	1997	0	25	2012	1
11	1998	0	26	2013	7
12	1999	1	27	2014	6
13	2000	0	28	2015	5
14	2001	0	29	2016	8
15	2002	1	30	2017	18
Total					*58*

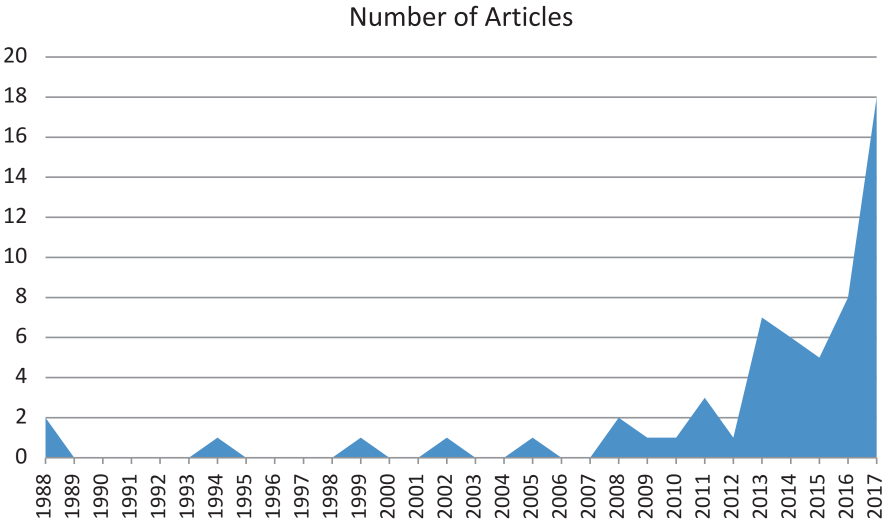

Fig. 10.5 The growth of the number of articles

Table 10.6 Distribution of the research articles based on method

No	Analysis method	No of articles	%
1	Econometric	23	40%
2	Optimization	13	22%
3	Simulation	22	38%
Total		*58*	*100%*

Fig. 10.6 The distribution of the articles in terms of quantitative method

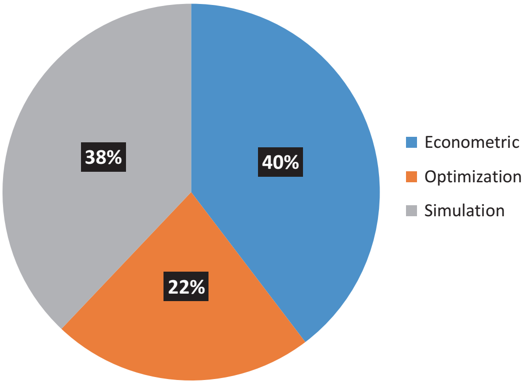

Table 10.7 Distribution of articles based on journal name and analysis method used

Analysis method				
Journal name	Econometric	Optimization	Simulation	Total
Applied Energy	1	6	7	14
Energy	6	4	2	12
Energy Economics	4	1	0	5
Energy Policy	5	1	2	8
Renewable and Sustainable Energy Reviews	7	1	11	19
Total	*23*	*13*	*22*	*58*

4.1 Analysis Based on the Taxonomy

The distribution of articles according to the quantitative method used and the journal name that it was published in was also deemed valuable by the authors in order to have a feeling about the match between the method type and the journal name. This match was presented in Table 10.7. Figures 10.7 and 10.8 present the distribution of the articles in two ways: the first according to journal name and methods and the second according to the method used and the journal names. From these figures we can observe that most of the simulation articles in the sample under study were published in two journals: *Applied Energy* and *Renewable and Sustainable Energy Reviews*. Optimization energy models can be found mostly in *Applied Energy* and *Energy*. Econometric models were found in all five journals but less in *Applied Energy*.

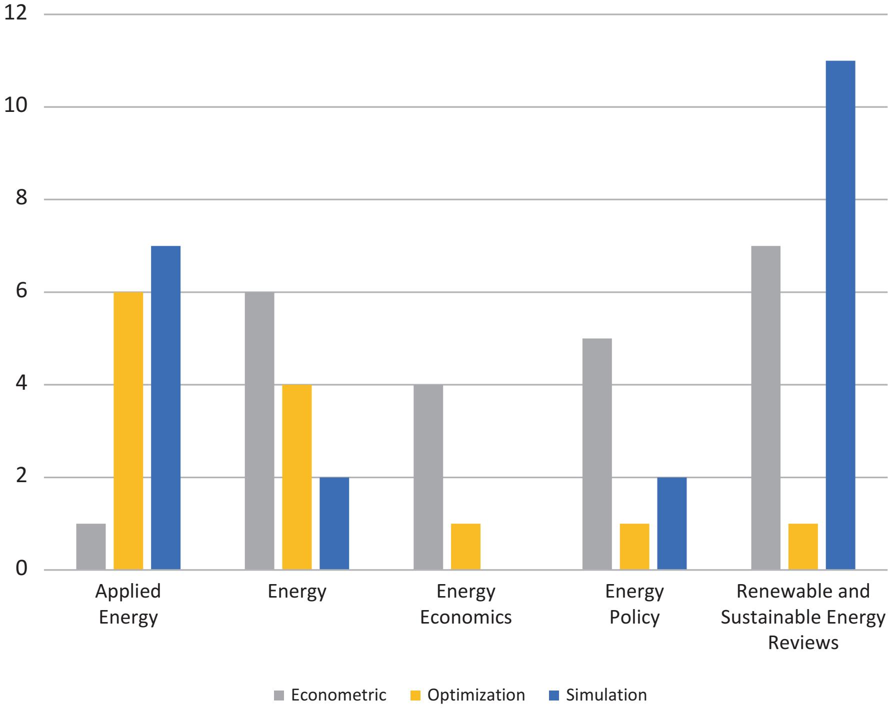

Fig. 10.7 The distribution of the articles by journal name in terms of quantitative methods

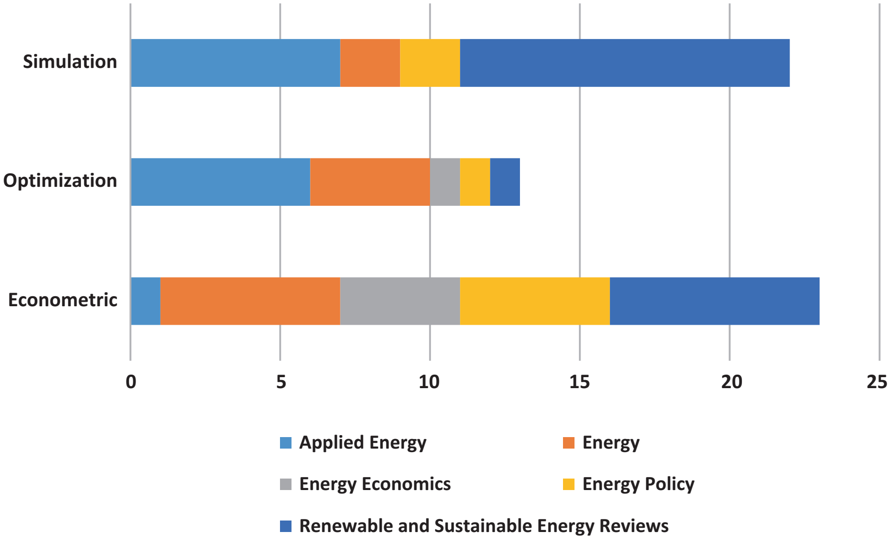

Fig. 10.8 The distribution of the articles by quantitative method in terms of journal names

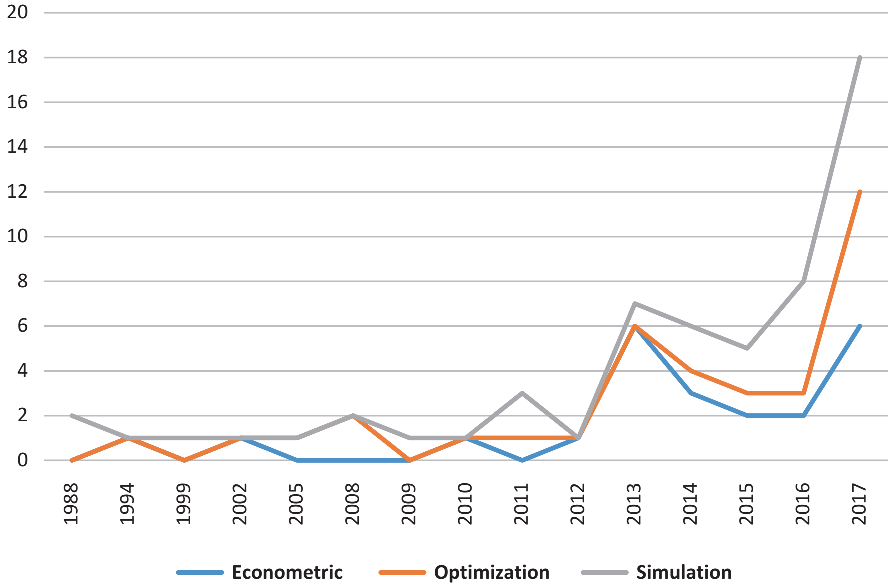

Fig. 10.9 The growth of various quantitative modelings of energy and environment in KSA

4.2 Propensity of Power Systems Modeling for KSA

The growth of the number articles that specifically used econometric, optimization, or simulation models to capture power systems and emissions reduction in KSA is an indicator of the country's growing concern and propensity to achieve sustainable development. In this regard, the authors found 44 out of the total 58 articles (76%) were published within the last 5 years only (2013–2017) indicating an exponential growth in quantitative modeling of energy and emission reduction (see Fig. 10.9). This snapshot observation of the sample of articles under study clearly indicated the propensity of research related to KSA's sustainable development to advance from descriptive studies to systems modeling.

5 Conclusion

As the Kingdom of Saudi Arabia pushes forward its sustainable development and renewable energy program that was prescribed in its "Vision 2030" strategic plans and goals, it will need to optimize its increasing power demand while maintaining a relatively low CO2 emission. Getting to that point will require advanced quantitative models that will assist policy makers in making the right decisions with regard to the types of renewable energy sources to expand on, as well as technology and capacity options.

The aim of this chapter was to provide a snapshot of recent quantitative research, in selected journal publications, which proposed quantitative energy systems models for Saudi Arabia. Decisions and policies regarding the correct energy and power generation mix that can contribute to emissions reduction of CO2, and other greenhouse gases, can be highly enhanced using such quantitative models. This preliminary investigation has assured us that the increasing quantitative modeling efforts in this area are also moving side by side with the strategic directions and actual actions that are taking place in the country.

Future research could expand on the sample of journals in order to compare and validate the findings of the current study. Investigations along this line could also use list all the various institutions, networks, policies, and functions that are needed to build a comprehensive system dynamic model that would capture all the important dimensions related to power generation, economic growth, emission reduction, and human factors that impact sustainable development in KSA.

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Part IV

Understanding the Dynamics of Clean Energy Using Conceptual Modelling Approach

Chapter 11
Transformation Toward Clean Energy in the Middle East: A Multilevel Perspective

Muatasim Ismaeel

Abstract The global energy sector is going through a radical change of its well-established systems. Global efforts to mitigate climate change effects, changes in the economics of hydrocarbon energy sources, and technological developments led to a global transition to renewable energy sources. The Middle East region is not an exception. During the last decade, the region witnessed the launch of successful renewable energy projects, especially in the electricity sector. They are mainly solar energy projects. The decline in the cost of solar panels and the good potential for solar energy in the region, in addition to economic challenges because of low oil prices and increasing population and urbanization, contributed to the case of transformation toward clean energy in the region. However, this transformation is in its early stages and requires careful planning and coordination of actions and policies from various parties at different levels. In this chapter, transformation toward clean energy in the Middle East is discussed as a sociotechnical change and analysed through the multilevel perspective theoretical approach. Different factors which affect the transformation are identified at the three levels of landscape, regime, and niche that need to be coordinated and aligned to ensure a successful transition.

Keywords Innovation · Sustainability · Environment · Renewable energy · Clean energy · Sociotechnical change · Multilevel perspective · Middle East

1 Introduction

Climate change is one of the significant challenges that face humanity in the twenty-first century. Therefore, it gained increasing global attention in the last few decades. This attention was manifested through the publication of global agendas like millennium goals and sustainable development goals (SDGs) by the United Nations (George et al. 2016; United Nations 2015). SDGs include seventeen goals that cover different aspects of sustainable development, mainly: poverty elimination,

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H. Qudrat-Ullah, A. A. Kayal (eds.), *Climate Change and Energy Dynamics in the Middle East*, Understanding Complex Systems,
https://doi.org/10.1007/978-3-030-11202-8_11

environment protection, and ensuring prosperity and equity among communities (George et al. 2016; United Nations 2015). All of the three aspects are affected substantially by global climate change. However, the response to climate change challenges has no straightforward approach since climate change is considered as a *grand challenge* (George et al. 2016). This expression (*grand challenge)* is increasingly used to refer to "problems that lack a clear single solution, and encompass incomplete, contradictory, or changing requirements that often unfold in complex systems" (Grodal and O'Mahony 2017: p. 1801).

The complexity of grand challenges necessitates approaching them at the field level rather than the organizational level. Different actions are needed from different social actors to respond to these challenges (Grodal and O'Mahony 2017). As Wright and Nyberg (2017) stated, a profound grand challenge like climate change needs coordinated responses from various organizations at different levels. Independent and separate actions by governmental or private organizations will not lead to any significant change if they are not part of a broad approach and coordinated efforts.

Increasingly, technological innovations are perceived as essential to meet climate change challenges. The incremental approach to improve eco-efficiency is not enough to meet these challenges. Such challenges require changing the way things are done through systemic innovations at different levels and aspects; including how the needs of governments, businesses, and societies are created and met (Dyck and Silvestre 2018; Wright and Nyberg 2017; Hargreaves et al. 2013).

The technological innovations in energy production and consumption are essential in responding to climate change causes and consequences. These changes can be seen as sociotechnical changes that need to be understood from certain theoretical perspectives that can reflect their richness and complexity. Among these theoretical perspectives, the multilevel perspective is common in sustainable innovation research (Hargreaves et al. 2013). This chapter uses this theoretical perspective to reflect on the sociotechnical changes toward renewable energy in the Middle East region. It includes a general description of recent trends in the region with a particular focus on the electricity sector.

In the Middle East region, changes toward clean energy practices in energy production and consumption are in their early stages. They are mainly led by governmental actions and policies with few innovative private sector initiatives. The region witnessed some successes in initiating the transition toward clean energy (Griffiths 2017). However, there is a need to consider the complexity of the social context to ensure the successful implementation of these changes.

This chapter continues as follows: in the second section, transformation toward clean energy is introduced as a form of sociotechnical change. In the third section, the multilevel perspective is explained as the theoretical approach used in this chapter with some examples from global practices. In the fourth section, transformation toward clean energy in the Middle East is discussed based on literature review with a focus on the electricity sector. The discussion builds on the multilevel perspective to identify the main features of this transformation in the region and possible policy consequences. Finally, the fifth section concludes the arguments of this chapter.

2 Transformation Toward Clean Energy as a Sociotechnical Change

Innovations and technological changes to respond to grand challenges are unique. They cannot be driven only by economic motives since these motives will not challenge the status quo and will not lead to dramatic changes. For instance, government and corporations are criticized for capturing the radical discourse on sustainability issues and reproducing it in accordance with their "business as usual" practices (Wright and Nyberg 2017). Therefore, it is argued that environmental sustainability issues should be managed at a broad scope of planetary boundaries with societal governance rather than limiting their scope to business boundaries and governance (Wright and Nyberg 2017; Gray 2010). However, *societal governance* does not refer to one *ideal* way of governance. Rather, it should include various mechanisms to govern multiple actors with contradicting interests (Grodal and O'Mahony 2017).

Incentive schemes are used by governments to encourage environmental sustainability practices. They form an example of the change mechanisms. Researchers found that the transition toward sustainability practices is affected negatively when these incentives stop (Aerni 2016; Chiaroni et al. 2015) because of the lack of financial sustainability of new technologies (Dyck and Silvestre 2018; Aerni 2016). In other words, economic motives are not enough to drive transformation toward environmentally sustainable practices, but they are necessary – in addition to other societal and political arrangements – to achieve this transformation. Both positive socioecological externalities and financial viability are needed to ensure the success of new technologies aiming to enhance environmental sustainability (Dyck and Silvestre 2018; Aerni 2016; El-Katiri 2014).

Dyck and Silvestre (2018) stated that successful *innovation for sustainability* should be associated with "(i) making rare sustainable innovations commonplace; (ii) making inimitable emerging sustainable innovations transferable; and (iii) developing institutional infrastructures and bundles of resources that counteract the non-substitutability of sustainable innovations" (Dyck and Silvestre 2018: p. 1593). Ensuring these success conditions requires addressing the trade-off between economic, social, and environmental objectives, which again assure the importance of innovation in all aspects of sustainability transformation.

Successful implementation of innovations in environmental sustainability – including responding to climate change – does not depend only on technological innovations. Various changes in individual and societal behaviours, consumption habits, forms of organization, discourses, and institutional arrangements are needed to ensure the success of these new initiatives (George et al. 2016; Praetorius et al. 2009). Consequently, technological innovations that aim to enhance the use of clean energy and respond to climate change should be perceived as *systemic sociotechnical changes.* To theorize and explain these systemic changes, researchers in the field of *innovation for sustainability* developed and adopted multilevel perspective as a distinct theoretical perspective (Hargreaves et al. 2013).

3 Theoretical Framework: Multilevel Perspective

The *multilevel perspective (MLP)* was initially proposed by Rip and Kemp and further developed by Geels (Hargreaves et al. 2013; Praetorius et al. 2009). It is well-accepted now in sustainability innovation studies (Hargreaves et al. 2013; Praetorius et al. 2009). It focuses on innovation strategies needed "to transform the cultural, institutional, social, political, market, industry, infrastructure, technology, and science 'subsystems of society' that are locked-in and characterize the dominant socio-technical regime" (Gliedt et al. 2018: p. 1248). Innovation in this perspective is conceptualized as dynamic and multilayered transformation rather than a linear process (Praetorius et al. 2009). MLP "sees system innovation and transitions as emerging through realignments between the vertical levels of niche, regime, and landscape" (Hargreaves et al. 2013: p. 402). These three levels are distinct in their temporal stability: a *niche* is flexible and fluid, a *regime* is semi-stable, while the *landscape* is more stable and slow to change; however, the landscape provides the context to enable regime stability or change (Gliedt et al. 2018).

Fundamental changes result when the three levels are realigned. The interaction between the three levels can take place in different transition pathways. Some argue that the conventional pathway of transition starts with external pressure at the *landscape* level that is reflected at the *regime* level to open opportunities for innovations at the *niche* level (Hargreaves et al. 2013). However, another pathway of transition starts with niches of deployment, then it diffuses into broader regimes, and if successful they will be embedded in the broader sociotechnical context. At this stage only, the new technology can be perceived as a successful innovation (Praetorius et al. 2009). However, in this chapter, both pathways are considered through the adoption of an iterative conception of the multilevel interaction; different pathways may co-exist and co-evolve to achieve the required change. This iterative interaction is explained in Fig. 11.1.

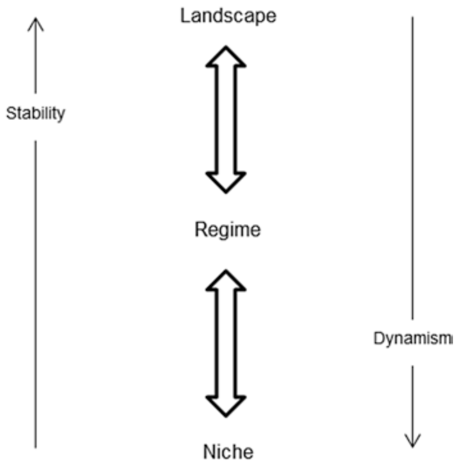

Fig. 11.1 Multilevel theoretical perspective of sociotechnical change

MLP departs from the old dichotomy in social sciences between structure and agency; no one of them is given primacy, instead, both interact dynamically to create social reality. It emphasizes the multiplicity of social actors and the non-linearity of change trajectories. Consequently, to successfully govern social change and innovation toward sustainability, adaptive and reflexive governance forms are needed (Hargreaves et al. 2013). This theoretical perspective enables deep understanding of conditions and causes of successes or failures in sustainability innovation.

In the next section, multilevel perspective is utilized to theorize the transformation toward clean energy in the Middle East region.

4 Transformation Toward Clean Energy in the Middle East

The Middle East region has critical importance in the global energy scene given its richness in oil and gas reserves. The boundaries of the region are not well-defined. Some researchers study the Middle East and North Africa (MENA) as one region. Some researchers include non-Arab countries in the region, while others focus only on Arab countries. The focus of this chapter is on Arab countries in the Middle East which include all Arab West Asian countries in addition to Egypt. These countries can be differentiated based on their position in the global energy market; they can be divided into two groups: Net oil-exporting (NOE) countries (mainly GCC countries) and net oil-importing (NOI) countries.

GCC countries are among the largest emitters of CO2 globally; their per capita emissions are at the top of global records (Seznec 2018; Poudineh et al. 2018a, b; Luomi 2014; van der Zwaan et al. 2013). These high levels are results of the reliance on fossil fuel and the high demand on energy given the hot climate, energy-intensive industries, and desalination demands (Luomi 2014).

All countries in the region have signed the major international convictions and agreements to respond to climate change. However, few countries have communicated their commitments to greenhouse gas (GHG) emissions (Griffiths 2017; Luomi 2014), which indicates that reducing GHG is not likely a primary driving force for energy policies in the region (Griffiths 2017). Nevertheless, the region is part of the world, and it is influenced by the global climate change mitigation efforts (van der Zwaan 2013). As in other regions, these efforts in the region can include "energy efficiency; fuel switching and renewable energy; and carbon capture and storage" (Luomi 2014: p. 34).

In addition to environmental considerations and global commitments, economic factors support the case for transformation toward clean energy in the region. For instance, technological advancement and the continuous decline in renewable energy costs enhanced the case for this transformation (Krupa and Poudineh 2017). In addition to cost minimization, renewable energy enhanced energy security especially in net-oil importing countries (Griffiths 2017). Moreover, the decline in oil prices since mid-2014 encouraged all countries in the region to revise their energy subsidies and consider lower-cost alternatives for their current energy sources

(Griffiths 2017). For net oil-exporting countries, the transition to renewable energy sources can free their hydrocarbon production for export to generate more revenues to meet fiscal challenges (Seznec 2018).

The generous subsidies to energy were common in the region since the independence of its states. This practice led to inefficiency in energy use and inflated demand for energy (Fattouh et al. 2016; Luomi 2014). Consequently, any new policy to reform the energy sector needs to tackle both energy production and consumption. The recent cuts in energy subsidies (in electricity and transportation) in almost all countries in the region help in changing social and business practices toward more efficiency in energy usage. Enhancement of energy efficiency in addition to the adoption of renewable energy may contribute to a successful transition in the energy sector in the region if accompanied by the right policies and actions at different levels. The current trend to cut subsidies and gradually increase energy prices paves the way to reduce consumption, enhance efficiency, and increase the viability of renewable energy in the region (Krupa and Poudineh 2017; Fattouh et al. 2016, El-Katiri 2014).

The Middle East region started its transition journey, which incorporates different aspects. However, coordination and alignment of these different aspects are not evidenced yet. Among these aspects of energy transition, the electricity sector received special attention in the region with relatively successful results. Transitions in this sector are discussed in a special subsection below. On the other hand, reducing the consumption and increasing the efficiency in energy usage form other essential aspects in the transition journey (Luomi 2014). Industrial consumption dominates energy consumption in the GCC countries, while buildings and transportation have a larger share in other countries in the region (Griffiths 2017). Globally, electricity and buildings "have a much better outlook for transition to low carbon energy supply than either the industrial or transportation sectors" (Griffiths 2017: p. 259). Some countries – like UAE and Qatar – are successful in introducing green building practices, for instance (Griffiths 2017).

The Middle East region has a high potential for renewable energy, especially solar energy and – to some extent – wind energy (Seznec 2018; Poudineh et al. 2018a, b; Griffiths 2017; Nematollahi et al. 2016). Besides, some countries in the region have other sources of renewable energy like hydro, geothermal, bio-based, and even nuclear energy (Seznec 2018; Griffiths 2017). However, solar energy is the most prevalent form of renewable energy in the region and has high growth potential, especially in the electricity sector. The next subsection explains the transformation in this sector in the Middle East region.

4.1 Transformation Toward Renewables in the Electricity Sector

Globally, electricity sector gained special attention and priority in the transition toward renewable energy more than other sectors like transportation or heating and cooling (Griffiths 2017). Middle East countries follow the same trend especially that they have good potential for solar and wind energy sources (Griffiths 2017). The last decade witnessed promising successes in using renewables in the power sector. Consequently, the focus now is on the scaling and mainstreaming of successful technologies like solar photovoltaic and onshore wind energy and integrating them in the national and regional energy systems (Griffiths 2017). However, despite the potential and the success of renewable energy initiatives in the region, it still "accounts for just 1% of total primary energy and 3.5% of electricity generation across the MENA. More than 90% of renewables consists of hydroelectricity, whilst non-hydro renewables barely exceed 1% of total electricity generation" (Poudineh et al. 2018a: p. 135).

This low percentage is expected to increase with the short-term and long-term targets that have been set by the countries in the Middle East. For instance, the following targets for renewable energy percentage to total power generation are set to be met by 2020: 16% in Qatar, 5% in Kuwait, and 7% in the emirate of Dubai (Krupa and Poudineh 2017). On the long run, the targeted percentages are more ambitious; "For instance, Kuwait is targeting 15% of electricity demand to be met by renewables by 2030" (Poudineh et al. 2018b: p. 9). These targets are expected to be achieved through some major projects, mainly using solar photovoltaic technology (PV) with few projects use concentrating solar power (CSP) technology (Seznec 2018; Poudineh et al. 2018b). In addition, some countries started planning for installing solar panels on rooftops (Seznec 2018), which diversify the renewable electricity production toward decentralized *prosumption* model.

The transition in the electricity sector is radical. To ensure success, it requires an organized and well-planned approach that aligns political views with economic considerations and policy tools (Griffiths 2017). These policies and plans may include removing subsidies on the use of hydrocarbons, smart demand management systems, and energy trade, in addition to resolving some climatic obstacles that negatively affect the performance of solar panels (e.g. sandstorms and dust) (Seznec 2018; Griffiths 2017). The complexity of this change is explained in the next subsection using the multilevel perspective.

4.2 Multilevel Perspective Framework for Renewable Energy in the Electricity Sector

The transformation of the electricity sector in the Middle East toward renewable energy is in its early stages. The change journey has started. However, the complexity of such a change implies that this journey will evolve in different directions at different levels before it reaches its destination of a stable new energy system that no one knows precisely how it will look like. In the remainder of this subsection, changes at the three levels of the multilevel perspective with regard to renewable energy and electricity sector in the Middle East are discussed.

Landscape

A key issue facing the countries in the Middle East, whether oil-exporting or oil-importing countries, is how to cope with and be part of the radical change in the global energy scene (Fattouh et al. 2018); this change in the global landscape of energy sector calls for actions at different levels in the region. However, any action by these countries should be grounded on long-term national plans and well-defined economic development and energy policy goals rather than being reactive to external factors (Luomi 2014). Historical changes in the global energy sector were opportunity-driven, while the current transition is problem-driven with deliberate planning and coordination to achieve its results in solving contemporary environmental and economic global problems (Fattouh et al. 2018).

Current institutional frameworks in the region "are largely dominated by the oil and gas sector and renewables have yet to be integrated within these" (Poudineh et al. 2018a: p. 10). Therefore, successful transformation toward renewable energy in the region requires an institutional change to align the regional and national landscape with the new global landscape.

Grand initiatives at national and regional levels are needed to support and complement global influences. In such a systemic change, there is a "considerable risk of lock-in in the well-established structures" (Praetorius et al. 2009: p. 37). Consequently, a gradual approach, with clearly defined goals and policy stages, needs to be considered. Countries in the region have completed the initial stage of the envisaged transformation. The priority now is to build on the small steps to achieve profound transformation through a critical mass of projects and comprehensive policy framework (Unctad 2014). Current decrease in oil prices and the associated efforts toward economic diversification may support such a change. These change forces need to be supported by new laws, regulations, and policies, in addition to well-defined national strategies on environmental sustainability.

Regime

Government-affiliated intermediary organizations have a positive role in supporting transformation toward environmental sustainability. These organizations are independent. They are not part of traditional government bureaucracy. Therefore, they have the flexibility needed to support and facilitate the dynamic transformation toward renewable energy. Governmental authorities and government-owned companies play an essential role in the current renewable energy projects. In addition, public-private partnerships are proved to be successful in improving environmental sustainability in various countries (Aerni 2016). In some countries in the region, private sector companies start to contribute to this transition journey.

Effective incentive schemes that are designed to enhance the economic viability of environmental sustainability innovations are needed (Aerni 2016). Such schemes may take the form of tax and customs exemptions or guaranteed purchase by the government as examples of various possible incentives. Moreover, the recent cuts in fuel and electricity subsidies may contribute to creating a favourable position for clean energy technologies. The challenge is to find the optimal option between various alternatives concerning energy markets. For instance, policymakers should decide if renewable energy should compete with current fossil fuel-based energy based on market dynamics or the two sources of energy should be regulated to ensure best social and economic outcomes (Poudineh et al. 2018a). Some researchers recommend a combinational approach that combines both regulative and free-market mechanisms to ensure a smooth transition (Poudineh et al. 2018a). Free competition may be useful for large customers, while regulation protects smaller customers (Poudineh et al. 2018b)

Change at the regime level is the final outcome of sociotechnical change. However, changes at this level are driven by macro changes at the landscape level and micro changes at the niche level. The stability of the new regime depends on the alignment of the three levels and its compatibility with social practices.

At the landscape level, grand strategies and laws related to energy subsidy, internalizing environmental costs in pricing, and incentivizing environmental positive externalities (El-Katiri 2014) affect the practices and systems at the regime level. In addition, since the current momentum for renewable energy in the region is motivated by the low oil prices and since the public finances in the region depend to a large extent on oil prices, substantial changes at the macro level in oil prices may have impacts on renewable energy systems and practices (Krupa and Poudineh 2017).

At the niche level, technology development and the outcome of the competition between different technologies will have an impact on practices and systems at the regime level. These technologies are not limited to those directly related to energy production, distribution, and consumption. For instance, developments in big data, internet of things, and smart intelligence technologies can advance specific applications in energy systems and direct them toward certain directions (Poudineh et al. 2018b).

The result of this interaction at the three levels and between them will shape the new energy system in the region. However, energy production, distribution, and consumption are connected and embedded in resilient social practices. Successful technological innovations are not enough to ensure the success of new practices. In the region, common social practices related to transportation, consumption, leisure, doing business, governmental spending, and other areas of social activities are developed, established, and gained resilience based on assumptions and habits incongruent with clean energy. Consequently, any success in transformation toward renewable energy requires effective policies and actions to change the resilient social practices and introduce new ones that are congruent with environmental sustainability concerns. Such policies and actions may include increasing the cost of fossil fuel energy, lowering the cost of renewable energy, providing a legal framework for decentralized energy generation, supporting the use of energy-efficient technologies, launching effective and affordable public transportation solutions, in addition to other policies and actions. Consequently, communication is essential to ensure successful change in social practices and public acceptance of the new transition (Poudineh et al. 2018b).

Niche

At the *niche* level, policies are required to support local businesses and researchers to explore, develop, and disseminate new ways of doing things to advance the use of renewable energy. As discussed in the first section, these new ways are not limited to technologies; they may include new ways of organizing, financing, operating, or performing different aspects of energy generation and consumption. In most Middle East countries, innovation practices are not well-developed yet (Cornell University, INSEAD, and WIPO 2017). However, the region witnessed the establishment of some leading research centres dedicated to research and innovation in sustainable practices (Seznec 2018). The challenge is to support these centres, commercialize their research outputs, and align them with other aspects of the transition at the three levels of the sociotechnical change.

Moreover, innovation of new economic products and practices at the niche level may take the form of importing new technologies and introducing them to the region. Such an approach is still innovative since it needs new business practices (Aerni 2016). Governments can encourage local firms to start importing technologies and liaising with the leading international companies in the field, while local firms can take care of the downstream services and support activities.

Oil-exporting countries in the region have accumulated experience and technical knowledge in the hydrocarbon energy sector. They face a real challenge now to develop their own technologies in the renewables (Seznec 2018). The region till now depends on imported technologies. Recently, the decline in Chinese technology prices, especially in solar PV panels, has an essential role in spreading solar technology globally. However, some companies in the Middle East already accumulated good experience and started to build their own projects which indicate that there is an opportunity for local technological expertise to develop in the region (Seznec 2018).

Public action at the niche level should be in line with actions at other levels. A comprehensive strategy is needed to ensure the alignment of all levels. At the *niche* level, this strategy may include three priorities: “articulation of expectations and visions, building of social networks and learning processes” (Kivimaa 2014).

Figure 11.2 illustrates the transformation toward clean energy in the electricity sector in the Middle East based on the multilevel perspective

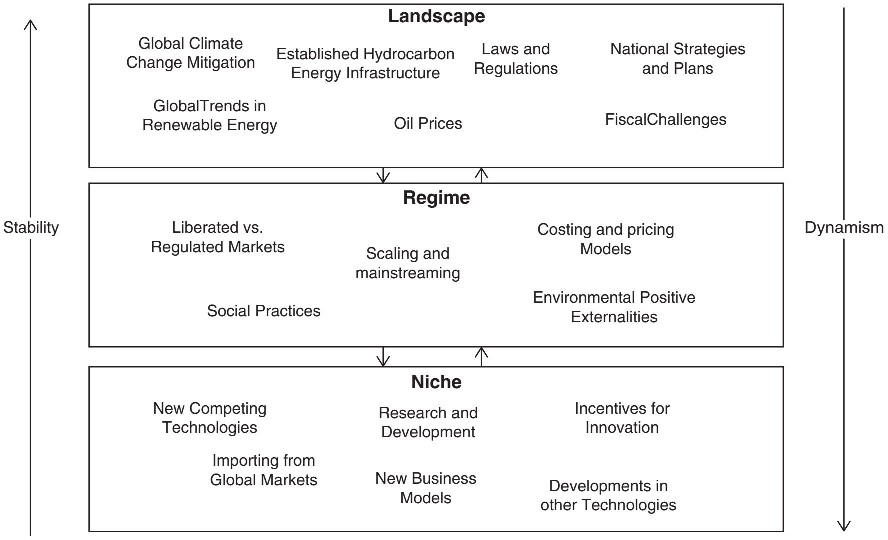

Fig. 11.2 Transformation toward clean energy in the electricity sector in the Middle East: a multilevel perspective

5 Conclusion

Despite the relative success of some initiatives, the lack of well-developed policy frameworks and instruments to support renewable energy projects forms a barrier to developing renewable energy in the region. In addition, for a long time, the electricity sector in the region (and other sectors like transportation) depends on fossil fuel. Consequently, changing the established behaviours, practices, and infrastructure will take time. However, the recent cuts in subsidizing fossil fuel prices may create a new context in favour of renewable energy generation and efficiency in energy usage.

Referring to the multilevel perspective theoretical framework for explanation, it is found that transformation toward clean energy in the region started at the landscape level as a response to global trends and extended to the regime level through the initiation of new projects, while changes at the niche level are characterized mainly by adopting new technologies developed and launched internationally. Moreover, a material change is not attainable without changing resilient social practices, especially in consumption, urbanization, and transportation. There are some efforts toward this change, but they are sporadic and isolated changes without comprehensive policies to ensure coordinated and integrated transformation.

The transformation in the region is mainly reactive and motivated by external factors. It is driven by initiatives from governments. In fact, this is identical to innovation practices in the region in general. Research and development is not a priority for firms in the region. However, new technologies are introduced through cooperation with international partners, thanks to the economic openness of most economies in the region that encourages internationalization and introduces dynamic change. To enhance this dynamism and accelerate its pace, effective incentive policies are needed to align the three levels of landscape, regime, and niche and to ensure that changes in social practices are in line with vertical sociotechnical change. Global Innovation Index states clearly that most countries in the region have sufficient institutional strengths to support innovation. What is needed is capitalizing on these strengths to introduce effective innovation practices (Cornell University, INSEAD, and WIPO 2017). The transition toward renewable energy forms a good opportunity for the Middle Eastern countries to develop their innovation capabilities given that technologies in this sector are not mature yet and given the competitive position of this region in traditional and renewable energy sectors. What has been achieved in the region forms a good start of the transformation. However, continuous efforts and coordinated plans and policies are needed in the next decade to ensure that transition toward renewable energy is an opportunity for the region rather than a threat.

Further research is needed to understand the social, economic, and institutional aspects of the transformation toward clean energy in the Middle East. Studies that document and analyse specific cases in the region can contribute to knowledge and provide a solid empirical base to inform energy-related policy development and planning in the region.

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Chapter 12
Global CO_2 Capture and Storage Methods and a New Approach to Reduce the Emissions of Geothermal Power Plants with High CO_2 Emissions: A Case Study from Turkey

Fusun S. Tut Haklidir, Kaan Baytar, and Mert Kekevi

Abstract CO_2 gas is a main cause of the greenhouse effect, with atmospheric concentrations reaching 405 ppm in 2018. The main sources of CO_2 around the world are electricity production, heating, industrial purposes, and transportation. One of the critical factors, global energy-related CO_2 emissions, increased to 32.5 Gt in 2017. However, carbon capture technologies have improved and carbon storage methods are beginning to be used widely around the world. One option to minimize the effects of CO_2 gas is converting it into another product.

In addition to carbon emissions due to hydrocarbons, geothermal power plants, which have the highest capacity among renewables sources, emit non-condensable gases such as CO_2 and H_2S at high concentrations, based on geothermal reservoir characteristics and power cycle type. In Turkey, Italy, and some African countries that have important geothermal sources, geothermal-based CO_2 gas emissions are greater than elsewhere in the world.

In Turkey, the country's 40 installed geothermal power plants produce energy by different power cycles, such as binary, single, and multi-flash systems. The total installed capacity was approximately 1200 MWe in 2018 and is expected to reach to 4000 MWe in 2030. The non-condensable gases emitted from these plants are composed of 95–98% CO_2 gas and are due to the reservoir rocks, such as marble and

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H. Qudrat-Ullah, A. A. Kayal (eds.), *Climate Change and Energy Dynamics in the Middle East*, Understanding Complex Systems,
https://doi.org/10.1007/978-3-030-11202-8_12

limestone from Paleozoic-aged Menderes metamorphic rocks. CO_2 emissions emitted by the geothermal power plants range from 900 to1300 gr/kwh and are inevitable because of the use of open cycles in Western Anatolia in Turkey. Only a small amount of waste CO_2 emissions have been used to produce dry ice in the region. However, Turkey is one of the countries that is required to reduce emissions according to the Kyoto and Paris Climate Agreements.

A global problem is the capture of CO_2 gas and its storage or conversion to another product, which has been studied by researchers for a long time. A solution may be biofuel production from geothermal-based CO_2 in countries with geothermal power plants that are high producers of CO_2 emissions, such as Turkey and Italy. In this study, a conceptual design of the Helioculture process is applied to geothermal power plants to produce biofuel by CO_2. The Helioculture process is a new approach by which it is possible to produce biofuel or ethanol using a photobiocatalytic process. The process uses solar energy and waste CO_2 to catalyze the direct-to product synthesis of renewable fuel. It is evaluated with applicable technology for high-CO_2 producing geothermal power plants, such as the Kızıldere (Denizli) geothermal field in Turkey. Based on the results, Helioculture-based fuel production may be five times greater than traditional biodiesel production in the region.

Keywords CO_2 emissions · CO_2 capture and storage · Geothermal power plant · Ethanol · Biodiesel · Hybrid system · Turkey

1 Introduction

With the beginning of the Industrial Revolution in the 1750s, humanity entered an age of industrialization with the invention of new machinery, factories, and mass production. All these facilities used water, wood, and steam as energy sources for their systems. The transition from these traditional energy sources to fossil fuels was the beginning of a new era of progression and prosperity on a scale that humanity had never before seen. However, these carbon-based energy resources have caused a significant imbalance in the world's ecosystem in recent years. The main cause of this imbalance is the gasses emitted from burning fossil fuels, which are called greenhouse gases. According to a report from the Intergovernmental Panel on Climate Change (IPCC), carbon emissions due to the combustion of fossil fuels, industrial processes and changes in land use have increased CO_2 concentrations, which caused global warming and thus climate change (Metz et al. 2007).

Although almost negative environmental effects of fossil fuels are widely known and accepted, it has been difficult for people to stop using fossil fuels due to increases in energy demands, especially abundant and easy-to-reach coal deposits. However, after the energy crisis in 1973, it became apparent that the use of renewable energy sources is important; in particular, wind, solar, and geothermal sources started to be used more widely around the world. The implementation of the Kyoto Agreement in 2005 and the Paris Climate Agreement in 2017 were important steps to reduce carbon emissions around the world. Today, de-carbonization is becoming an important term in all industrial sectors, and companies' awareness of their carbon footprints is increasing around the world. The use of alternative energy sources and technologies, including renewable energy, nuclear power plants, and new vehicle technologies such as electrical and hydrogen fuelled cars, has become even more important for the future of the world.

2 Carbon Cycle and Carbon Inventories of the World

Carbon is an essential element that helps to build life; all living creatures on earth are carbon-based. Essentially, we are living in a carbon-based world, as carbon-based living beings. Most of the carbon in the world is trapped in sediment rocks, the atmosphere, and the ocean. Carbon moves through these reserves in different periods of time and different amounts, which creates the global carbon cycle (Fig. 12.1).

The carbon cycle on earth can be analyzed as two segments: the geological process (which takes millions of years) and the biological/physical processes (which take days to thousands of years). The total carbon in the cycle can be separated into four categories: atmosphere, biosphere/soil, oceans, and lithosphere.

The carbon concentration in the atmosphere is mainly in the form of CO_2 and other forms of 780 Giga ton (Gt)-C to make 5*107 Gt-C, of which 4000–6000 Gt-C originates from fossil fuels (Rackley 2010). Much of the carbon was stored in the

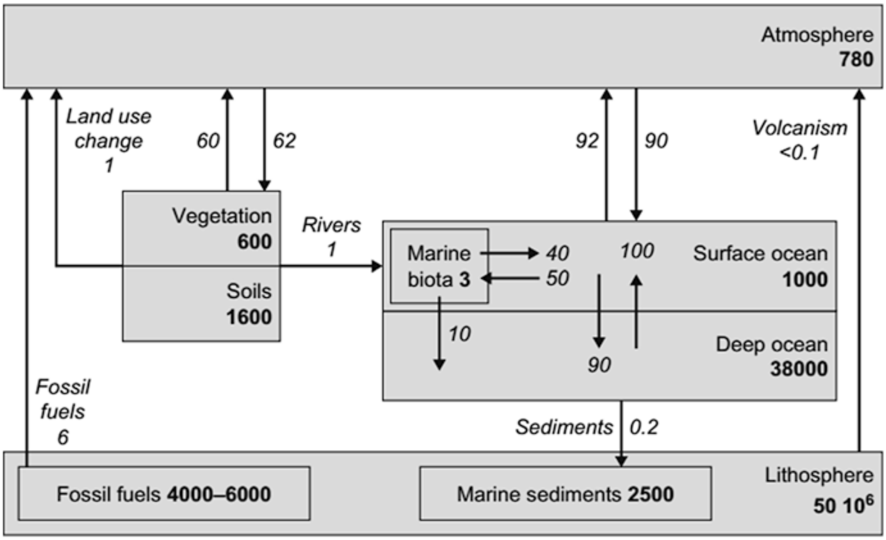


Fig. 12.1 Inventories and fluxes in the carbon cycle (Gt-C/year; Rackley 2010)

mantle when the earth was formed; meteorites also contributed to increased carbon levels on the planet. Carbon in the atmosphere dissolves in the surface waters of the earth and creates carbonic acid, which is later combined with minerals in the crust of the earth to create insoluble carbonates. These carbonates settle at the surface of the deep ocean by subduction and lithospheric plates of the earth contain these carbonates, which cascade under each other based on plate tectonics theory. Volcanic activities release these carbonates back into the atmosphere at the edge of the tectonic plates. Thus, weathering processes, subduction, and volcanic activities create the geological carbon cycle.

Biological activities play a vital role in the global carbon cycle; these activities can be categorized as photosynthesis and respiration. Different plants, certain algae, and bacteria use stored carbohydrates as a source of energy; they produce these carbohydrates by combining CO_2 from the atmosphere and water with the help of the energy of sunlight, as photosynthesis. The main source of CO_2 due to human activities is fossil fuels used in electricity generation, transportation, and heating purposes. CO_2 is being exchanged between the world's ecosystems in a balance with no human intervention. Since the beginning of the Industrial Revolution in 1750, many heat-trapping gasses have been added into the atmosphere, including CO_2, which contributed to climate change in the 1900s.

3 The Greenhouse Effect and the Role of CO_2

The greenhouse effect is a natural process that tends to heat Earth's surface. Thermal radiation comes from the sun and is absorbed by greenhouse gasses, which causes an increase of the temperature of atmosphere (Fig. 12.2). CO_2 is the most influential greenhouse gas, even though it comprises only 0.03% of the atmosphere; however, just this small amount causes a temperature increase of the earth.

Heat is absorbed above the atmosphere by greenhouse gases and that heat radiation is captured at the surface. Ultraviolet radiation passes greenhouse gases, so the surface gets warm before the atmosphere. Thus, molecules of greenhouse gases capture heat and send their heat to the earth's surface (Fig. 12.2). The earth's surface temperature has increased 1 °C since the Industrial Revolution, where a 2 °C temperature increase has been agreed by the United Nations to be the limit for CO_2 levels. Direct measurements show that the CO_2 concentration is still increasing, which directly affects global land-ocean temperatures and sea levels (Fig. 12.3). CO_2 is the most critical gas of the greenhouse gases (Fig. 12.4). The concentration of CO_2 reached 405 ppm in 2018. The goal of the climate agreements is to reduce the concentration to less than 350 ppm.

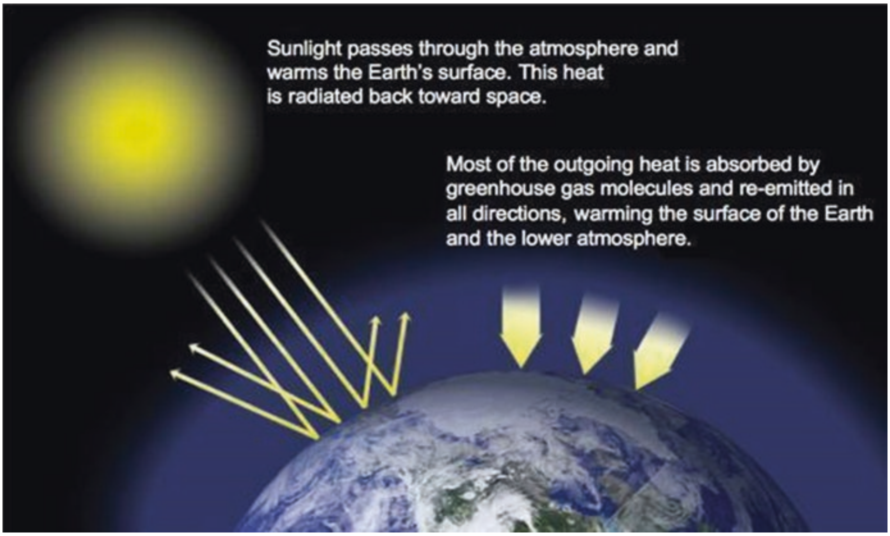


Fig. 12.2 Occurrence of greenhouse gases (NASA 2015)

Naturally, CO_2 concentrations are at a balance in the atmosphere. Volcanoes, hot springs, carbonate rocks, and the respiration of all aerobic organisms are some natural CO_2 producers. However, human activities have been increasing carbon emissions, thus disturbing the balance of the carbon cycle on the earth. The combustion of fossil fuels is the main reason for increased CO_2 emissions due to energy production, transportation, and industrial processes (Fig. 12.5).

The largest proportion CO_2 emissions is from electricity generation and heating because coal is used widely around the world. Coal is still abundant and is an inexpensive fuel for the world. Manufacturing and transportation are other important manmade CO_2 producers.

Depending on the emission scenario, the world's average temperature is predicted to increase between 2 °C and 6 °C by the end of the twenty-first century (NASA 2015). According to IPCC's climate model, there may be three main emission scenarios regarding future global surface warming (Fig. 12.6): low, moderate, and high growth.

Greenhouse gasses are not the only contributors to global warming, but they are stimulating different mechanisms in nature. The most well-known effect is the melting of glaciers in the Arctic sea. Although the increased CO_2 levels in the atmosphere may enhance the plant growth in some ecosystems, the plants' growth is usually limited by water, nitrogen, and temperature. For this reason, it is not clear how much carbon dioxide will be absorbed by plants around the world (NASA 2015).

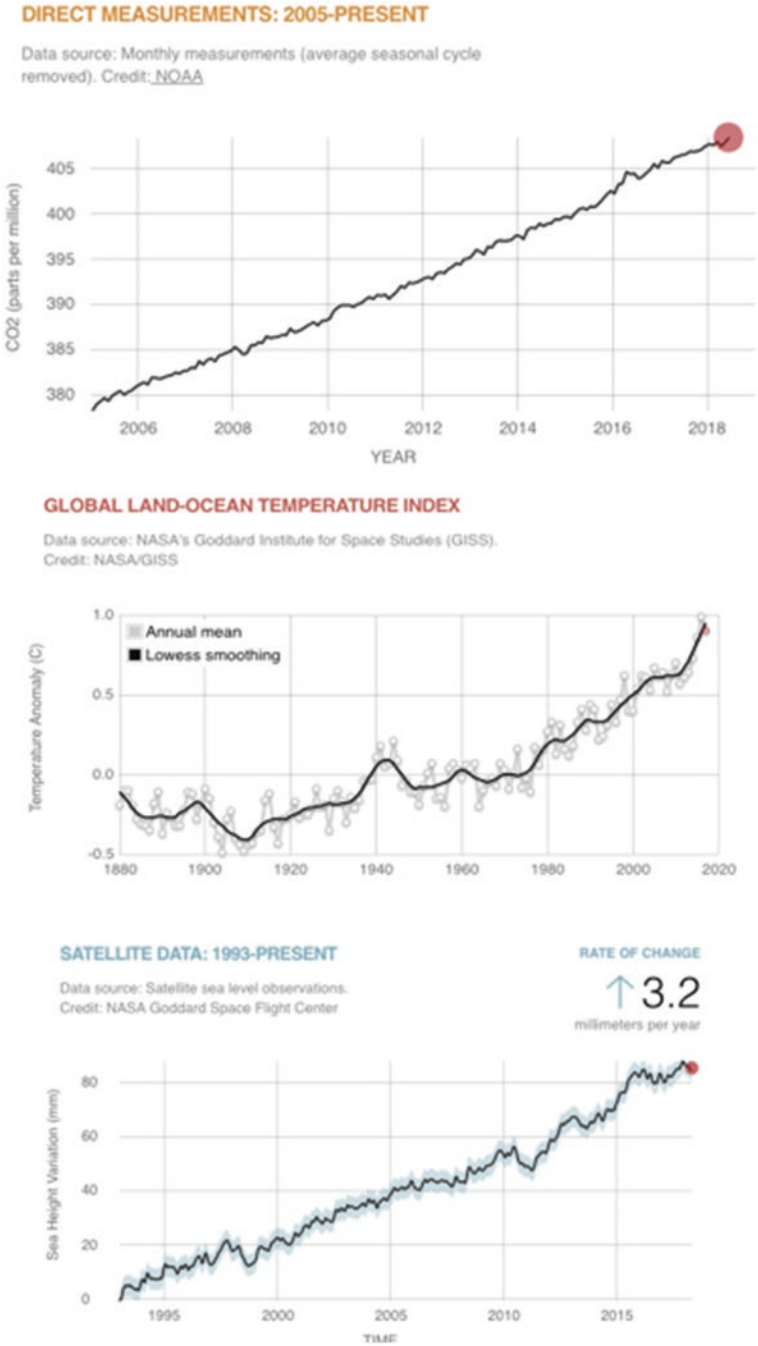
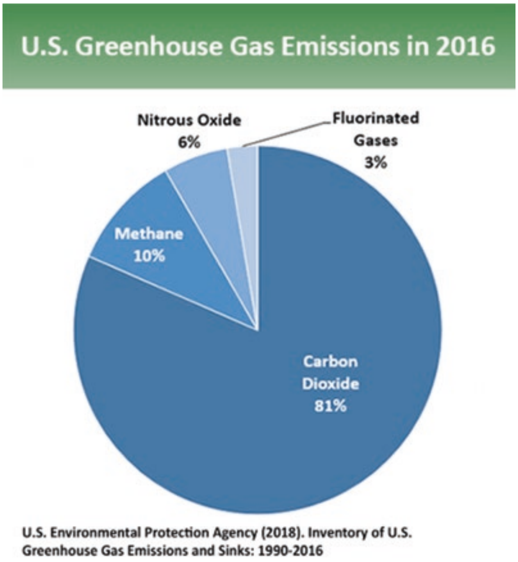


Fig. 12.3 The relationship between CO_2 concentration, annual temperature anomalies, and sea level (NASA 2018)



U.S. Environmental Protection Agency (2018). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016

Fig. 12.4 Greenhouse gas emissions in the United States in 2016 (https://www.epa.gov/ghgemissions/overview-greenhouse-gases)

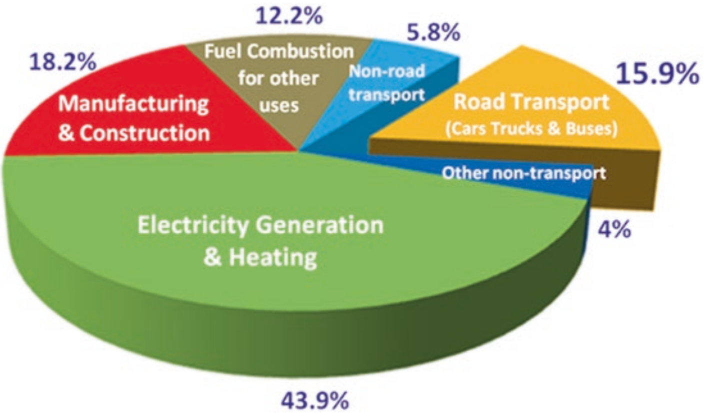


Fig. 12.5 Man-made CO_2 emissions (http://www.oica.net/category/climate-change-and-co2/)

3.1 The CO_2 Controlling Policies

Kyoto Protocol and Paris Climate Agreement

The Kyoto Protocol is an agreement between countries about reducing greenhouse gas emissions to the decided target levels. It was first endorsed on 11 December 1997 in Kyoto (Japan) and put into practice on 16 February 2005. The protocol is discussed in the United Nations Framework Convention. There are two commitment periods and target levels of emissions in the agreement. For the first period, it was decided that 37 industrialized countries and the European Union need to reduce

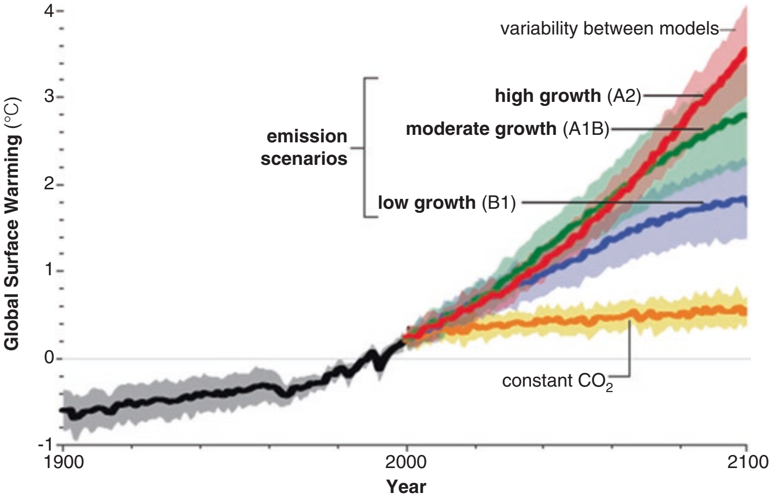


Fig. 12.6 Possible Future Scenario of Global Surface Warming, NASA (2015)

their emissions to 5% less than the levels in 1999. This was the first important step for decarburization around the world. The second important step is the Paris Climate Agreement, signed by 175 countries in 2016; that number has since increased to 180 countries in 2017's United Nations Framework Convention on Climate Change (UNFCCC) (2018).

The agreement outlines a global action plan to climate change around the world. The governments agreed on the following: a long-term goal of a reduction of 2 °C above pre-industrial levels; a focus to maintain the increase to 1.5 °C for significant climate change effects; the need for global emissions to peak as soon as possible; the need to identify the total risk for developing countries; and the need to make quick reductions in suitability with the best available science.

4 Carbon Capture Methods and Technologies

CO_2 emissions have to be reduced by 50% to balance a temperature increase limitation of 2–3 °C, according to the IPCC. Based on the Blue Map of the International Energy Agency (Rackley 2010), the capture of CO_2 will play an important role in reducing emissions to 14 $GtCO_2$ by 2050, within a wide range of reduction measures (Fig. 12.7).

If the CO_2 reduction goals are successful, then carbon capture and storage technologies must reduce emissions by approximately 8.2 $GtCO_2$. Carbon can be captured in different ways depending on the sector, including carbon capture from industrial processes, absorption capture systems, adsorption capture systems, membrane separation systems, cryogenic and distillation systems, and mineral

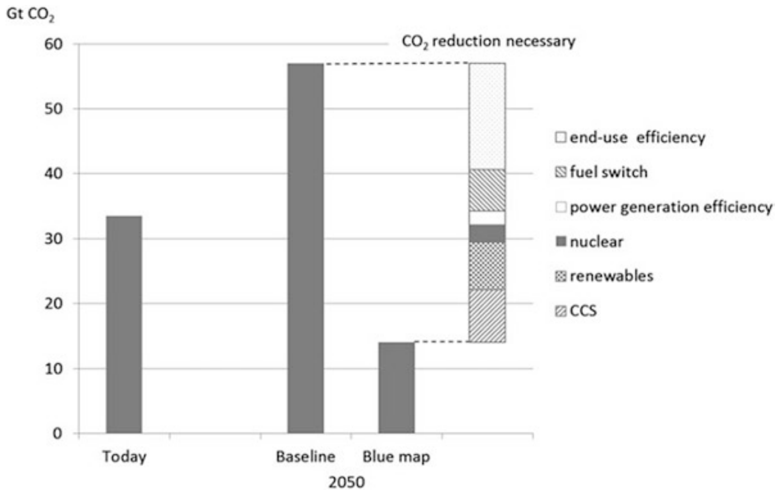


Fig. 12.7 The International Energy Agency's Blue Map scenario (Rackley 2010)

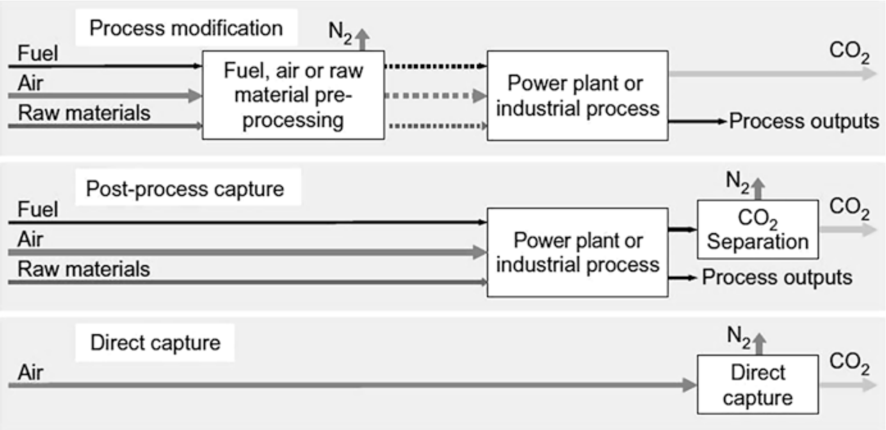


Fig. 12.8 Main approaches to CO_2 capture (Rackley 2010)

carbonation. This chapter is focused on CO_2 emissions from power plants, for which the main approaches to CO_2 capture are as follows:

- Pure CO_2 by re-engineering a process to generate such a stream (power plant, pre-combustion fuel gasification)
- Separation of CO_2 and N_2 to capture CO_2
- Direct air capture of CO_2 (Fig. 12.8).

Currently, three main technologies are used for in CO_2 capture: post-combustion, oxyfuel combustion, and pre-combustion. All of these methods have some advantages and disadvantages (Table.12.1). Possible applications of the methods are given for a coal-fired power plant in Fig. 12.9.

Table 12.1 Advantages and disadvantages of CO_2 capture technologies (Rackley 2010)

Capture option	Advantages	Disadvantages
Precombustion	Lower energy requirements for CO_2 capture and compression	Temperature and efficiency issues associated with hydrogen-rich gas turbine fuel
Postcombustion	Fully developed technology, commercially deployed at the required scale in other industrial sectors	High parasitic power requirement for solvent regeneration
	Opportunity for retrofit to existing plant	High capital and operating costs for current absorption systems
Oxyfuel combustion	Mature air separation technologies available	Significant plant impact makes retrofit less attractive

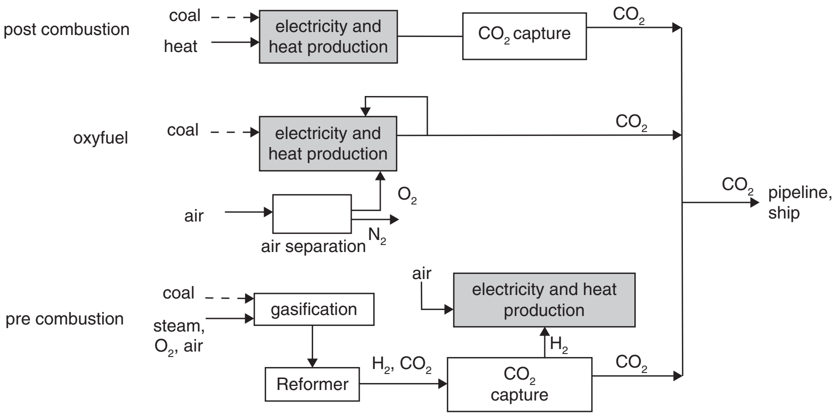


Fig. 12.9 Principles of carbon capture technologies (Surampalli et al. 2015)

4.1 CO_2 Separation and Capture Technologies

Carbon separation is mainly provided by sorbents, solvents, membranes, and other technologies such as distillation, refrigeration, and cryogenics (Fig. 12.10).

Absorbents

During combustion in a power plant, flue gases have a high temperature and need to be cooled to 40–60 °C for absorption (Verma et al. 2015). The first step is to separate CO_2 in the absorption chamber (Fig. 12.11). Enriched and cooled CO_2 solvent is sent to the desorber chamber. The chemical adsorption of CO_2 has been used for natural gas by chemical industries.

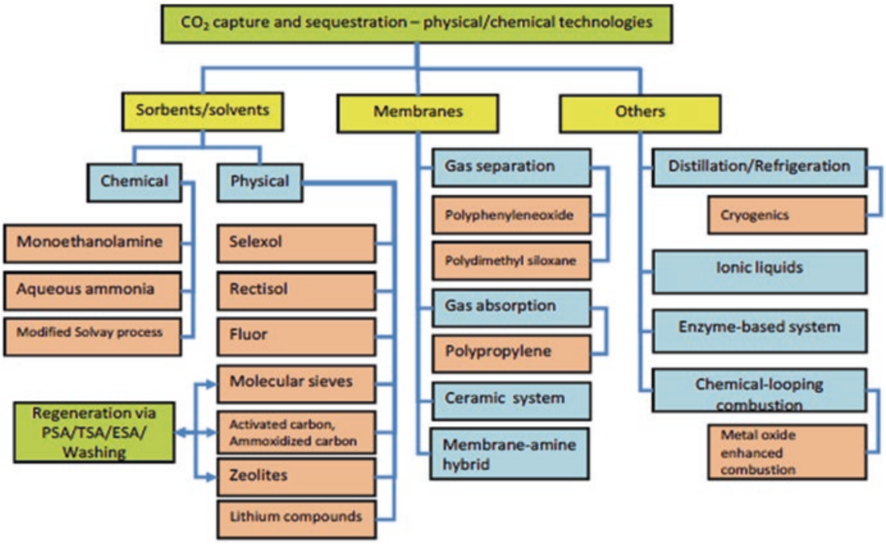


Fig. 12.10 CO_2 separation and capture technologies: pressure swing adsorption (PSA), temperature swing adsorption (TSA), and electric swing adsorption (ESA) (Verma et al. 2015)

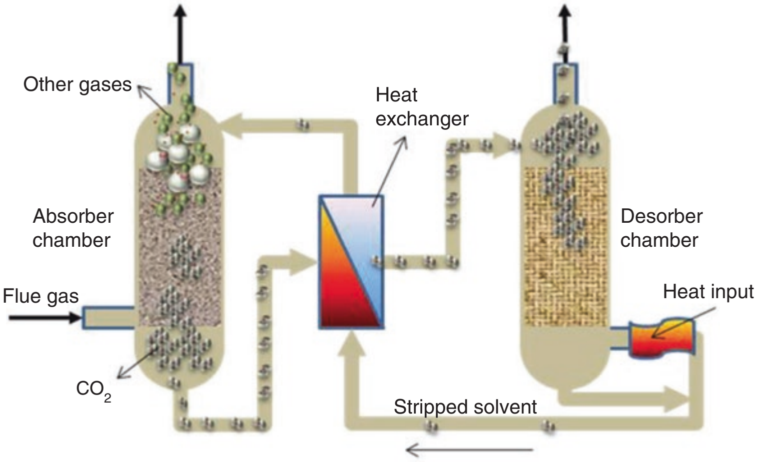


Fig. 12.11 CO_2 separation from flue gases by absorption (CO2CRC 2010, Verma et al. 2015)

Adsorbents

CO_2 may also be obtained from flue gas using non-reactive sorbents, such as carbonaceous materials and zeolites (Hinkov et al. 2016). CO_2 adsorption depends on temperature, pressure, surface force, and pore size parameters. Thus, the gas is adsorbed by the many layers for regeneration. Physical or chemical adsorbents can be used for the CO_2 capture (Yu et al. 2012); Fig. 12.12).

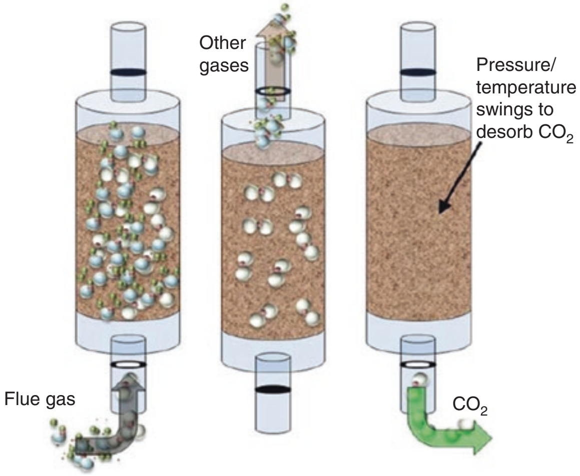
This method of CO_2 capture is not preferred for use in large-scale power plants and industrial areas because of the low and limited selectivity for CO_2 (Surampalli et al. 2015).

Cryogenic Distillation

CO_2 can be captured from flue gases by cryogenic carbon removal methods in a liquid form. In this method, compression, cooling, and expansion are critical stages for the capture. Flue gases such as H_2O, NO_x, SO_x, and O_2 are taken away in this method, excluding N_2. In the sequence, temperature and pressure are increasing and decreasing to liquefy CO_2 (Fig. 12.13).

The aim of this method is to condense CO_2 to be solid and remain in gaseous form at the same time, while N_2 remains in the gaseous phase. The main advantage of this method is its high recovery of CO_2. It is easy to transport liquid CO_2 for industry or storage in oil and gas reserves.

Fig. 12.12 CO_2 separation from flue gases by adsorption (Surampalli et al. 2015)



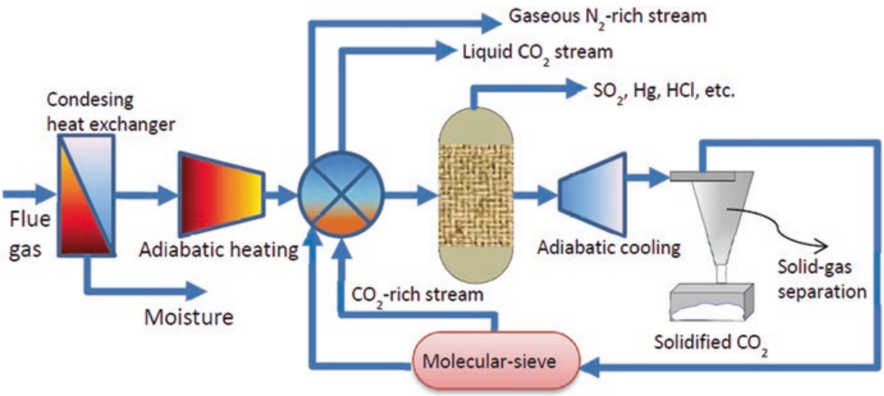
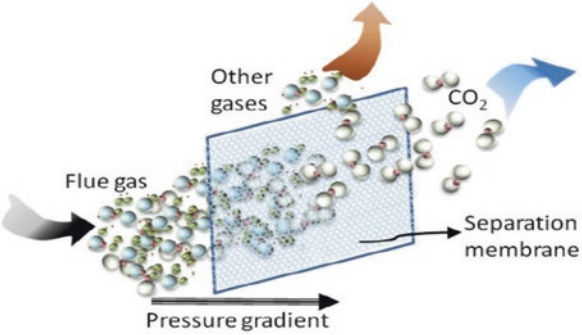


Fig. 12.13 Schematic diagram of cryogenic capture (Baxter 2009, Surampalli et al. 2015)

Fig. 12.14 Gas separation membrane (Surampalli et al. 2015)



Gas Separation by Membranes

The principle of using a membrane is based on the permeability of the required components' different porous forms in a system. The efficiency of the separation depends on the selection of a membrane material with higher permeability.

The gas mixture is fed inside a hollow section of a separator at an elevated pressure. The CO_2 preferentially infiltrates these membranes and is recovered at a reduced pressure on the other side of the separator as filtered, whereas the rest of the gasses are recovered as unfiltered in the system (Fig. 12.14). There are several advantages to using a method with membranes: high packing density, high flexibility with flow rate and absence of foaming, channeling, transportability, durability, and entrainment.

The membranes may be recycled in pre-combustion, oxy-fuel combustion, and post-combustion methods and can be used to separate CO_2 from hydrogen, CO, natural gas, and flue gases.

5 Carbon Storage Technologies and CO_2 Utilization

Carbon capture and storage (CCS) technologies are the most critical components in the decarburization of power generation and industrial sectors. CCS technologies directly involve the capture of CO_2 emissions (especially from coal power plants, cement factories, or steel production blast furnaces), the transport of captured CO_2, and storage in onshore or offshore geological structures; these technologies have been studied since the 1970s (IPPC 2014, Galan et al. 2014). They have been proposed as a good way to reduce anthropogenic CO_2 levels in the atmosphere. CCS research has been accelerated since the 1990s, corresponding to the dramatic increase of CO_2 concentrations in the atmosphere. IEA (2016) predicted that approximately 90 Gt of storage capacity will be required if CCS is to contribute to a 12% emissions reduction; in 2050, that may equate to approximately 6 Gt per year (Consoli and Wildgust 2017).

Converting a pure CO_2 storage process to value-added CO_2 injection process and possibly accelerating the implementation of CCS has attracted interest worldwide (Wei et al. 2015). Certain sectors that require large amounts of CO_2 gas have great motivation to implement large-scale CO_2 storage at a reasonable cost because it can help to reduce CO_2 emissions at the same time. This provides different storage opportunities, including enhanced oil recovery (CO_2-EOR), natural gas recovery (CO_2-EGR), coal-bed methane (CO_2-ECBM), shale gas (CO_2-ESGR), geothermal energy (CO_2-EGS), and in situ uranium leaching (CO2-IUL) (Zhang and Huisingh 2017).

Before the storage of captured CO_2, transportation to geological storage sites or other areas is a critical step. Trucks and ships are some transportation options, along with pipelines (although they have leakage risks and high transport costs). Pipelines have been evaluated to be the most applicable transportation method; in particular, the oil industry in the United States has transported up to 5000 km of CO_2 by pipelines (Ming et al. 2014). The transportation of CO_2 faces some technical problems, such as pipeline integrity, flow assurance, and safety and operational issues. The most cost-efficient transportation method is to compress the gas under supercritical conditions (at 80–150 bar), where it exists in liquid form at 900 kg/m^3 (Pires et al. 2011).

5.1 Geological Storage

Geological storage is a carbon storage method for capturing CO_2 in naturally occurring underground reservoirs. It is the only carbon storage method that has been commercially used. For the geological storage of CO_2, oil and gas industry methods can be used, such as well-drilling technologies, injection technologies, computer simulation of reservoirs, and CO_2 monitoring technologies. In addition, previous experience from natural gas storage, acid gas disposal, and disposal of oil-field

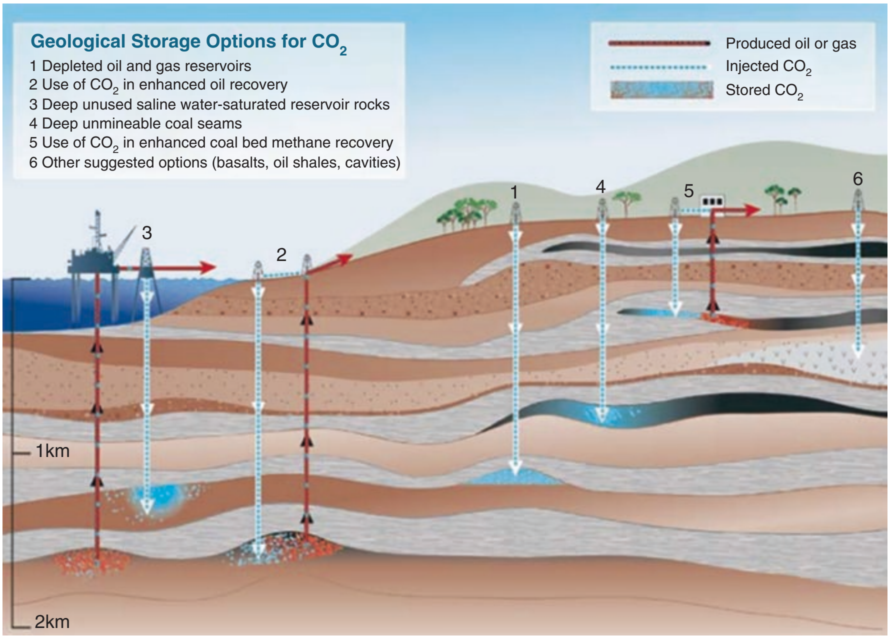


Fig. 12.15 Options for storing CO_2 in deep underground geological formations (Cook 1999, IPCC 2005)

brines are crucial sources of information for constructing long-term storage projects (Fig. 12.15).

Existing capture practices concerning injection and/or underground storage of CO_2, such as the Sleipner (North Sea), Weyburn (Canada), and Salah (Algeria) projects, suggest that underground storage of CO_2 is a feasible option in naturally occurring geological formations. Approximately 1 Mt/CO_2 per year has been injected at the Sleipner project, 1–2 Mt/CO_2 at the Weyburn project, and 1.2 Mt/CO_2 at the Salah project (IPCC 2005). Indications from these projects and elsewhere in the oil and gas industry suggest that at least 99% of the CO_2 stored in the carefully selected underground reservoirs is considered to be preserved for approximately 100 years. The cost of the geological storage varies based on certain factors, such as depth of the reservoir, the number of wells needed, and whether the storage will be onshore or offshore. The total costs vary roughly between 0.6 US \$/tCO_2 and 8.3 \$/tCO_2 (Rackley 2010).

The trapping mechanisms play a crucial role in the effectiveness of the CO_2 storage. The ideal storage site must be able to keep the stored CO_2 trapped and immobile under a seal with low permeability. Tectonic and gravitational forces can cause deformation and faulting of the sediments, which results in various structural features. A structural trap occurs when these structural features prevent upward movement of the fluids (mainly water with small amounts of oil and natural gas) to the surface.

Hydrodynamic storage is another physical trapping method. Saline formations are porous rocks that are filled with brine. CO_2 can be dissolved in fluids in saline formations with no physical trapping. The fluids in saline formations migrate very slowly over long distances; it would take millions of years for them to reach the surface, which makes them suitable media for CO_2 storage. Another geological CO_2 storage method is residual gas trapping. CO_2 is injected into the pore spaces of rocks, becoming immobile and trapped when the saturation of CO_2 is less than the residual gas saturation. This method was recognized recently and is very important for the security of CCS (Rackley 2010).

CO_2 can go through some chemical interactions with the rocks and formation water (water that occurs naturally in the pores of rock). CO_2 can be dissolved in the formation water and be converted into stable carbonate minerals, becoming a part of the solid mineral matrix. This process is called geochemical storage. Although the process is slow, the great capacity and permanence of the storage makes up for it.

The chemical reaction of geochemical storage is as follows:

(i) $CO_2(g) + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^{-} + H^{+} \leftrightarrow CO_3^{2-} + 2H^{+}$

Before the geological storage of CO_2, a detailed site selection must be conducted and the capacity of possible capture volume predicted. The available data vary depending on the formation type of the storage site (e.g., oil/gas reservoirs, coal bed reservoirs, saline formations). Although in general there are more data available for oil and gas fields compared to the saline formations due to vast experience in the oil and gas industry, there are many examples of saline formations for which the site characterizations of large areas were predicted accurately. To predict the performance, the potential storage sites must be characterized in terms of geology, geochemistry, hydrogeology, and geo-mechanics. In addition, the layers above the storage site also must be analyzed. The data gathered from the site, directly from the reservoir, are used to create a detailed reservoir simulation for the capture.

5.2 CO_2 Utilization Options

CO_2 utilization is an alternative to storage when captured CO_2 can be used as a commercial product, either directly or after a conversion process. These applicable alternatives include the direct utilization of CO_2, the conversion of CO_2 gas into chemicals and fuels, mineral carbonation, and biofuels from microalgae (Cuellar-Franca and Azapagic 2015).

A few industries use CO_2 gas directly, such as in the preservation or preparation of foods and beverages, pharmaceutical processes, and decaffeination processes. CO_2 can be utilized by processing and converting it into chemicals or fuels. It can replace petrochemical feedstocks in the production phase of chemicals, such as the Fischer–Tropsch process (Steynberg and Dry 2004) and fuels. Mineral carbonation is a chemical process in which CO_2 reacts with a metal oxide, such as magnesium or calcium, to form carbonates (IPPC 2005). In this method, the use of pure CO_2 is

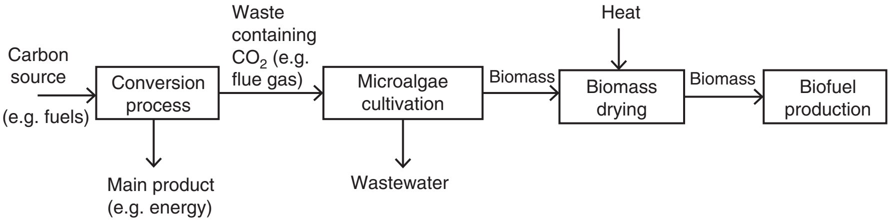


Fig. 12.16 CO_2 utilization to produce biofuels from microalgae (Cuellar-Franca and Azapagic 2015).

not required for mineral carbonation because the presence of impurities will not interfere with the carbonation reaction. The main advantage of this method is the formation of stable carbonates that are capable of storing CO_2 for long periods without the risk of CO_2 leakage IPPC (2005). New studies show that some carbon minerals, such as ikaite ($CaCO_3.6H_2O$), can be stored in sea water or basalts in ocean ridges (Stockmann et al. 2018; Snæbjörnsdóttira et al. 2014).

CO_2 can be used to cultivate microalgae used for biofuel production (Li et al. 2008; Brennan and Owende 2010; Cuellar-Franca and Azapagic 2015). Micro-algae can take CO_2 directly from waste streams, such as flue gas or cooling tower gas, as well as use nitrogen from the gas as a nutrient (Fig. 12.16). The conversion of CO_2 into fuels can be carried out by thermochemical or biochemical reactions. This process is also suitable for geothermal reservoirs with high non-condensable gases (Haklıdır Tut 2018).

6 Greenhouse Gas Emissions Due to Power Plants

Power plants can be categorized into two groups: conventional power plants (fossil fuel–based and nuclear power plants) or renewable energy power plants (e.g., wind farm, solar photovoltaic, concentrated solar, geothermal, biomass, hydroelectric). A global trend is de-carbonisation; to reach to the climate goal, renewable energy sources are now also widely used for power production. Life cycle assessment (LCA) is used to calculate the emissions. This assessment uses the following items to calculate emissions: fuel production and transportation, facility construction, facility operations and maintenance, and dismantling (Amponsah et al. 2014).

Greenhouse gases (GHG), such as CO_2 and CH_4, and other environmental emissions (NOx and SOx) may be produced by the power plant. However, the most important emission is CO_2, which warms the world day by day. GHG emissions can be calculated by the following formula:

$$GHG\,emissions = \frac{Total\,CO_2\,emissions\,life\,cycle\left(gCO_{2eq}\right)}{Annual\ power\ generation\left(\frac{kwh_e}{yr}\right)lifetime\left(yr\right)} \tag{ii}$$

6.1 Emissions of Conventional Power Plants

Fossil fuel power plants use carbon-based fuels and combustion processes that emit large amounts of greenhouses gases, including CO_2. The processes of coal-based fuels are less effective than other natural gas power plants and are considered to be responsible for global warming (Table 12.2). However, new coal gasification systems have started to reduce the carbon emissions of coal-based power generation (Fig. 12.17).

Table 12.2 Emissions due to each fossil fuel source (IEA 2016)

Fuel type	Emissions (kg/kWh)
Anthracite	1.043
Bituminous Coal	0.939
Sub-bituminous Coal	0.975
Lignite	0.984
Natural Gas	0.549
Distillate Oil	0.757
Residual Oil	0.816
Gasoline	0.718
Diesel Fuel and Heating Oil	0.736
Propane	0.634

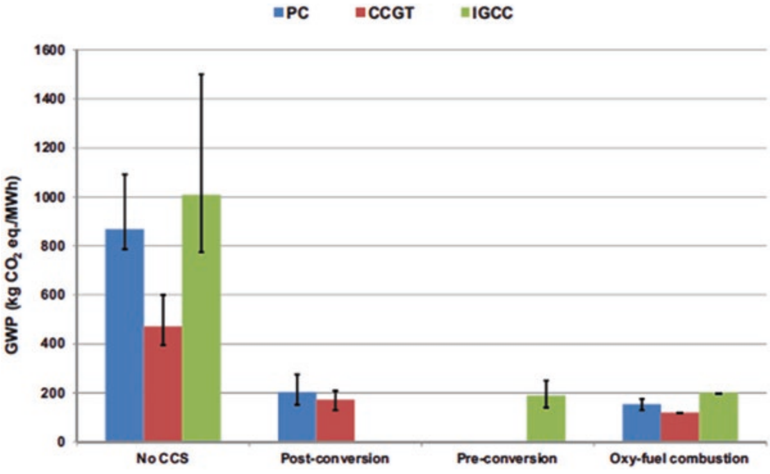


Fig. 12.17 Global warming potential of CCS options for pulverized coal (PC), combined cycle gas turbine (CCGT), and integrated coal gasification combined cycle (IGCC) plants (Cuellar-Franca and Azapagic 2015)

Table 12.3 Emissions of Power Plants (kg CO_2 equivalent/MWh) (IPPC, 2014)

Type of power plant	Direct emissions min/median/max	Infrastructure and supply emissions	Methane emissions	Lifecycle emissions min/median/max
Nuclear	0	18	0	3.7/12/110
Coal	670/760/870	9.6	47	740/820/910
Natural gas	350/370/490	1.6	91	410/490/650

Among the conventional power plants, nuclear power plants release no greenhouse gasses during their operational phase (Table 12.3). These emissions occur during the construction of the power plant, mining, processing and transportation of uranium, and storage of waste.

6.2 Emissions of Renewable Energy Power Plants

Global energy demand grew by 2.1% in 2017 and has been estimated at 14.050 million tons of oil equivalent (Mtoe). IEA noted that the growth rate was more than twice that of 2016. Energy-related CO_2 emissions increased by 1.4% and reached to 460 Mt in 2017. In addition, global CO_2 emissions reached a historic high of 32.5 Gt (IEA, 2018; Fig. 12.18). The growth of energy-related carbon dioxide emissions in 2017 is an important warning for climate change efforts, indicating that current efforts are still not sufficient to meet the objectives of the Paris Agreement.

The overall percentage of fossil fuels in the global energy demand of 2017 was reported to be 81%—a level that has remained stable for more than three decades despite strong growth in renewables (Fig. 12.19). Renewables had the highest growth rate of any energy source in 2017, with wind power generation accounting for 36% of the growth in renewable-based energy production (IEA 2017).

New renewable energy projects have helped to change old technology-based power plants and generate lower emissions. There are renewable systems to reduce global emissions using new technologies. Table 12.4 shows that new energy technologies produce lower CO_2 emissions. The emission levels may also change depending on the technologies used for renewables (Sims et al. 2003; Varun et al. 2009). Renewable energy sources are considered to be primary, clean, low risk, and inexhaustible. These energy sources include wind (onshore, offshore), solar (photovoltaic, thermal), geothermal, biomass, and hydropower.

Sustainable development requires methods and tools to measure and compare the environmental impacts of human activities. Studies on GHG emissions can be analyzed and compared with the environmental burdens of energy produced from renewable and conventional resources. Figure 12.20 shows a comparison between renewable electricity generation technologies and conventional electricity generation sources. The data are maximum emission values, which represent the worst scenarios for renewable and conventional sources.

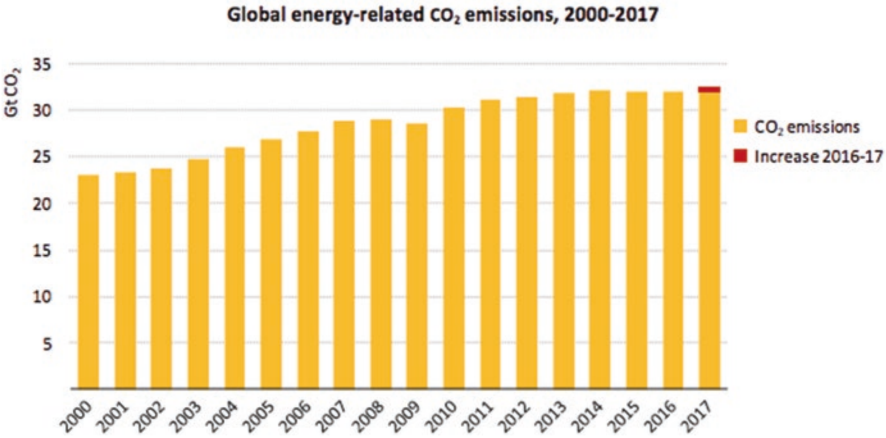


Fig. 12.18 Global energy-related CO_2 emissions between 2000 and 2017 (IEA 2018)

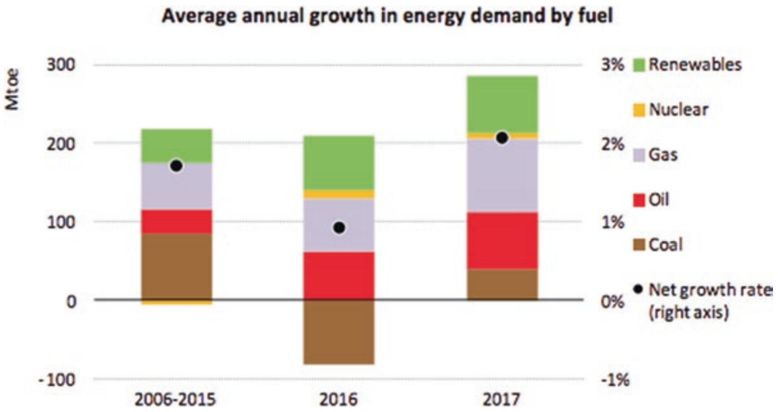


Fig. 12.19 Average annual growth in energy demand by different energy sources (IEA 2018)

Table 12.4 Emissions of selected electricity supply technologies (gCO_2 eq/kWh) (IPCC 2014)

Available technologies	Supply chain emissions	Methane emissions	Lifecycle emissions (median)
Biomass – Co-firing	–	–	740
Biomass – Dedicated	210	27	230
Geothermal	45	0	38
Hydropower	19	0	24
Solar Photovoltaic – Rooftop	42	0	41
Solar Photovoltaic – Utility	66	0	48
Wind onshore	15	0	11
Wind offshore	17	0	12

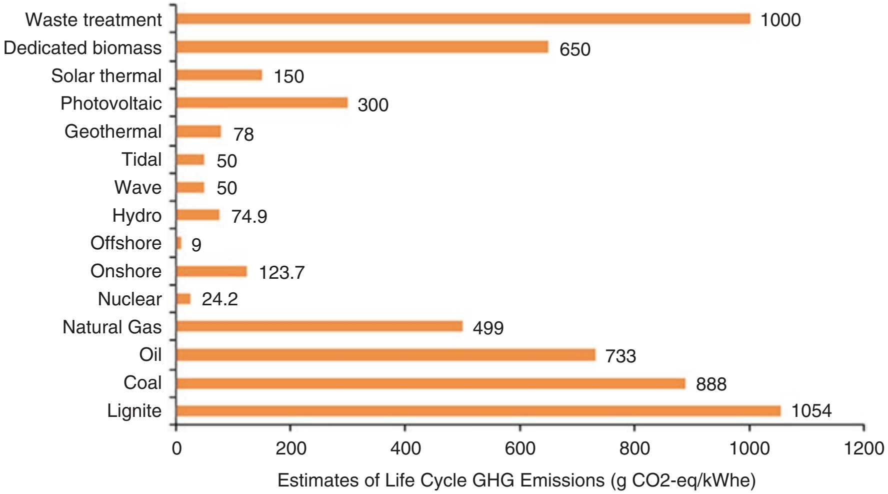


Fig. 12.20 Maximum GHG emissions levels by electricity generation method (Amponsah et al. 2014)

7 Case Study: CO_2 Emission Reduction Methods in Kızıldere Geothermal Field (Denizli City, Turkey)

Geothermal energy is a renewable, sustainable, and environmentally friendly source for electricity production. It plays an important role in reducing the effects of global climate change. Globally, the emission levels associated with geothermal power plants are much lower than those from coal or natural gas-fired power plants (GEA 2012).

Geothermal fluids consist of hot water, steam, and gases in liquid-dominated geothermal reservoirs and only steam and gases at steam-dominated reservoirs. The gas phase includes non-condensable gases (NCG), such as CO_2, H_2S, H_2, N_2, and very small amounts of hydrocarbons (e.g., CH_4) (Table 12.5).

In geothermal systems, binary systems, flash systems, and dry steam are used to produce electricity around the world. If the reservoir is liquid dominated and reservoir temperatures are greater than 200 °C, a flash cycle is selected to provide more energy from geothermal sources. Higher reservoir temperatures and pressure provide an opportunity to use more than one separation phase of water and steam in a system. To increase of the system efficiency for high-enthalpy sources, multi-flash processes have been used since the 1960s (Aksoy 2014). However, flash cycles cause more NCG in a geothermal power plant than do binary cycles (in both zero-emission systems and open systems), and high NCG amounts result in very high CO_2 emissions, especially in high NCG reservoirs as in Western Anatolia (Turkey). However, reservoir pressures have been decreasing after production year after year, especially carbonate-origin geothermal systems. In other words, the CO_2 amount cannot stay stable; rather, it decreases from the initial condition of the reservoir after steam production in this type of reservoir.

Table 12.5 General NCG Composition of Geothermal Fluids (Bloomfield and Moore 1999)

Noncondensable gas component	Dry gas % by volume
Carbon Dioxide	97.8
Hydrogen Sulfide	1.2
Methane	0.5
Ammonia	0.05
Total	*100*

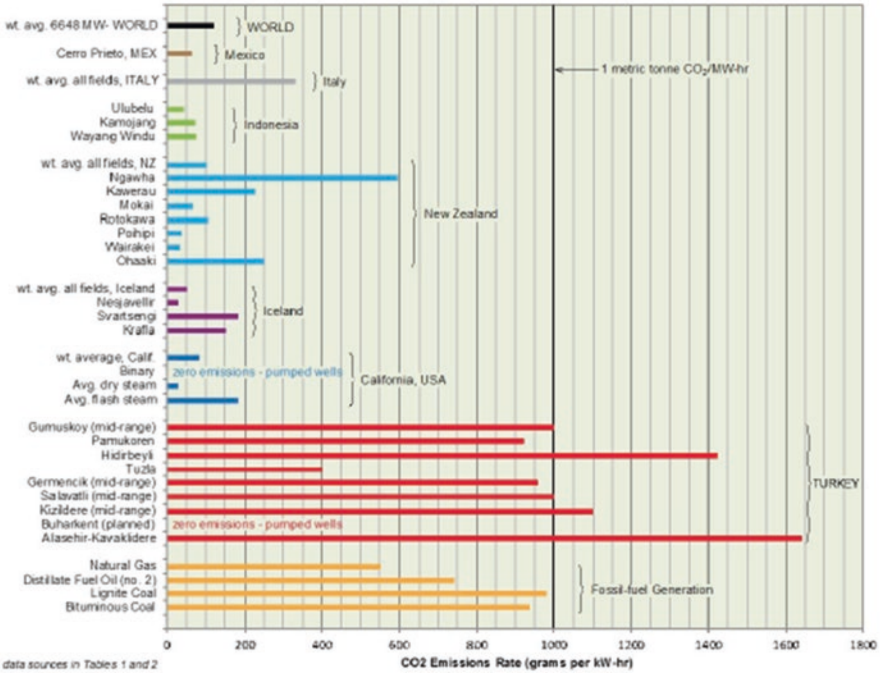


Fig. 12.21 CO_2 emissions from different geothermal power plants around the world and fossil fuels (red bars represent some of the geothermal power plants in Turkey; Layman 2017)

Although geothermal power plants produce fewer emissions than fossil fuels, the situation looks different in Turkey. Turkey is an important country for geothermal power production; in 2008, it had more than 1.2 GWe installed capacities. However, geothermal emissions were detected to be higher than other geothermal power plants around the world (Aksoy 2014; Layman 2017; Fig. 12.21). There are more than 34 geothermal power plants, using technologies that include flash, multi-flash, advanced (multi-flash+binary) and binary types (not zero emission) (Haklıdır Tut 2017). Geothermal power plants emit 800–1600 g/kWhr CO_2 in Turkey. The reason for the high CO_2 emissions is the reservoir rocks in Western Anatolia. All geothermal power plants are located in large graben systems, which are called Büyük Menderes Graben and Gediz Graben; the basement rocks are Menderes metamorphics in both graben systems. Carbonate-type reservoir rocks, such as limestones and marbles ($CaCO_3$-based rocks), cause high amounts of NCG in geothermal systems (Haizlip et al. 2013).

In the presence of H^+ ions, the dissolution of calcite can produce CO_2 directly. This reaction would be as follows:

(iii) $CaCO_{3(solid)} + 2H^{+}_{(aq)} = Ca^{2+}_{(aq)} + CO_{2(gas)} + H_2O_{(liquid)}$

Although geothermal energy is a renewable and clean option for power production, it is an important natural CO_2 producer in Turkey. Because of the high CO_2 emissions, it was classified as risky by the geothermal sector in Turkey, who signed the Kyoto Protocol in 2009. Currently, Turkey has no commitment to reducing greenhouse gas emissions. However, when the commitment starts, Turkey may pay a substantial carbon tax for this reason in the future. CO_2 emissions from geothermal power plants may result in carbon taxes of up to 4.5 ¢/kWh in Turkey (Aksoy 2014).

Emitted CO_2 is almost pure (98–99%) in NCGs (Haizlip et al. 2013) . It is possible to use the gas directly to transform to different forms or fuel to reduce CO_2 emissions. The Kızıldere-I Geothermal Power Plant (GPP) was selected as case study in Turkey.

7.1 Kızıldere Geothermal Field and Kızıldere-I GPP

The Kızıldere Geothermal Field was the first-discovered high-temperature geothermal field in the 1960s. The geothermal system is water dominated and suitable for power production with a reservoir temperature of 200 °C. The Kızıldere-I GPP was installed as a 17.2 MWe_{gross} single-flash type GPP in 1984 and was the first power plant in Turkey (Fig. 12.22). From 1984–2008, it was operated by the government. After the privatization of the Kızıldere Geothermal Field, the Zorlu Energy company has drilled 19 new wells (up to 3500 m in depth) and built the 80-MWe_{gross} Kızıldere-II GPP (60 MWe triple-flash + 20 MWe binary organic Rankine cycle [ORC]) in 2013.

The reservoir temperature is approximately 220 °C for Kızıldere-II. The company still continues to increase the capacity in the field. The Kızıldere III GPP was built as two units: the first unit consists of a 72-MWe_{gross} flash type + 23-MWe binary ORC, whereas the second unit consists of a 50-MWe_{gross} + 23-MWe_{gross} ORC. The total power capacity reached 265 MWe in the Kızıldere field in 2018. There are more than 100 geothermal wells for production and re-injection in the field now.

The Kızıldere geothermal system consists of three main reservoirs. The shallow reservoir is in fractured Mesozoic limestones. An intermediate-depth reservoir is in the uppermost Paleozoic-aged carbonates. The third and deepest reservoir is in fractures, primarily in the brittle sections of the Menderes metamorphics in the eastern part of the Büyük Menderes Graben (Haizlip et al. 2013).

Fig. 12.22 Kızıldere Geothermal Field (Denizli city, Turkey) and Kızıldere-I GPP

Kızıldere-I GPP

Kızıldere-I is a single-flash geothermal power plant, which was revised and adapted to Kızıldere-II GPP in 2013. Kızıldere-I had 7–8 production wells; each well had a separator system at wellhead between the years 1984 and 2013. After the steam separation process, all brine (hot wastewater) is collected in a brine tank and sent to re-injection wells. The wastewater temperature is around 145 °C (still high); this water is sent to a low-pressure separator system at Kızıldere-II GPP to provide more energy from the geothermal system in Kızıldere (Fig. 12.23). For this reason, the Kızıldere-I GPP design was revised and a common separator system is now used, with all production wells connected to the common separator system.

Kızıldere-II has three separation systems: high-pressure (HP), intermediate-pressure (IP), and low-pressure systems (LP). The brine phase is sent to the LP system. The Kızıldere-I and II GPP's are mixed and sent to reinjection wells together (Haklıdır Tut and Şengün 2016).

The gas chemistry of geofluids shows that 98% of gas consists of CO_2 (Table 12.6), which indicates a high purity of CO_2. The gas may directly pump or be turned into another product without capture methods. CO_2 emissions from the Kızıldere-I GPP are calculated as 0.43 t/MWh, whereas they are approximately 0.59 t/MWh for Kızıldere-II and 0.70 t/MWh for Kızıldere III GPP (EBRD 2016). To understand gas solubility in the water phase, the hydro-geochemistry of the reservoirs is given in Table 12.7.

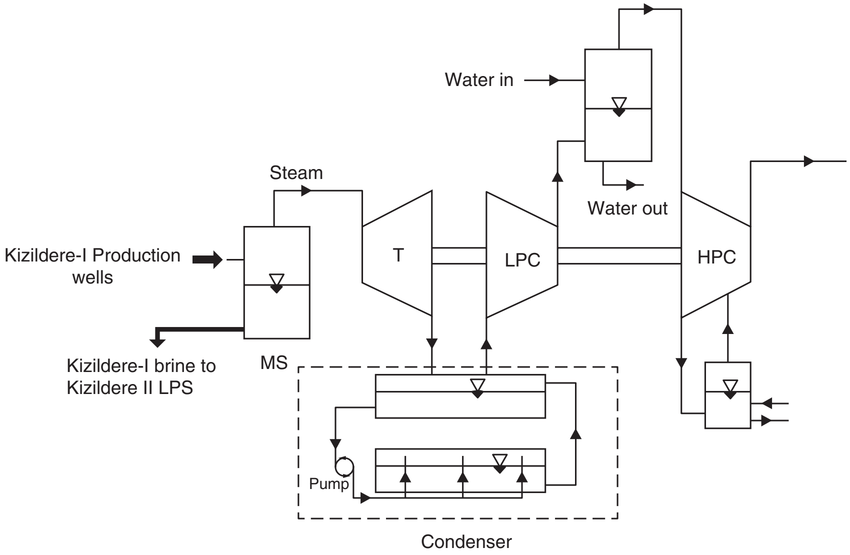


Fig. 12.23 Process flow diagram of the revised Kızıldere-I GPP (MS: Main Separator, T: Turbine, LPC: Low-Pressure Compressor; modified from Gökçen et al. 2004)

Table 12.6 Gas chemistry of the Kızıldere geothermal reservoirs (Haizlip et al. 2013)

Kızıldere Geothermal	Reservoir gas/steam (kg/kg)	CO_2 %	H_2 S %	Ar %	N_2 %	CH_4 %	H_2 %
Deep Reservoir	0.030	98.7	0.021	0.01	0.67	0.56	0.025
Intermediate Reservoir	0.015	98.6	0.005	0.003	0.81	0.42	0.003

Table 12.7 Hydrogeochemistry of the Kızıldere geothermal waters (Haizlip et al. 2013)

Analyte (mg/L)	Deep reservoir	Intermediate reservoir
Na	1078	1019
K	186	107
Ca	2	1.8
Li	3.5	3
SiO_2	492	280
B	21	16.7
Cl	104	85
F	18	14.5
SO_4	548	595
HCO_3	2157	1592
NH_4	7.6	5.3
TDS	4671	4152
Average temperature (°C)	*220*	*200*

7.2 *The Conversion of Geothermal Origin CO_2 to Fuel by a Photo-Biocatalytic Process*

New energy technologies aim to reduce greenhouse gas emissions and provide feasible new fuel alternatives to fossil fuels. One attractive option is to provide liquid fuel (e.g., ethanol and/or biodiesel) by the direct conversion of solar energy, which depends on the efficiency of its conversion (Robertson et al. 2011).

Ethanol production may contribute to reduced CO_2 emissions due to power generation (e.g., geothermal, coal) and transportation. One of the new ethanol production methods, the Helioculture process, is a transformative technology that is contrary to conventional biomass feedstock-based processes (Fig. 12.24). This direct process was developed by Joule and combines an engineered cyano-bacterial organism augmented with a product pathway and secretion system to produce and secrete a fungible alkane diesel product continuously in a photobioreactor (PBR). It is designed to efficiently and economically collect and convert photonic energy (Robertson et al. 2011). The Helioculture process uses solar energy and waste CO_2 to catalyze the direct-to-product synthesis of renewable fuel (Joule 2015) and appears to be an applicable technology for high-CO_2 producing geothermal power plants (Fig. 12.25).

A photosynthetic cyanobacterium has been designed to divert 90–95% of its fixed CO_2 to a synthetic metabolic way to produce fuels or chemicals and to operate for an extended time in a closed PBR, which is called the SolarConventer system (Joule 2015). Removing process steps and extending time periods significantly lowers costs and multiplies the annual productivity. This process directly converts

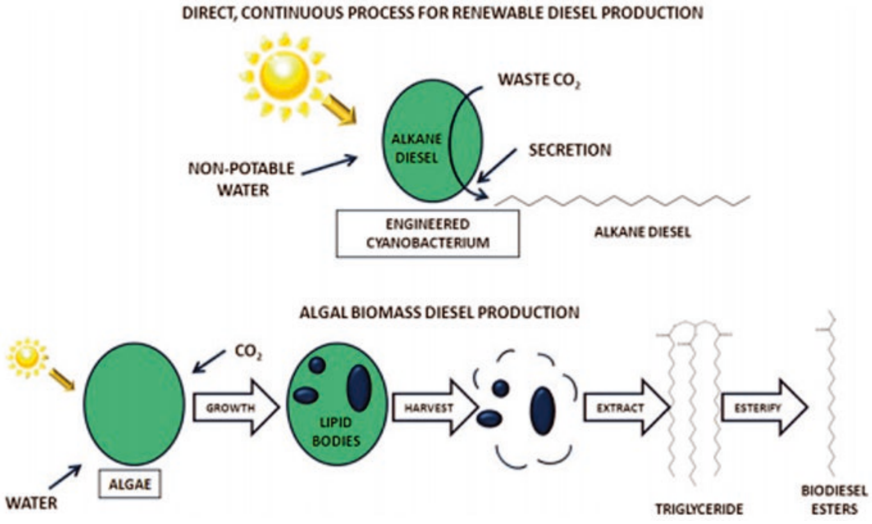


Fig. 12.24 Schematic comparison between algal biomass and direct photosynthetic processes (Robertson et al. 2011)

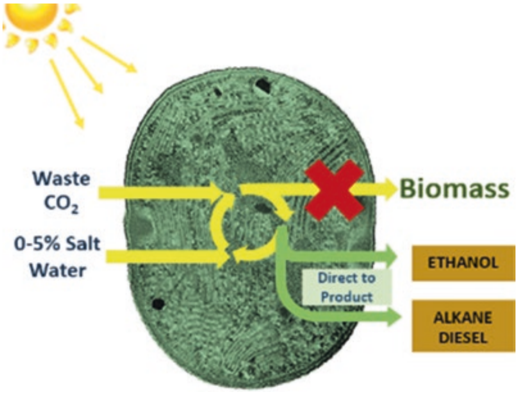


Fig. 12.25 Continuous synthesis by an engineered, product-secreting biocatalyst (Joule 2015). Sunlight and waste CO_2 are continuously and directly used in the Helioculture process

energy and waste CO_2 feedstock into fuel and operates photo-biocatalytically, allowing a continuous process with 8- to 12-week production cycles without batch processing.

This technology can achieve more than 70% CO_2 to meet the Environmental Protection Agency's Renewable Fuel Standards. In addition, the scalability, volume, and costs may make carbon-neutral mobility a reality.

Basic Principles of Photosynthesis and CO_2 Fixation

Photosynthesis is a biological energy capture and delivery system that is carried out in all cellular processes. Cyanobacteria can efficiently capture and convert the widest range of solar energy, using existing CO_2 and releasing O_2 to an O_2-rich atmosphere (Joule 2015). Solar photons can be used to drive cellular metabolism; the photon packets need to efficiently convert into high-energy chemical forms in adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide phosphate (NADPH), which carry these chemical energy packets to catalyze individual enzymatic changes.

CO_2 immobilization is the process by which carbon is built into its 3-C metabolic intermediate, 3 photoshoglycerate (3PG). This cycle is active in all cyanobacteria, algae, and plants. To incorporate 3 CO_2 moles, the cycle must occur three times, with each cycle consuming the ATP and NADPH synthesized by the photosynthetic machinery. After that, 3PG attends to the cell's intermediate metabolism, leading to metabolic separation points for engineered pathways to either ethanol or alkene (Joule 2015; Fig. 12.26). According to the technology provider, a Helioculture plant may produce 25,000 gallons of ethanol per acre per year or 15,000 gallons of diesel per acre per year (1 gallon is equal to 3.785 L and 1 acre is equal to 4046 m^2). A 1000-acre commercial facility will use 150,000 tons of CO_2 per year with the new process. CO_2 concentration, light intensity, temperature, and salinity positively affect biofuel production (Cuellar-Bermudez et al. 2015; Elçık and Çakmakçı 2017).

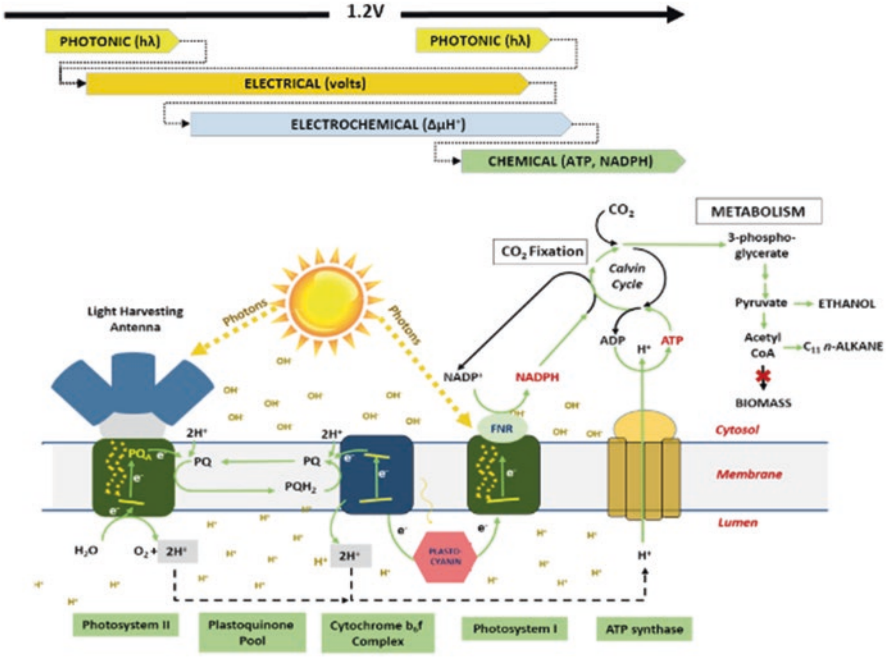


Fig. 12.26 The photosynthetic architecture for solar energy transduction (Joule 2015)

7.3 Photo-Biocatalytic Conversion of CO_2 to Fuel in the Kızıldere Geothermal Field

Geothermal power plants emit high amounts of CO_2 in Turkey. Geothermal-originated CO_2 is almost pure, with 98–99% in non-condensable gases. For this reason, the Helioculture process may be used with this pure CO_2 to produce ethanol and diesel in a geothermal power plant area. Fuel production technologies for geothermal-originated CO_2 have been supported by The European Bank for Reconstruction and Development (EBRD) for Turkey (EBRD 2016). The Kızıldere-I single-flash GPP was selected as a case study to determine a conceptual design to produce additional products besides geothermal power in Turkey.

The Kızıldere geothermal field is a serious CO_2 producer with three flash-type geothermal power plants in Western Anatolia. Although the amount of CO_2 gas naturally decreases in a geothermal reservoir year after year, it will still account for a significant proportion of emissions in the near future in Turkey. Table 12.8 shows the CO_2 emission expectations in 5, 10, and 30 years in the Kızıldere field (Fig. 12.27 a, b). Approximately 4% of the total CO_2 has been used to produce dry ice by the Linde Gas Company in the field. The Kızıldere-I GPP has been in operation since 1984 and has the lowest power capacity; thus, it has the lowest CO_2 emissions at approximately 52,000 tons/year in the field.

Table 12.8 CO_2 Emissions in Kızıldere Geothermal Field (data is modified from AECOM 2016)

Power Plant ID	Total Output (GWh)	CO_2 Production over 5 Years		CO_2 Production over 5 Years		CO_2 Production over 5 Years	
		CO_2 e t/MWh	Annual tons CO_2-e	CO_2 e t/MWh	Annual tons CO_2-e	CO_2 e t/MWh	Annual tons CO_2-e
Kızıldere-I GPP	121	0.43	52.508	0.43	52.508	0.43	52.508
Kızıldere-II GPP	645	0.51	379.000	0.43	276.039	0.27	173.327
Kızıldere-III(I) GPP	767	0.77	632.016	0.66	501.811	0.41	311.731
Kızıldere-III(II) GPP	564	0.76	512.179	0.65	438048	0.40	269.568

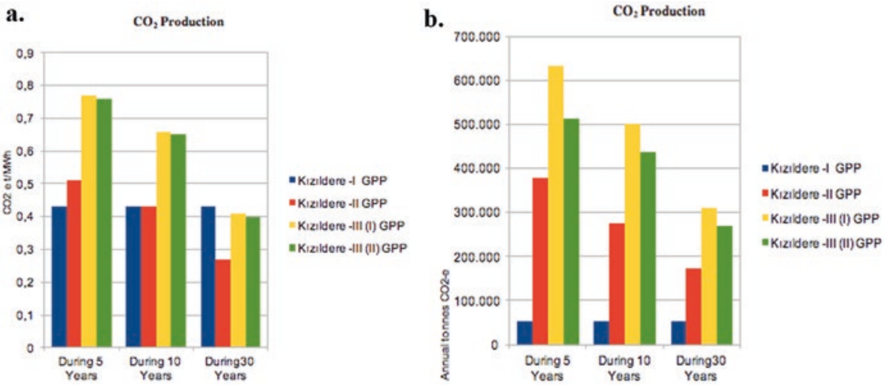


Fig. 12.27 (**a**) CO_2 emissions per MWe/h in the Kızıldere Geothermal Field, (**b**) Annual CO_2 emissions in the Kızıldere Geothermal Field

The system produces only one product (ethanol or diesel) each time it is operating. The engineered pathways and synthetic switches to direct carbon flux are given Fig. 12.28 for the Kızıldere-I case system. The system requires a solar converter, salty water supply (geothermal brine for this study), biocatalyst preparation, a main separator for the separation ethanol and diesel, ethanol and diesel tanks, and water and wastewater tanks (Baytar and Kekevi 2016; Fig. 12.29 and Fig. 12.30). For the case study, three different scenarios are modelled for biodiesel production, in which 30%, 35%, and 40% of CO_2 emissions are assumed to be used for biofuel production in the system (Table 12.9).

In Table 12.9, which is based on annual CO_2 emissions from Kızıldere-I GPP and other geothermal power plants in the Kızıldere region, the three scenarios are calculated for biodiesel production from biomass using a traditional method and the new Helioculture process. For these scenarios, it is assumed that 15,752 and 21,000 tons/year CO_2 are provided from the Kızıldere-I GPP to produce biodiesel. Based on the

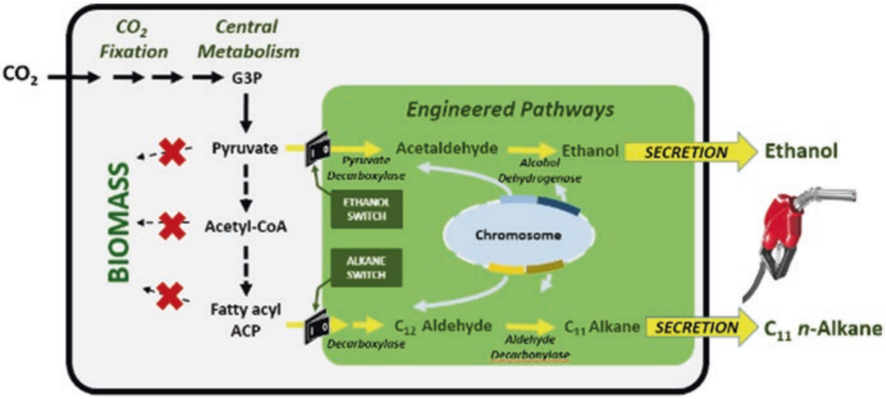


Fig. 12.28 Applicable **e**ngineered photo-biocatalyst pathway for Kızıldere-I GPP (Joule 2015)

Fig. 12.29 Required system for the Kızıldere-I GPP (demonstration in Hobbs-New Mexico; https://www.chemicals-technology.com/projects/joule-sunsprings-biofuel-plant-new-mexico)

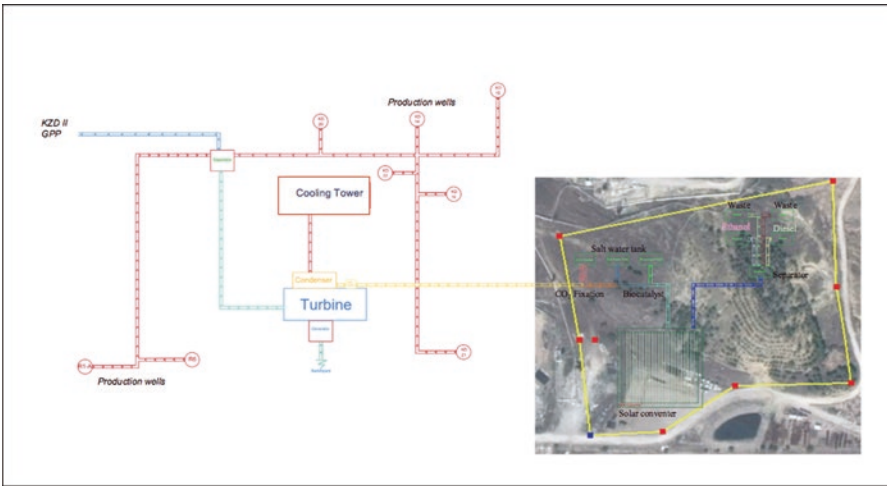


Fig. 12.30 Demonstration of biofuel production at Kızıldere field (Turkey)

results, Helioculture-based fuel production appears to be 5 times greater than traditional biodiesel production (Table 12.9). The results show that if 30% of the CO_2 from Kızıldere-I is used for biodiesel production, it is possible to produce 5.028 tons/year (1,575,187 gallon); 1 gallon of biodiesel costed approximately $2.87 in the United States in 2018.

8 Conclusion

CO_2 capture, storage, and utilization methods are quite critical steps in the reduction of CO_2 concentration in the atmosphere, which was recorded to be greater than 400 ppm in 2018. In particular, energy-based CO_2 production is still high because of the extensive use of fossil fuels; alternative energy sources appear to be good options for CO_2 mitigation in energy production now and in the future. In the literature, there are many carbon capture methods; some of them are still cost prohibitive.

After capturing CO_2, there are two main options to reduce the concentration of this gas: storage or utilization. CO_2 storage has been attempted in different fields; some barriers, such as high-pressure conditions and determination of underground crack systems, are still being investigated by researchers for storage. The utilization of CO_2 to produce a new product seems to be a good option and may provide benefits for CO_2 producers in addition to reducing the gas in a system. This approach may especially help to reduce energy-based CO_2 emissions in different fields around the world.

Table 12.9 Biodiesel production scenarios from biomass and the Helioculture process (the CO_2-to-biomass transform ratio is 0.5, the biomass-to-biodiesel transform ratio is 0.179, and the CO_2-to-biodiesel ratio by Helioculture is 0.3192 for 1000 acres)

Power Plant	CO_2 Amount (Tons/year)	Biomass (Tons/year)	Biodiesel (Tons/year)	Biodiesel directly by Helioculture (Ton/year)	Energy Yield for Biodiesel (MJ)	Energy Yield for Biodiesel directly by Helioculture (MJ)
Scenario 1: Using 30% of CO_2 Emissions						
Kızıldere-I GPP	15.752,4	7.876,2	1.415,9	5.028,2	48.991.734	173.974.546
Kızıldere-II GPP	113.700,0	56.850,0	10.220,2	36.293,0	353.619.775	1.255.739.184
Kızıldere-III (I) GPP	189.604,8	94.802,4	17.043,1	60.521,9	589.692.232	2.094.056.085
Kızıldere-III (II) GPP	153.653,7	76.826,9	13.811,6	49.046,3	477.880.271	1.697.000.632
Total	*472.710,9*	*236.355,5*	*42.490,9*	*150.889,3*	*1.470.184.013*	*5.220.770.447*
Scenario 2: Using 35% of CO_2 Emissions						
Kızıldere-I GPP	18.377,6	9.188,9	1.651,9	5.866,2	57.157.023	202.970.304
Kızıldere-II GPP	132.650,0	66.325,0	11.923,6	42.341,9	412.556.404	1.465.029.048
Kızıldere-III (I) GPP	221.205,6	110.602,8	19.883,6	70.608,8	687.974.271	2.443.065.432
Kızıldere-I GPP	179.262,7	89.631,3	16.113,5	57.220,6	557.526.983	1.979.834.071
Total	*551.496,1*	*275.748,0*	*49.572,7*	*176.037,5*	*1.715.214.681*	*6.690.898.855*
Scenario 3: Using 40% of CO_2 Emissions						
Kızıldere-I GPP	21.003,2	10.501,6	1.887,9	6.704,2	65.322.312	231.966.062
Kızıldere-II GPP	151.600,0	75.800,0	13.627,0	48.390,7	471.493.034	1.674.318.912
Kızıldere-III (I) GPP	252.806,4	126.403,2	22.724,2	80.695,8	786.256.309	2.792.074.780
Kızıldere-III (II) GPP	204.871,6	102,435,8	18.415,4	65.395,0	637.173.695	2.262.667.509
Total	*630.281,2*	*315.140,6*	*56.654,5*	*201.185,8*	*1.960.245.350*	*6.961.027.263*

Geothermal energy is a sustainable energy source; however, in some cases, this energy source may produce naturally non-condensable gases via cooling towers, as in Turkey. To solve the high CO_2 emission problem due to geothermal power plants, a geothermal-biofuel hybrid system may be considered for Turkey and other countries that are high NCG producers. In generally, CO_2 is the dominant gas with a proportion of more than 95%; it is nearly pure in high non-condensable geothermal systems. In addition, it is technically easier to capture the gas from a steam turbine's condenser system than other systems. The Helioculture process can use some part of the gas to produce biofuel in geothermal power plants.

The Helioculture process is a new photo-biocatalytic approach to produce biofuel. The process needs solar energy and CO_2 to catalyze the direct-to-product synthesis of renewable fuel. Instead of traditional biofuel production from biomass, the Helioculture process can be used for bioethanol or biodiesel production using geothermal CO_2, solar energy, and salty water (geothermal brine). The process produces only one product—ethanol or biodiesel—each time it operates. Although geothermal power plants provide the required CO_2 and salty water for the process to grow the bacteria, large areas near a geothermal power plant are also required (15,000 gallons of diesel per acre per year). Thus, the process can use some CO_2 from high-NCG geothermal systems; however, biodiesel production will be still beneficial because of biodiesel prices. This type of hybrid system may have additional benefits for geothermal investors in addition to its potential for CO_2 reduction in the future.

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Part V
Finally

Chapter 13
Finally: Key Insights and Future Research for Better Understanding of Climate Change and Energy Dynamics

Aymen A. Kayal

Abstract To better understand the dynamics of energy and climate change in the Middle East, this final chapter synthesizes the knowledge and learning we have gained from going through Chapters 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12 of this book. Key insights are presented for both the policymakers and the administrators of energy policy domain. The future research directions that will support both the sustainable development in the Middle East and modeling the dynamics of energy and climate change are also presented.

Keywords System dynamics · CO_2 emissions · Renewable energy generation · Energy consumption · Energy efficiency · Levelized cost of electricity (LCOE) · Biofuel · Geothermal · Sustainable development

1 Introduction

By now you have covered much ground in this book. You have learned about current research describing the dynamics of energy and climate change in the Middle East and how it applies to some sectors. You discovered the strengths of system dynamics, simulation, econometrics, and other quantitative methods, in capturing relevant issues and providing solutions or assisting decision-makers in envisaging better decisions. These quantitative tools must be part of the backbone that supports policies and decisions that shape the future of sustainable development and economic growth in the region.

By creating this edited volume, we believe that the contributing authors have added relevant knowledge about the dynamics of energy and climate change in the Middle East. One of the main advantages of developing a thematic edited volume book is that it is based on contributions from a fairly large number of authors with

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H. Qudrat-Ullah, A. A. Kayal (eds.), *Climate Change and Energy Dynamics in the Middle East*, Understanding Complex Systems,
https://doi.org/10.1007/978-3-030-11202-8_13

diverse expertise and knowledge domains, providing the readers with a level of insight not readily available in regular books and journal publications.

By synthesizing the knowledge and learning we have gained from going through Chaps. 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12 of this book, we are now able to discuss key insights and future research directions that will support, firstly, sustainable development in the Middle East and secondly modeling the dynamics of energy and climate change.

2 Key Insights for Energy Policy Decision-Makers

The conclusions and recommendations discussed at the end of each chapter provided a wealth of information and implications for policymakers as it pertains to its context. When we go through the unique contributions in this book, predominantly three thematic dimensions about climate change and energy decisions stand out: (i) environmental, (ii) economic, and (iii) social. These dimensions were operationalized by various metrics that could be used in future studies that focus on dynamic modeling of energy and climate change. Below are the key insights gained from Chaps. 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12.

- The dominant factors affecting the promotion of renewable energy in Oman are the environmental indicator of “total CO_2 emissions”; economic indicators of “gas savings”; and a social indicator of “job creation” (green jobs). These factors influence the government’s desire to invest in renewable electricity generation. These influencing factors apply not only to Oman but to most countries in the Middle East as well.
- Electrified vehicles are fuel-efficient regardless of the aggressive and congested driving patterns in the city of Beirut, Lebanon, and other cities with similar driving conditions.
- Considering how a range of actors, including scientists, government officials, and international experts, understand the future of a climate-linked resources and that there is no single solution to adapt and mitigate climate to solve energy problems due to different geographical conditions, characteristics, etc., each country has to consider its own climate and resources to specify what is most suitable to accomplish the best results.
- The DC meshed micro-grid with voltage and current-mode control for the power converter is a novel system for smart grid development that may contribute to renewable energy development in the Middle East.
- The analysis of the energy-water-health nexus in UAE showed that energy efficiency and renewable energy can lead to significant reductions in annual greenhouse gas emissions as well as a decrease in premature mortality and healthcare facility visits in the urban environment.
- Integrating variable renewable energy generation and storage into the power system modeling framework (and eventually the power grid) will result in a decreased overall system levelized cost of electricity (LCOE) and decreased emissions.

- The grid-connected hybrid system is profitable, economic, environmentally friendly, and effective in maintaining continuity of power supply. If the grid-connected hybrid systems are set up in Egypt and other Middle East counties, energy dynamics problem due to climate change can easily be mitigated.
- GDP per capita has a positive and renewable energy use which has an adverse effect on carbon dioxide emission in the Middle Eastern countries.
- Decisions and policies regarding energy and power generation mix that can contribute to emission reduction of CO_2, and other greenhouse gases, can be highly enhanced using quantitative models.
- Transformation toward clean energy in the Middle East should be considered as a socio-technical change, and this transformation can be identified at the three levels of landscape, regime, and niche which need to be coordinated and aligned to ensure a successful transition.
- Helioculture process is applied to geothermal power plants to produce biofuel by CO_2, and it is possible to produce biofuel or ethanol by photo-biocatalytic process with this method.

3 Future Research in Climate Change and Energy Dynamics with Specific Focus to the Middle East

In this section, we have summarized the main directions for future research as prescribed by the contributing authors of the book.

The authors of Chap. 2, “Socio-economic and Environmental Implications of Renewable Energy Integrity in Oman: Scenario Modelling Using System Dynamics Approach,” proposed the following:

- Policymakers should consider future mitigation of adverse environmental consequences that might emerge from the continuous use of fossil fuel resources in power generation.
- There is a need to consider the deployment of alternative energy sources like renewables due to the potential number of green jobs that can be created throughout the renewable energy life cycle.

In Chap. 3, the authors of “Energy and Emissions Modelling for Climate Change Mitigation from Road Transportation in the Middle East: A Case Study from Lebanon” suggested the following:

- Future work could capture additional key factors and relationships specific to the context of developing countries, such as government investment in the backbone and refueling infrastructure, policy enablers for incentivizing the most beneficial technologies, and the preferences of end users for new technologies. User adoption models should include several attributes such as vehicle costs, driving range, environmental awareness, word of mouth, and refueling infrastructure availability, all of which are context-specific and require local data and assumptions.

Authors of Chap. 4, “Climate Change and Energy Decision Aid Systems for the Case of Egypt,” pointed out to the following:

- Influence of anthropogenic climate change drives us to think about the interactions of natural and human agency in forging environmental outcomes. Actors, including scientists, government officials, and international experts who understand the future of a climate-linked resources, can influence policymakers in Egypt as well as other countries in the region.

In the fifth chapter, “Control Strategy and Impact of Meshed DC Micro-Grid in the Middle East,” its authors suggested that:

- Enabling easy integration of renewable energy resources particularly photovoltaic ones will contribute to future renewable energy development in the Middle East.

In Chap. 6 “The Energy-Water-Health Nexus Under Climate Change in the United Arab Emirates: Impacts and Implications,” the authors discussed the impact of climate change on health and made the following suggestion:

- The gradual introduction of energy efficiency and renewable energy measures can lead to substantial decreases in premature mortality and healthcare facility visits in urban areas. From our perspective, this argument is more vital than Co2 reduction or financial gains from using renewables.

The authors of Chap. 7 “Leapfrogging to Sustainability: Utility-Scale Renewable Energy and Battery Storage Integration – Exposing the Opportunities Through the Lebanese Power System” pointed out:

- Future work should include utilizing more complex modeling tools in building a stochastic modeling framework while co-optimizing all assets, stacking grid-connected BESS value streams, and internalizing power plant cycling costs and other externalities to achieve more confidence in evaluating sustainable energy transitions.

In Chap. 8, “Climate Change and Energy Dynamics of the Middle East: Challenges and Solutions,” the authors suggested the following:

- Future studies should be searching and analyzing various combinations of different renewable energy sources based upon the location. If these hybrid systems are placed all over the Middle East and if they are connected, then it fulfills the desired load demand by using only renewable energy sources very easily.

In the ninth chapter, “Greenhouse Gases Emissions and Alternative Energy in the Middle East,” its authors recommended the following:

- Future studies could further investigate the relationship between CO_2 emission, growth, and renewable energy for different economic sectors. Further studies could use a broader range of models and use variables such as industrial production index, energy prices, and oil production. Also, different greenhouse gases could be used to discuss the climate mitigation potential.

The authors of Chap. 10, “Quantitative Analysis Methods Used in Modelling Power Systems and Climate Change for Saudi Arabia,” recommended the following:

- To list all the various institutions, networks, policies, and functions that are needed to build a comprehensive system dynamic model that would capture all the important dimensions related to power generation, economic growth, emission reduction, and human factors that impact sustainable development

In Chap. 11, “Transformation Toward Clean Energy in the Middle East: A Multilevel Perspective,” the authors suggested that:

- Further research is needed to understand the social, economic, and institutional aspects of the transformation toward clean energy in the Middle East. Studies that document and analyze specific cases in the region can contribute to knowledge and provide a solid empirical base to inform energy-related policy development and planning in the region.

Finally, the authors of Chap. 12 “Global CO_2 Capture and Storage Methods and the New Approach to Reduce Emission for Geothermal Power Plants with High CO_2 Emission: Turkey Case Study” pointed out:

- The helioculture process is a new hybrid system that uses geothermal CO_2 emission to produce biofuel. This new process should be further explored because it may provide additional benefits for geothermal investors.

4 Conclusions

The unique chapters presented in this book have provided us with a wealth of information regarding the dynamics of energy systems and climate change in the Middle East. Although the overwhelming discussions focused on the power sector since it represents the major sector of energy use and Co2 emissions in the Middle East, one chapter covered transportation, and two others covered energy in its universal application.

One of the aims of this book was to capture relevant current research to deduct from it the main variables that impact energy systems as they apply to various dimensions and sectors. The three main dimensions of interest found were (1) environmental, (2) economic, and (3) social. It is believed that new directions of energy system modeling should take into consideration the integration of these dimensions in the model before making policy recommendations. Although other dimensions, like technology, could also be considered, nevertheless, environment, economic, and social are considered the most relevant for sustainable development in the Middle East.

Since most of the Middle East countries are considered developing countries, their economic growth should fall under sustainable development as prescribed by the United Nations. However, environmental and climate change issues are considered new and have less priority relative to the growing power demand needs of these developing economies. This presents a major challenge to policymakers in the region. Furthermore, due to its newness to the region, a significant amount of research still needs to be conducted to fully understand the real of energy and climate change dynamics in each country in the Middle East. In this regard, the future research suggestions that were captured in this book only scratch the surface.

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