AN INVESTIGATION INTO THE CONTRIBUTION OF HYBRID RENEWABLE ENERGY SYSTEM TO UTILITY GRID IN THE REGIONS WITH ARID CLIMATE

A DISSERTATION IN
Electrical and Computer Engineering
and
Physics

Presented to the Faculty of the University
of Missouri-Kansas City in partial fulfillment of
the requirements for the degree

DOCTOR OF PHILOSOPHY

by
YAHYA ZAFI ALHARTHI

M.Sc., University of Missouri-Kansas City USA, 2015
B.E, Riyadh College of Technology, 2011

Kansas City, Missouri
2019

AN INVESTIGATION INTO THE CONTRIBUTION OF HYBRID RENEWABLE ENERGY SYSTEM TO UTILITY GRID IN THE REGIONS WITH ARID CLIMATE

Yahya Zafi Alharthi, Candidate for the Doctor of Philosophy Degree

University of Missouri-Kansas City, 2019

ABSTRACT

Increasing the emissions of carbon have a negative impact on our environment, since the beginning of industrial revolution. There is a wide consensus that climate change occurred due to human behavior, mainly from burning fossil fuels. This raises the future concern of the world carbon-based energy and economy, particularly, developing countries that heavily dependent on Oil, such as the Kingdom of Saudi Arabia (KSA) which is the case study of this research. It has a power sector which is heavily reliant on fossil fuels. The fuel types used by current generation units in the KSA are Heavy Fuel Oil (HFO), Natural Gas, Diesel Oil, and Crude Oil. The conventional generation and continued use of the fossil fuels as the main source of electricity will cause fuels depletion, environmental pollution, and impacts to human health through the emission of exhaust gases.

Implementing renewable energy would be the way to reduce the country’s dependency on fossil fuels for power generation. In KSA, there are several researches are done for renewable energy resources availability and the growth of power generation. However, studies assessing the performance, cost, and effects of different Renewable Energy Sources (RES) on the utility grid and demand curve are very limited.

This dissertation illustrates the big picture of the Kingdom of Saudi Arabia regarding the current status of power generation, consumption, and the expected increase in power demand & supply, as well as availability and assessment of the most effective renewable energy resources. It also presents a techno-economic analysis of a grid-connected solar PV-wind hybrid system for different locations inside the country along with sensitivity analysis to give a blueprint of the system reliability and determine how sensitive the outputs are to any changes in the system's variables. In addition, the grid codes of developed countries are investigated in order to form the infrastructure for renewable energy projects, build up the sector and take the advantages of the exploitable renewable energy sources, and bring knowledge to system operators from other developed and experienced countries.

APPROVAL PAGE

The faculty listed below, appointed by the Dean of the School of Graduate Studies, have examined a dissertation titled "An Investigation Into the Contribution of Hybrid Renewable Energy System to Utility Grid in the Regions With Arid Climate" presented by Yahya Zafi Alharthi, candidate for the Doctor of Philosophy degree, and hereby certify that in their opinion it is worthy of acceptance.

Supervisory Committee

Ghulam M. Chaudhry, Ph.D., Committee Chair
Department of Computer Science & Electrical Engineering

Mahbube Khoda Siddiki, Ph.D.
Department of Computer Science & Electrical Engineering

Ahmed M. Hassan, Ph.D.
Department of Computer Science & Electrical Engineering

Paul Rulis, Ph.D.
Department of Physics and Astronomy

Cory Beard, Ph.D.
Department of Computer Science & Electrical Engineering

CONTENTS

LIST OF ILLUSTRATIONS

Figure Page

LIST OF TABLES

ABBREVIATIONS

GCC	Gulf Cooperation Council
G20	Group of Twenty
SEC	Saudi Electricity Company
KACARE	King Abdullah City for Atomic and Renewable Energy
IPCC	Intergovernmental Panel on Climate Change
NREL	National Renewable Energy Lab
ECRA	Electricity and Cogeneration Regulatory Authority
SWCC	Saline Water Conversion Corporation Company
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
MSW	Municipal Solid Waste
RRMM	Renewable Resource Monitoring and Mapping
GHI	Global Horizontal Irradiance
DNI	Direct Normal Irradiance
DHI	Diffuse Horizontal Irradiance
PV	Photovoltaic
CSP	Concentrated Solar Power
GDP	Domestic Product
NPC	Net Present Cost
LCOE	Levelized Cost of Energy
HFO	Heavy Fuel Oil

RES	Renewable Energy system
RE	Renewable Energy
SAM	System Advisor Model
HOMER	Hybrid Optimization of Multiple Energy Resources
GHG	Greenhouse Gas
MTOE	Million Tons of Oil Equivalent
VSWT	variable-speed wind turbines
FSWT	Fixed -speed wind turbines
DFIG	Doubly Fed Induction Generator
GSC	Grid-Side Converter
RSC	Rotor-Side Converter
WECS	Wind Electric Conversion System
HOMER	Hybrid Optimization of Multiple Energy Resources
PDM	Power Density Method
CDF	Cumulative Distribution Function
REFIT	Renewable Energy Feed in Tariff
DCF	Discounted Cash Flow
LDC	Load Duration Curve
AGC	Automatic Generator Controls
VRE	Variable Renewable Energy
PVPP	Photovoltaic Power Plant
TSP	Transmission Service Provider

GC	Grid Code
NERC	North American Electric Reliability Corporation
PCC	Point of Common Coupling
LVRT	Low-Voltage Ride Through
HVRT	High-Voltage Ride Through
PREPA	Puerto Rico Electric Power Authority
APC	Active Power Control
TSO	Transmission System Operators
WPP	Wind Power Plant
SCADA	Supervisory Control and Data Acquisition
BPS	Bulk Power System
HRES	Hybrid Renewable Energy System

ACKNOWLEDGEMENTS

First and foremost, I would like to express all Praise and Thanks to God, for giving me the opportunity to continue my education. I would also like to express my special appreciation and thanks to my research advisor Dr. Ghulam Chaudhry, who advised me, offering me valuable insights and help as needed. His mentorship helped me develop my skills as a researcher and kept me motivated and made me stay focused towards my goals. His academic achievements, expertise and insights proved to be an inspiration to me. I would like to express my great thanks to my supervisor Dr. Mahbube Khoda Siddiki who motivated me during my PhD studies. His guidance helped me throughout my program which gave me the confidence to achieve my goals. Dr. Mahbube always showed the highest level of respect for his students. I am very grateful to him for his scientific advice and knowledge and many insightful discussions and suggestions. Without Dr. Chaudhry and Dr. Siddiki precious support, it would not be possible to conduct this research.

It is my great pleasure to thank my Ph.D. committee members: Dr. Ahmed Hassan, Dr. Cory Beard, and Dr. Paul Rulis, for accepting my invitation and for their insightful comments and encouragement, which incanted me to widen my research from various perspectives. Also, I would like to thank the Student Services Coordinator Coretta Carter and the other staff in the department of Electrical and Computer Engineering at the University of Missouri Kansas -City for their help during my PhD study.

I gratefully acknowledge the financial support from the Ministry of Education for their scholarship program through the Saudi Arabian cultural mission to the US. Also, I highly value collaboration from King Abdullah City for Atomic and Renewable Energy (KACARE), Saudi Electric Company (SEC), the electricity and cogeneration regulatory authority (ECRA), and the National Aeronautics and Space Administration (NASA) for providing required data for my study. This work would not have been possible without their generous help.

Most importantly, I owe my loving thanks to my parents, brothers, and sisters for their continuous prayers and showing belief in me. My deepest thanks go to my old brother Obaid Alharthi for his support during my study. Many thanks are due to my wife Amira Alharthi for her love, support, patience and understanding, without her support this work would have not been possible

Finally, I would like to thank all of my friends and PhD colleagues who worked alongside me, and specifically those who collaborated with me as well.

CHAPTER 1

INTRODUCTION

1.1 Overview and Motivation

Tropical and hot climate regions all over the world are underutilized in generating power and providing alternative resources of energy [1]. For example, the Gulf Cooperation Council (GCC) countries in the Middle East, which have an abundance of natural resources, provide less incentive to develop Renewable Energy (RE) projects. Other reasons may be related to political and economic instability that deprive governments of financial resources to invest in new technology [2,3]. The Kingdom of Saudi Arabia (KSA) is considered to be one of the top countries for having some of the hottest weather worldwide. It is also the top fossil fuel consumer for electric power generation in the Middle East [4].

The power industry in KSA faces a lot of challenges, and the rapid increase of power demand forced the government to take quick action to expand or build new power plants in order to meet new loads. KSA's power demand has significantly increased over the last two decades [5]. In 2003, the Saudi Electricity Company (SEC) report showed that the peak load of the national grid was 26.2 GW. In 2016, the total amount of electricity generated, reached more than 74 GW, as shown in Figure 1 It is expected to reach more than 100 GW by 2030 due to both rapid population and economic growth [6,7]. The report also presented the total number of customers, which was 3,622,390 in 2000, and recorded an average annual growth of 5.4% from 2000 to 2014.

The power sector of KSA relies heavily on fossil fuels for electric power generation [8,9]. Heavy Fuel Oil (HFO), natural gas, diesel oil, and crude oil are the types of fossil fuels used in power plants. Figure 2 illustrates the development of fuel consumption for power generation from 2000–2014 [6]. Due to the rapid increase in commercial and residential loads every year, appropriate and sufficient electrical power generation must be provided to meet the growth of such demands. However, continued dependence on fossil fuel as the primary energy source will cause fuel depletion, environmental pollution, and have an extremely negative impact on human health[9].

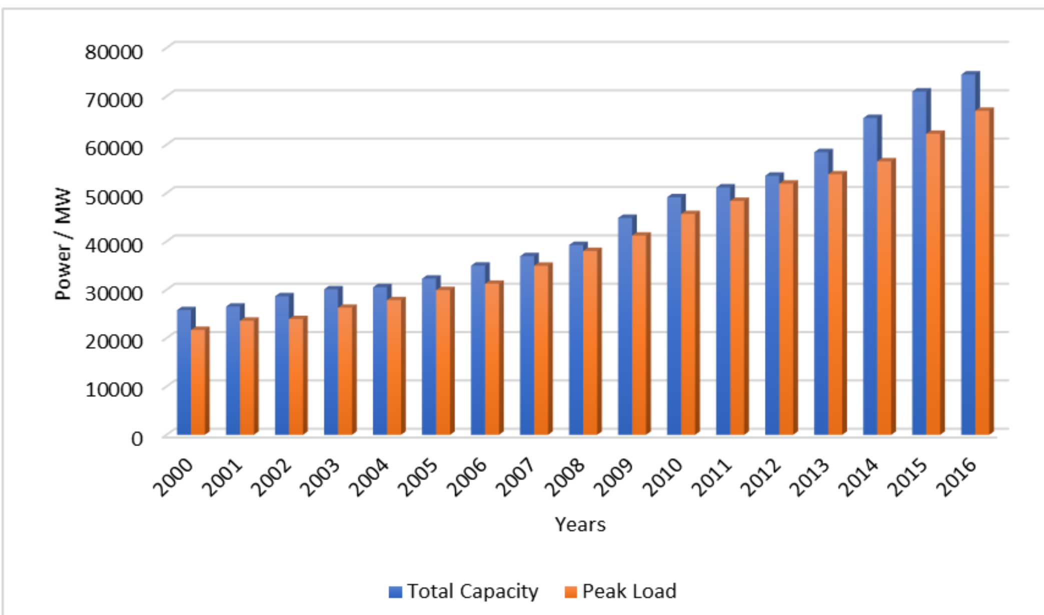


Fig. 1 Peak Load versus Generation Capacity for (SEC) [10]

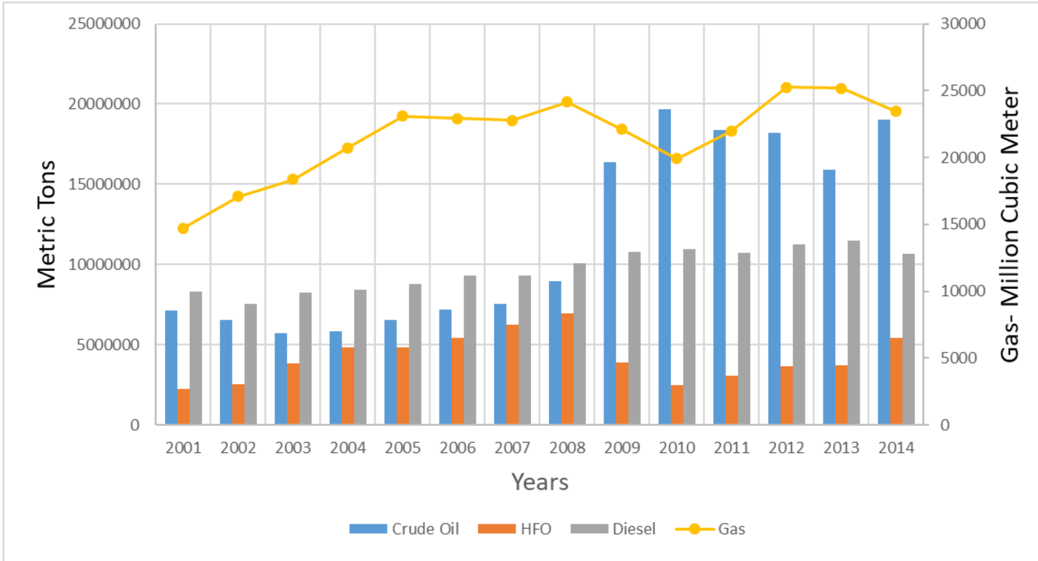


Fig. 2 Fuels Consumption scenario in SEC Power Plants from 2000 to 2014 [6]

The report in Reference [10] shows that KSA is one of the top producers of carbon dioxide (CO_2) in the world. Hence, implementing renewable energy projects for power generation will not only reduce the level of CO_2 emissions in KSA, but will also contribute to increasing the kingdom's revenues [11]. KSA has several suitable locations for implementing renewable power generation projects. Wind and solar energy have the highest potential in the kingdom among all other RE resources [12]. An analytical study, made for evaluating different renewable energy sources in Saudi Arabia, shows that photovoltaic (PV), concentrated solar power (CSP), and wind energy are the most effective RE technologies, respectively [13]. Another study, conducted by Munawwar et al. [14], reviewed the growth of the solar industry and renewable energy in the Gulf Cooperation Council (GCC) areas, and stated that solar power production is expected to represent up to 16–22% of the KSA's total energy generation by 2032. Regarding wind energy, the KSA authorities responsible for energy and environment recognize the importance of wind energy, and will support investments in this sector [15].

There is a need to address climate and environmental issues not only in developed countries but also in developing countries. This is because of the fact that the effect of climate change is supposed to hit hard not only coastal regions of the world but also countries with arid climate like KSA. This country is global leader in fossil fuel production as well as one of the top GHG emitter. It has also huge potential for renewable and the government has outlined the plan in Vision 2030 to address those issues. All these motivations showed that there is a need to investigate renewable energy resources and their impact on economy and energy use of the country and this research aims to fill this gap.

1.2 Research Questions and Objectives

1.2.1 Research Questions

This study aims to answer the main research question: Responding to the climate change challenges and the world's transition towards sustainable energy, could renewable energy sources (hybrid grid-connected system) reduce dependency on fossil fuels for power generation in KSA?

This question can be further divided into sub-questions:

1. Why it is important to enhance transition to sustainability in KSA?

2. What are the important technical and economic aspects of connecting different RE sources to the utility grid in KSA?
3. What is the RE production costs at the KSA's grid price compared to the capital costs and net present cost (NPC), over the RE project considering lifetime?
4. What are the grid code requirements for solar and wind technologies in KSA to make them grid compatible?

1.2.2 Objectives

The main objective of this research is to contribute to the development of renewable energy in the Kingdom of Saudi Arabia and enhance sustainability and the role of renewable energy.

To achieve this goal, the following objectives are aimed to be:

1. Quantify the current electricity demand and the expected increase in power generation.
2. Investigate the availability of the renewable energy resources of KSA using the installed resource monitoring stations data.
3. Examine the performance of Renewable Energy System (RES) and its contribution in the electricity production of KSA using simulation, optimization, and sensitivity analysis.

4. Compare the effects of different RES technologies on the electricity generation and demand curve considering technical, economic and environmental feasibility.
5. Explore the standards and codes for RE-Grid integration from top RE using countries in order to build up the sector.

1.3 Research Methods

The optimization and sensitivity analysis algorithms of RE Software allow users to assess the technical feasibility and economic of a large number of technology options and to account for variations in electric load, technology costs, and the availability of energy resources.

The weather data in this study were collected from NASA Surface Meteorology, National Renewable Energy Lab (NREL), and King Abdullah City for Atomic and Renewable Energy (KACARE). Also, real electricity rates were applied to discuss the expected electricity purchase and sale to the grid.

Based on the information collected, we designed a hybrid PV/Wind grid-connected system and carry out its techno-economic analysis. The analysis of this system shows the correlation between production, demand, and economics of renewable energy compared to the utility grid. The simulation results reflect the technical, economic and environmental feasibility of using a hybrid grid-connected system in the selected locations. An energy analysis software named HOMER (Hybrid

Optimization of Multiple Energy Resources) was used for the simulation to predict the best correlation between demand and production.

1.4 Interdisciplinary Nature

A wide range of skills and disciplines are involved in RE technologies Research, Development and Demonstration (RD&D). They include chemistry, physics, electrical and mechanical engineering, biological sciences, and the materials sciences. Multidisciplinary team in many cases are required to tackle posed multifaceted problems. Renewable energies were found to be the technologies where physicists were making a significant contribution for electricity production. Physics and physicists can make a great contribution in several areas. As an example, but not limited in the PVs, where physicists are carrying out much of the fundamental research required to develop novel types of solar cells. Techniques from physics drive developments in many disciplines, including medicine and the life sciences, engineering, computing, materials, mathematics, science, and meteorology and statistics[16]. In this research, understanding electrical impedance, static electric and magnetic fields, the solid-state physics of electronic components and their operation through both theory and practical lab would contribute in this study as they are a related with my co-discipline which is Physics.

1.5 Contribution

This research supports the reduction of some greenhouse gasses as well as the reduction of energy costs. Investigating the potential of a large-scale grid-connected solar PV/Wind hybrid system considering real grid prices along with system sensitivity analysis to explore the system's reliability and determine how sensitive the outputs are to any changes in the system's variables are the main contributions of this research, specifically for KSA. It also contributed towards a better understanding of the technical, economic, and environmental impact of utilization of such system. This is due to the fact that most of the previous research work focused on the performance evaluation of RE standalone (off-grid) systems either a hybrid or single type of RE sources. Previous works' emphasis was placed on resources assessment, energy production, and energy storage for small scale (kW) off-grid systems. As per the author's knowledge, none of the existing work explored this issue which is considered a very important missing aspect.

The contribution of my research paper is discussed below separately. In [6], we discussed the current electricity production, consumption of the conventional power generation, and the expected growth of solar power in the upcoming 15 years regarding the KSA. In [17], we investigated the performance of five solar monitoring stations located in deferent provinces in KSA. The data of GHI, DNI, DHI and temperature were used in this study to analyze the stations performance and compare the solar potential of each. Also, an old data from NREL were used to compare them with the new monthly and annual data provided by KACARE. In [18] we presented a method to design, simulate and perform financial analysis of 1.2 MW commercial photovoltaic system and tested the best and highly productive PV tilt angle. In [19] we designed and investigated the optimal sizing of a stand-alone PV-diesel-battery hybrid system for a 90 kWh/day load. The optimization was done for different tracking systems, considering several technical and economic factors including levelized cost of energy (LCOE), net present cost (NPC), and photovoltaic power generation. The paper also presents the environmental impact of using different tracking systems. In [20] different hybrid grid connected configurations were investigated to determine the best option that has high Return on Investment (ROI) and less payback period. In [21] we presented resource assessment and techno-economic analysis of a grid-connected solar pv-wind hybrid system for different locations in KSA. The proposed system helped to select the location that has the highest renewable energy penetration, lowest net present cost (NPC) and levelized the cost of energy (LCOE), highest total energy that can be sold to the grid, as well as the lowest CO_2 emissions.

1.6 Dissertation Structure

Second chapter introduces the current state and the expected increase of electricity generation and demand in KSA. It provides concise information about climate change, geography, and demography of the country. Power generation, fuel consumption and the corresponding CO_2 emission have been illustrated as well. The strategic goal of the country known as 2030 Vision and its renewable energy planning has been introduced. Furthermore, this chapter investigates the potential renewable energy resources giving emphasis to wind and solar due to their availability. Concerning maps and characteristics of these sources have been produced and added.

Third chapter introduces different technologies for exploiting wind and solar energy. It compares these technologies and provides insight to their inner workings, pros and cons. Power systems of renewable energy are generally classified according to their component configurations, their operational and functional requirements, and how the equipment is connected to electrical loads and other power sources. This chapter also provides information about grid-connected and stand-alone (off-grid) renewable energy systems.

Fourth chapter provides techno-economic analysis of a grid-connected solar pv-wind hybrid system. Four different cities in KSA were selected to do the analysis using the meteorological data of these locations. Technical, economic and environmental feasibility of each system is investigated according to the conditions and resources of KSA. Simulations results of the technical and economic analysis are provided. Furthermore, to give a blueprint of the system reliability and determine how sensitive the outputs are to any changes in the system's variables, sensitivity analysis was performed.

Fifth chapter explores the renewable energy technology integration requirements to the KSA's grid system. It starts with the conventional operation and the importance of system flexibility. It introduces the requirements of system flexibility and explores the effects of renewable energy sources variability on the system operation. Furthermore, it investigates the grid codes of different developed countries and identifies the mandatory codes for renewable energy systems connected to utility grid which can be added to the current grid code.

Sixth chapter summarizes all findings and results of this research. Furthermore, introduces ideas and cases for further research.

Seventh chapter lists all the references and sources used in this study.

CHAPTER 2

PROJECT BACKGROUND

2.1 Climate Change Overview

Climate change is one of the main problems that primarily motivate the topic. Energy use is changing fast. Therefore, the shift to renewable sources is needed in the near future. In order to check the rise in global temperatures, transition to renewable energy needs to happen faster, not just in power generation but in heating, buildings and public transportation.

Understanding greenhouse effect is important to understand climate change. As it can be seen from Figure 3 that the sunlight passes through the atmosphere and warms the Earth's surface. After the heat got absorbed it will be radiated back toward the space. The vast majority of the heat is then absorbed by the greenhouse gases and radiated back toward the Earth's surface. Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O) and Water vapor (H_2O) are the gases that contribute to the greenhouse effect which block heat from escaping [22]. Since the pre-industrial era, anthropogenic greenhouse gas (GHG) emissions have driven large increases in the atmospheric concentrations of these gases [23].

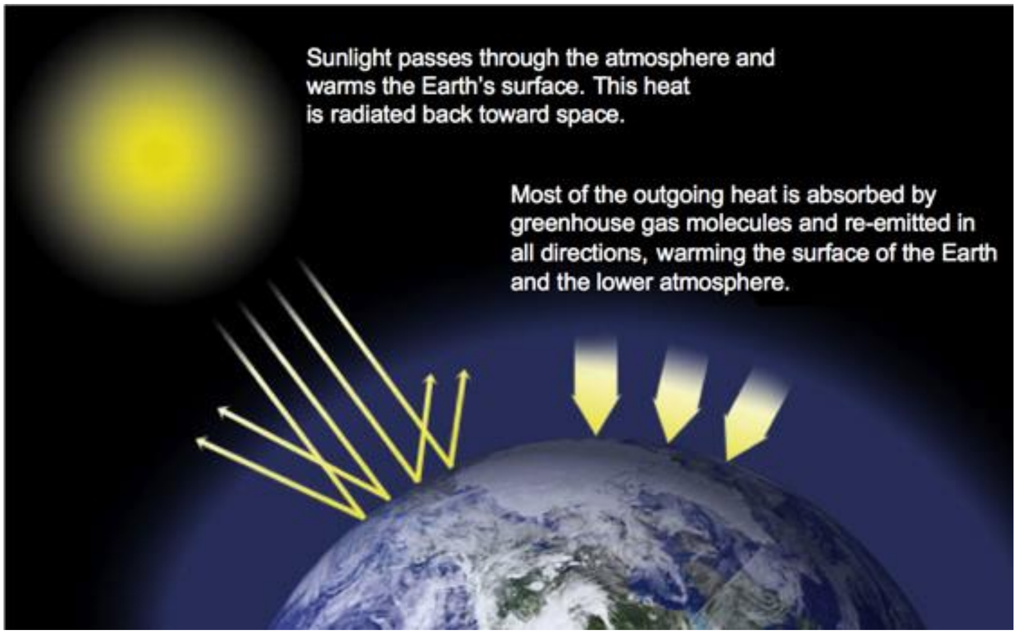


Fig. 3 Green House Effect [22]

Most climate scientists agree that the main cause of the current global warming is human activities on the Earth. Over the last century, the use of fossil fuels like oil and coal has increased the concentration of carbon dioxide (CO_2)[24]. The reason is because the oil or coal burning process combines carbon and oxygen in the air which make CO_2. Also, clearing land for, industry, agriculture, and other human activities have increased greenhouse gases.

Global average temperature, sea level, arctic sea ice, carbon dioxide concentration, ozone hole, and other observed changes are the key indicators of climate change. Figure 4 shows the combined global land and marine surface temperature from 1850 to 2017. Based on the analysis, the results showed that 2015 and 2016 are clearly the warmest years.

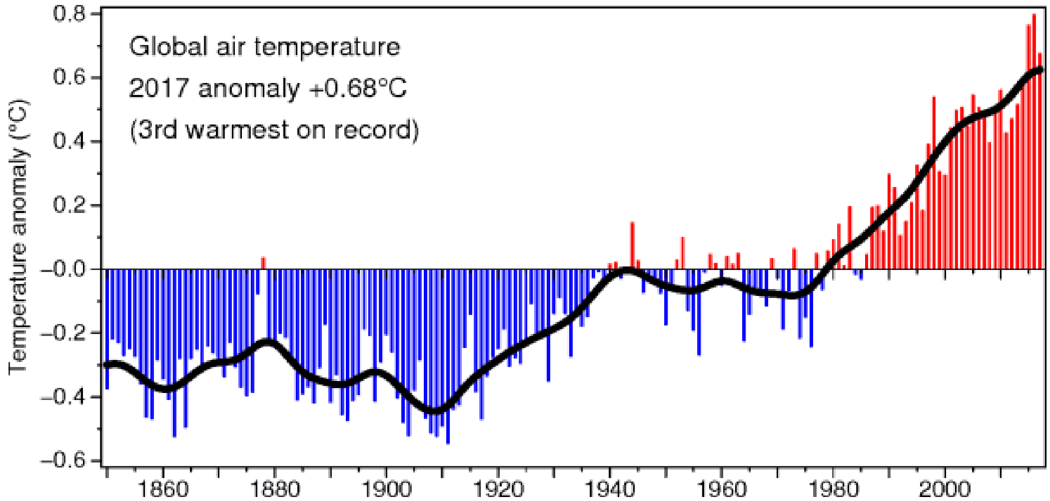


Fig. 4 Global Air Temperature [20]

Figure 5 shows the sea level rise. This rise is caused primarily by the added water from melting ice and the expansion of seawater when it warms. Graph (5a), shows the rate of change of the sea level since 1993 and it is 3.2 millimeters per year as it observed by the satellites. Line graph (5b) represents the sea level change using the costal tide data from 1870 to 2000.

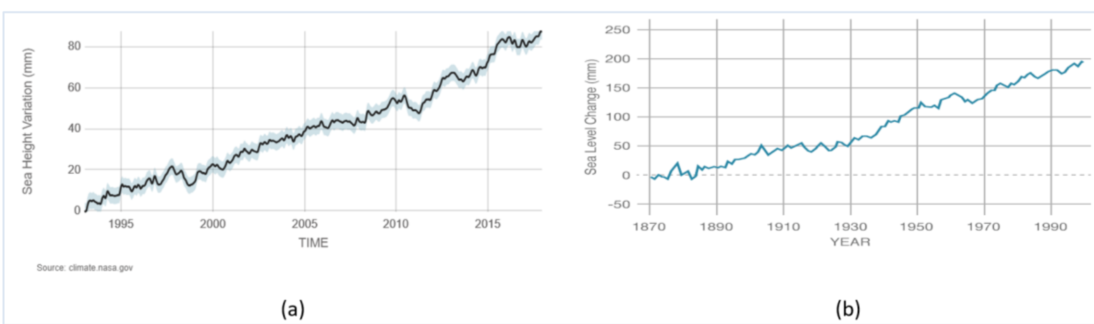


Fig. 5 Sea Level [22]

Regarding the future risks and impacts, the Intergovernmental Panel on Climate Change (IPCC) report published in 2014 stated that, continued emission of greenhouse gases (GHG) will cause further warming and induce many changes in the global climate system. These changes will have impacts on people and ecosystems. To limit risks caused by the climate change, sustained and substantial reductions in GHG emissions are required [23].

2.2 Geography and Demographics of KSA

Figure 6 below is a map extracted from Google Maps showing Saudi Arabia and its location in the southwest Asia. It occupies the largest part of the Arabian Peninsula with a total area of around 2,000,000Km^2, having total costal line of 2,640 Km. The country is divided into 13 provinces. Regarding its climate, typically it has quite high temperature during the summer season, which reaches to almost 50 C° in some areas and the minimum temperature occurs during January. It has total population of 33,413,600 according to the latest census published by General Authority of Statistics [25].

KSA is a member of the Group of Twenty (G20). The country's economy is the largest in the Arab world and strongly dependent on oil. It ranks as the largest exporter of petroleum since it possesses around 18% of the world's proven petroleum reserves. The oil and gas sector accounts for about 85% of export earnings, and about 50% of gross domestic product (GDP)[26].

Fig. 6 Kingdom of Saudi Arabia Map

2.3 Power Generation and Fuel Consumption in KSA

2.3.1 Power Generation in KSA

Power demand in Saudi Arabia has been significantly increasing especially over the last two decades. According to the electricity and cogeneration regulatory authority (ECRA) annual statistical booklet for electricity and seawater desalination industries' report in 2016, the average customer growth was 5.09% per year over the last twenty years. Also, according to the report, total; electricity capacity provided by all licensed providers is 87754MW which is produced by 81 power plants across the country [6]. The approximate percentage of each electricity producer showed that the Saudi Electricity Company (SEC) represents the highest electricity producer with

68% of the total generation, followed by Saline Water Conversion Corporation Company (SWCC) with 9% and 23% by others.

In 1990, the number of customers was almost 2,366,878 and the peak load recorded was 13069 MW. In 2016, the number of registered customers recorded was more than 8,600,000 and the peak load was around 60,828 MW as it can be seen from Figure 7. In the same year, the available generation capacities from all providers were more than 80,000 MW in order to meet the peak load demand over the summer season[27]. The SEC annual reports also showed that there is a huge growth in electricity generation and that referred to the rapid population and high economic growth, along with many other factors playing an important role in causing this increase in power generation.

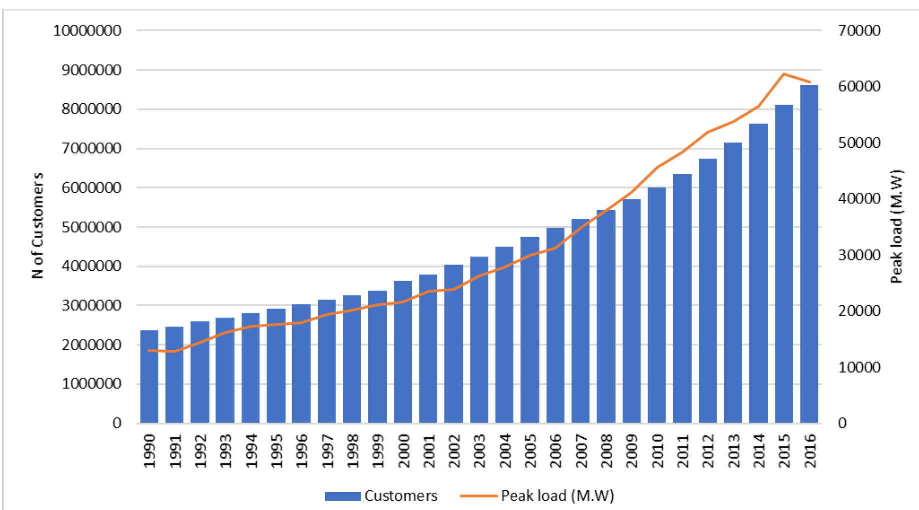


Fig. 7 Customers verses Peak load in KSA

2.3.2 Electricity Fuel Consumption in KSA

Saudi Arabia's current demand for electricity relies heavily on the combustion of fossil fuels. The whole electricity providers presented in Figure 8 used fossil fuel to generate power for their customers. Figure 9 represents the annual fuel consumption for electricity and seawater desalination industries in 2016. Crude Oil, HFO, Diesel, and Gas are the fuels that have been used in power plants. For SEC, Crude Oil is found to be the highest consumed fuel by and an increase of 185% was recorded in between 2010 and 2014, followed by Gas with a 66% rise as illustrated in Figure 2 in chapter 1.

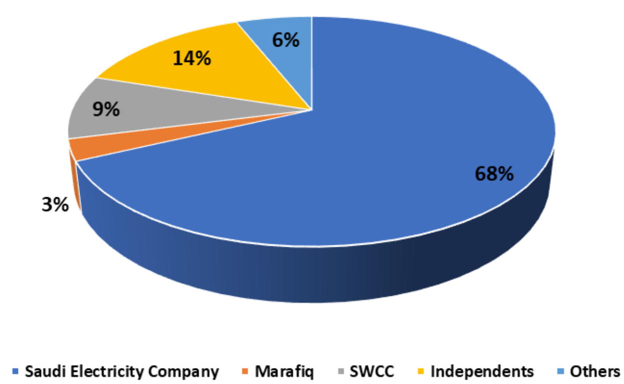


Fig. 8 Electricity Producers in 2016

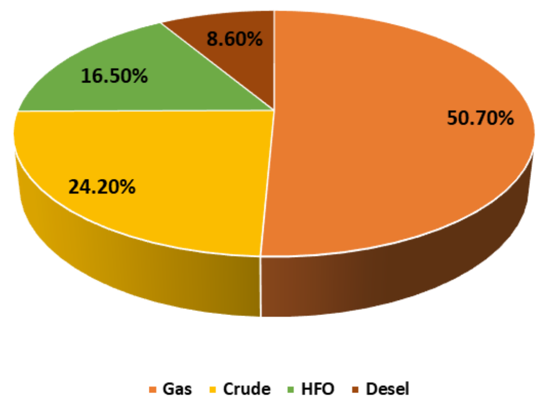


Fig. 9 Fuel Types used by Power Plants in 2016

Figure 10 shows the percentage of each type of electricity consumers in 2016. Due to the expected increase in the industrial and residential growth in the future, oil consumption for electrical generation is expected to record an increase by 100% in the period spanning 2015 to 2030 [6]. Therefore, it is essential to find an alternative method of electricity production to reduce the country's power generation dependency on fossil fuel.

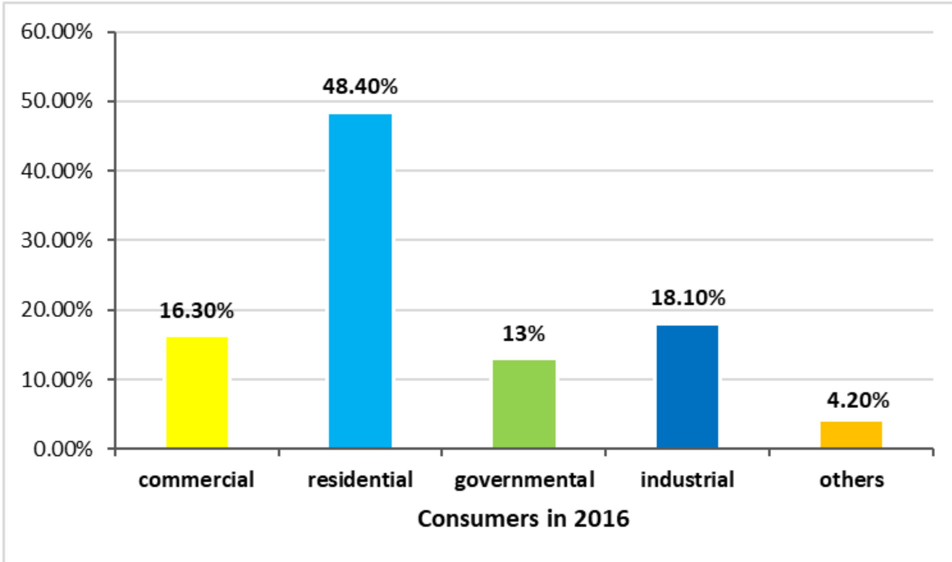


Fig. 10 Electricity Consumers in 2016

2.4 Power Generation and Corresponding CO_2 Emission

Greenhouse gases, climate change, and environmental pollution have been among the most important environmental concerns worldwide, in recent decades. Currently, CO_2 level and other greenhouse gases in the atmosphere are among the greatest environmental threats. CO_2 plays a significant role in enhancing the greenhouse effect and it represents more than 60% of this effect [28].

Electricity and heat generation are two sectors which produced two-thirds of global CO_2 emissions in 2015. The report of CO_2 emissions in 2017 showed that electricity and heat generation, by far the largest, which accounted for 42%, and followed by transportation systems, accounted for 24%, as it illustrated in Figure 11.

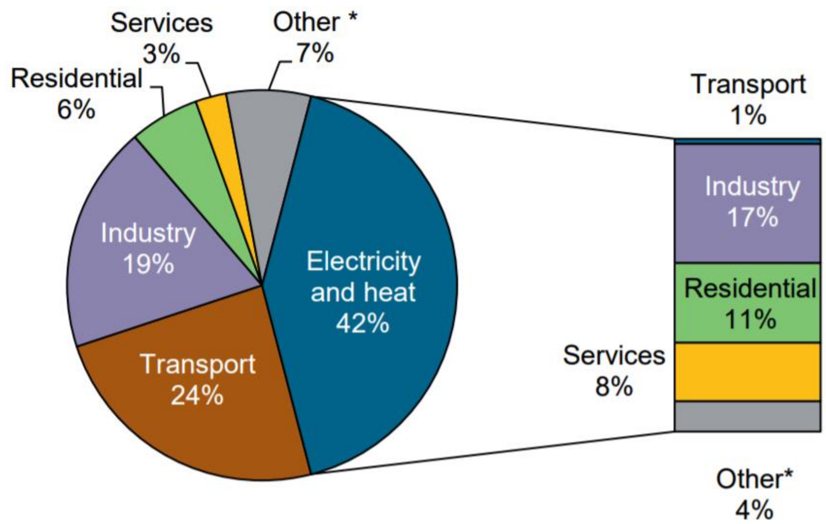


Fig. 11 World CO_2 emissions from fuel combustion by sector in 2015 (IEA) [24]

Over two-thirds of global emissions for 2015 originated from just ten countries, with a total of 21.7 Gt CO_2. Saudi Arabia is one of the top ten countries that have the highest CO_2 emission recorded. Figure 12 shows the comparison between the top producers of Carbon Dioxide emission in the world and KSA is recorded the lowest amount among these countries.

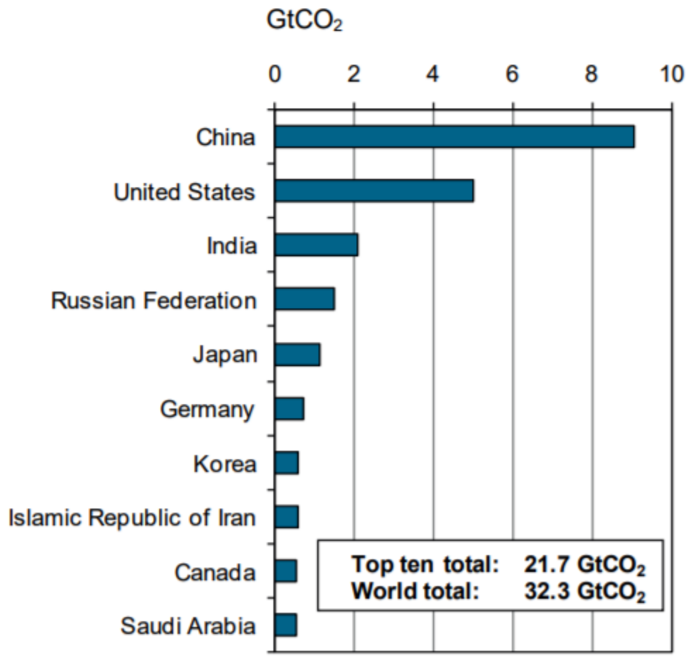


Fig. 12 Top ten CO_2 emitting countries, 2015 (IEA) [24]

2.5 Vision 2030 and Renewable Energy Planning for KSA

2.5.1 Saudi Arabia 2030 Vision

Saudi Arabia has unveiled its vision 2030 roadmap with more than 20 goals that have been mentioned in the vision's report. One of the main targets will be focused on reducing the country's oil dependency. Also, the government is seeking to move from the current position as the 19th largest economy in the world into the top 15 by 2030. Investment in renewable energy sector will play an important role in achieving the vision's main goals. At present, RE is getting government attention in order to build up the sector and exploit the natural potential of different sources like solar and wind power [6].

2.5.2 Renewable Energy Planning for KSA

The significant increase of electricity demand in KSA means that power generation will expand and that will lead to increased consumption of fossil fuels. This rapid increase of the conventional generation is the major cause of environmental pollution and impacts on human health as described in the previous chapter. Studies show that power demand in KSA is expected to continue its significant increase to reach more than 100,000 MW over the coming 10-15 years. Also, that will affect the country's fuels exportation and the revenue earning. Meanwhile, the main goal of the country's vision 2030 is focusing on the economy and prosperity. Therefore, it is essential to enhance transition to sustainable energy to avoid the rapid increase in the future generation capacity and reduce the country's power generation from conventional power plants.

In establishing the King Abdullah City of Atomic and Renewable Energy (KACARE) in 2010, the aim was to build renewable energy power sector for KSA. One of the most important projects is the renewable resources atlas of the KSA, which KACARE is developing. Almost 32 monitoring stations across the country are providing extensive information about solar resources, and nine stations for wind resources are providing limited information [29]. By using these types of data to analyse the potential of renewable energy resources in such hot climate regions, researchers, and power project developers would contribute to the achievement of KSA's 2032 and 2040 RE visions mentioned in References [18,19].

Based on the vision 2030 report, the initial target of renewable energy production is 9.5GW by 2030. However, several studies show that the future production is expected to be more than that [30]. One of those studies made by KACARE stated that by 2032, the production from renewable energy is expected to have a capacity of 54 GW [31]. This future capacity is planned to be provided by Solar PV, Solar CSP, Wind, Geothermal, and Waste-to-energy. Also, The International Renewable Energy Agency (IRENA) report in 2015 mentioned that the capacity targets of Saudi Arabia for the upcoming 15 years disaggregated as follows 16 GW solar PV, 25 GW CSP, 9 GW wind, 3 GW waste-to-energy and 1 GW geothermal. The solar power will represent 75% out of the total RE production followed by wind energy.

Figure 13 represents renewable electricity generation targets by target dates. It includes 24 countries having different percentage levels and types of targets based on spectrum categories. This figure can help policy makers to better understand more about where their own national targets fit. Also, in visualizing the absolute level of clean energy production to be reached by the target date.

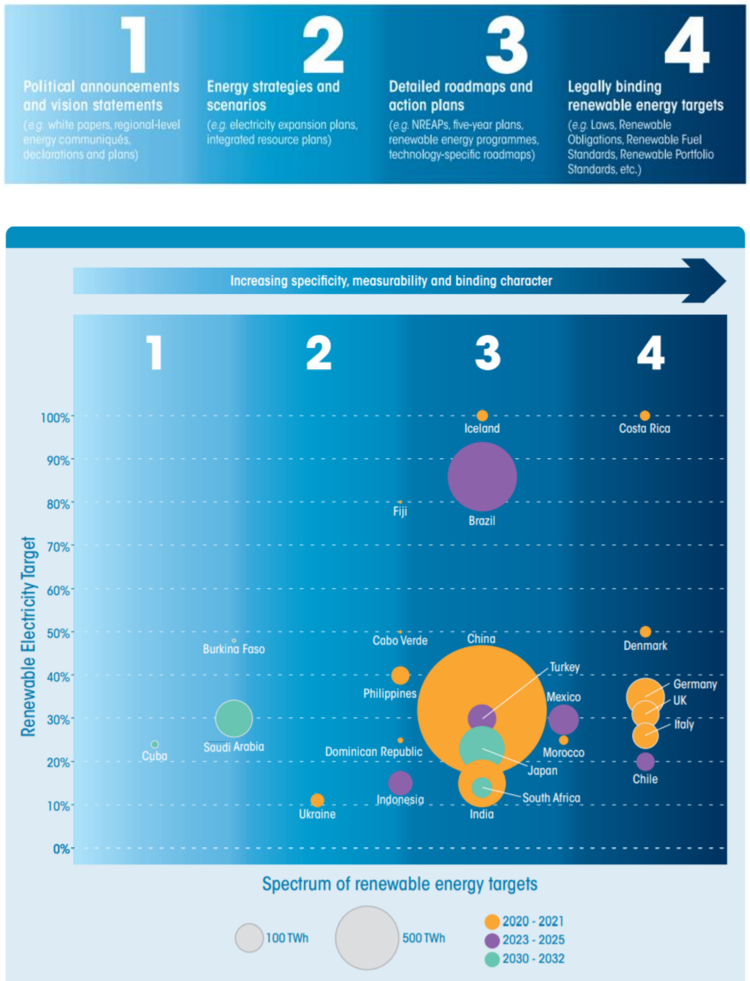


Fig. 13 Renewable Electricity Generation Targets by Target Date [32]

2.6 Renewable Energy Resources in KSA

2.6.1 Assessment of Renewable Energy Resources in KSA

Most types of renewable energy resources have encouraged the establishment of technologies. RE exploitation mainly depends on the potential of RE resources and economic analysis based on a certain site data. In addition to the importance of feasible costs analyses and the adequate resources, technical and environmental issues also play a significant role in the project's viability and sustainability.

Lack of rivers and huge dams with sufficient yearly flows draws the line under the hydropower technology opportunity in Saudi Arabia. This is due to the low average precipitation in such hot climate region. Hence, the potential for hydro power plants is very limited. In terms of geothermal resources which can be utilized in various forms such as direct use, electricity generation, space heating, and industrial usage, studies of this type of RE resource exploration were started in 1980 in Saudi Arabia. The results showed that, Saudi Arabia is among the most geothermally active countries in the Middle East [33]. However, power plants are not yet installed due to the availability of abundant natural resources.

Biomass energy is a RE source derived from organic materials. Due to various human and natural activities, carbonaceous waste can be used as sustainable source of energy to create electricity or other forms of power. Biomass resources in Saudi Arabia include a wide range of biomass residues, generated mainly in the form Municipal Solid Waste (MSW), Industrial Organic waste, and sewage. A Study has been conducted by M. Sadiq et al. [34] showed the potential of biomass energy in the Arab countries. KSA stands fourth after Morocco, Egypt and Sudan and its estimated total biomass energy potential is 3.0 (mtoe). This amount of organic waste generation can be converted into useful energy instead of being harmful to the environment as well as human health as study mentioned.

Regarding the wind potential, in Saudi Arabia there are some areas with mean wind velocity of 5.5-6 m/s and few areas with 7-8 m/s. Based on KACARE, the likelihood is that wind turbines with different sizes will be installed along the coasts of Red Sea and east Gulf with the aim of generating electricity for seawater desalination and the conversion of brackish water to potable water by 2032.

Concerning solar energy potential, Saudi Arabia has plentiful sunlight throughout the year, and has one of the highest insolation rates in the world. KACARE started the collection of sunshine duration data at several meteorological stations in 2013 and created the network map and stations details. Statistical analysis shows that all parts of Saudi Arabia enjoy a sunny climate and also shows the expected potential of solar power under consideration especially during the summer months.

An analytical study, made for evaluating different renewable energy sources in KSA, shows that PV, CSP, and wind energy are the most effective RE technologies, respectively [13]. Based on the information of this study, solar and wind energy resources were used to carry out designed and analysis of the hybrid grid connected system.

2.6.2 Solar Resource in KSA

Solar energy has long been considered promising in Saudi Arabia based on the expected large solar resources. KACARE is developing the Renewable Resource Monitoring and Mapping (RRMM) as part of its mission to establish a sustainable energy mix in Saudi Arabia. The purpose of RRMM is to collect and deliver renewable resource data in an online with an initial focus on solar and wind resources. The online Renewable Resource Atlas for Saudi Arabia is part of this project and high-quality resource data, maps, and analysis tools are provided for users to understand the magnitude, characteristics, and variability of solar and wind resources. Figure 14 shows different types of solar resource monitoring stations, by Province [17].

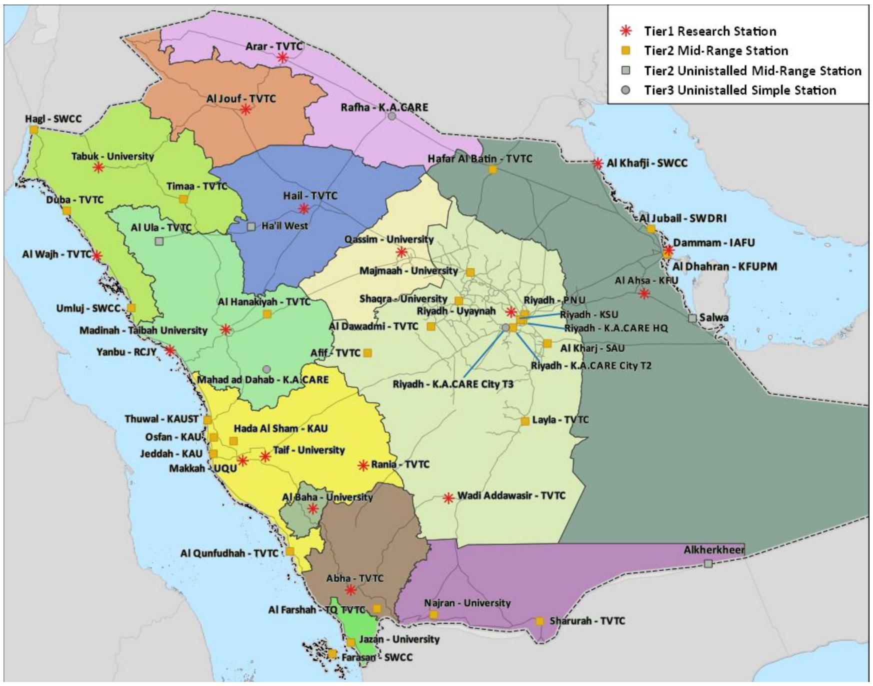


Fig. 14 Solar resource monitoring stations, by Province [17]

Under the supervision of KACARE, and in partnership with universities, colleges and institutes, and government agency partners in KSA, more than 25 solar monitoring stations across the country are being operated and maintained on a rigorous schedule. These stations have been installed to collect solar data and Figure 15 depicts the flow of this data from collection to dissemination.

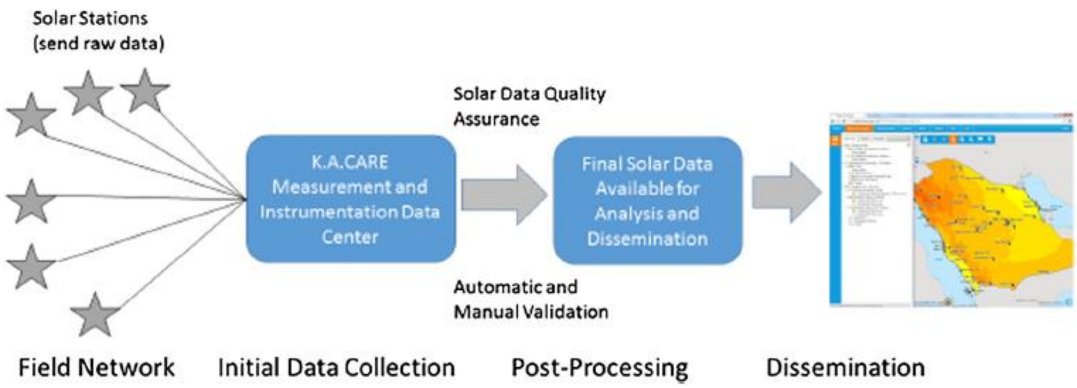


Fig. 15 Solar resource data flow [35]

Several studies have been conducted and showed the potential of solar power resources in the KSA. A study conducted by Erica et al. [35] summarized one year of solar resource measurement data for 30 stations, which KACARE provided across the country. They analyzed the Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), and Diffuse Horizontal Irradiance (DHI) data, based on one-minute measurements for the first twelve months of data collection as ilustrated in Figure 16. The results shwoed that GHI values are high at all locations in the country with relatively low variability. Arif et al. [36] addressed the solar energy future aspects and the applications of solar power along with different studies conducted in the same field with the aim of establishing energy polices for KSA [37,38]. In addition, Almarshoud [39] presented a review of the photovoltaic system for 32 sites of solar resources across KSA using three modes of a sun tracking system. That study showed a high productivity of energy and the difference in percentages of using a fixed tilt angle, and 1-axis and 2-axis tracking modes for the 32 sites. A.M. Ramli et al. [40]

conducted experimental investigations to study the effect of weather conditions on PV output power production using a simple rule-based model. This study came up with results presented as a percentage and showed the significant effect of dust, rain, and clouds on PV panel's efficiency.

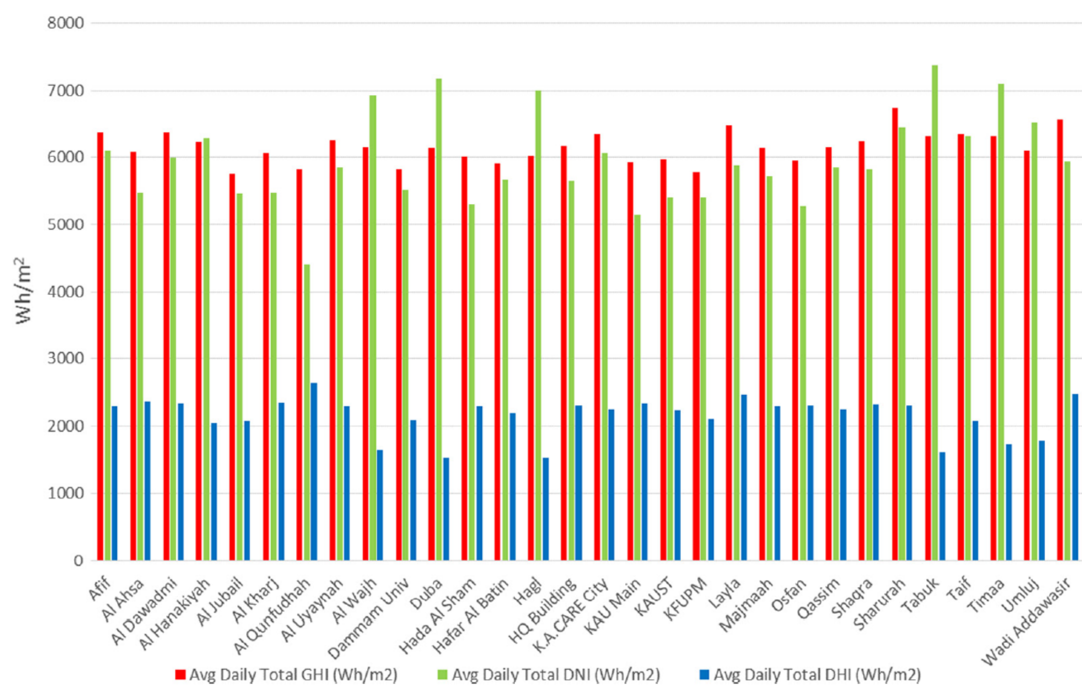


Fig. 16 Solar irradiance summary by station (Oct 1, 2013–Sept 30, 2014) [35]

The map of global horizontal irradiation of Saudi Arabia based on annual monthly average sunshine for the year of 2016 is showen in Figure 17. This figure shows that some areas in southeren and northern provinces of Saudi Arabia receive higher GHI with an approximate range of 7500 – 8000 Wh/m^2/day.

Solar energy has been exploited in some areas in Saudi Arabia during the last decade. However, to date, the electricty generation from solar projects have been under personal or commercial use with no option to sell electricity to the grid. Also, there is no utility scale solar project connected to the Saudi Arabia electricity generation system.

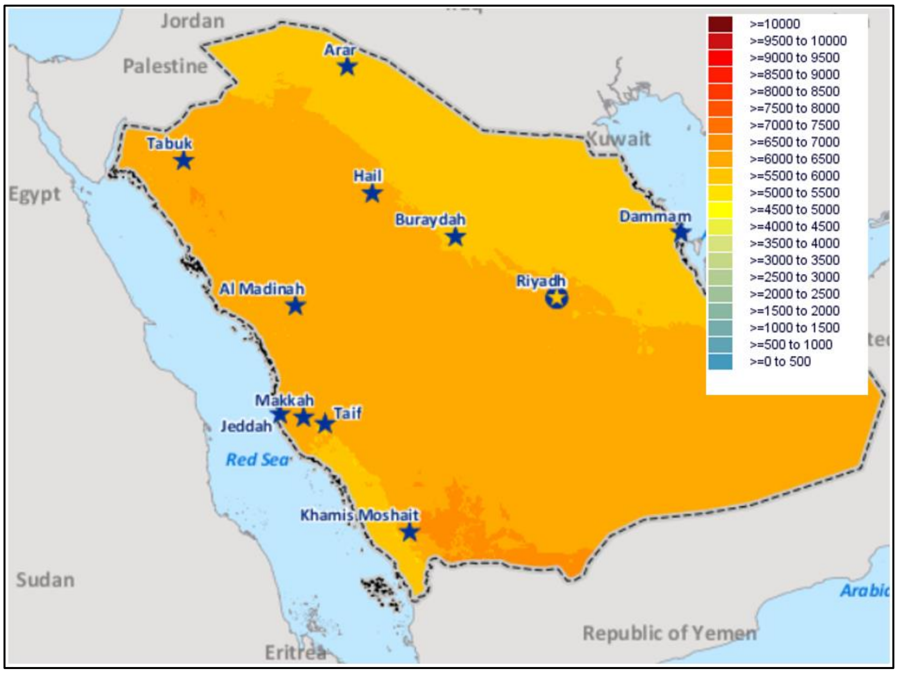


Fig. 17 Annual Monthly Average GHI (Wh/m^2/day) for the yare 2016 [29]

2.6.3 Wind Resource in KSA

For wind energy, researchers conducted several studies for evaluating the potential of wind energy and resources for different locations in Saudi Arabia. S. Rehman et al. [41] presented an analysis of 14 years of wind data for five costal locations in the KSA with the aim of assessing the potential wind energy. In their research, they found the most suitable location for harnessing the power of wind.

Another study regarding wind power costs in 20 locations in KSA, used data recorded from 1970 to 1982. Here, S. Rehman et al. [42] showed that the minimum cost of electricity generated by using different wind turbines with a maximum output of 2500,1300, and 600 kW was found to be 0.0234, 0.0295, and 0.0438 $/kWh in the same city. In 2005, Alabbadi [43] assessed the power density and wind energy resources for five locations by using the data collected between 1995 and 2002. Another assessment of wind energy performed in 2012, for five different locations in KSA, was introduced by Eltamaly et al. [44] through a computer program for the purpose of selecting the most effective size of wind turbine for each site. In 2015, Baseer et al. [45] analyzed and presented the characteristics of wind speed for Jubail Industrial City at three different heights. They also analyzed seven locations in the same city by using different wind data at 10 m above ground level (AGL) [46]. The results showed that the East of Jubail Industrial City is the most promising area for wind energy production from a 3 MW wind machine. S.M. Shaahid et al. [47] presented an economic feasibility study for the development of 75 MW wind power plants in four coastal regions in KSA using different combinations of 600 kW wind turbines (wind farms). This research showed that the energy from a wind electric conversion system (WECS) would not produce for 41–53% of the time during the year. Davut Solyali et al. [48] and Farivar Fazelpour et al. [49] did similar studies in other countries and presented the technical assessment of wind resources and energy density using the Weibull distribution function to do the estimation. Additionally, A. Dabbaghiyan et al. [50] and A. Allouhi et al. [51] evaluated the wind energy potential for different sites at various heights in different countries using Weibull distribution to assess the wind power density. In the Bushehr province, the average wind power density was approximately 265 W/m^2 at the height of 40 m. In Morocco, the results showed the most suitable location for harnessing the wind power among six coastal locations.

In this study, wind resources in several locations in KSA have been assessed and used, particularly in hybrid grid-connected system design as there was not a similar study done before that assessed the wind resources potential using RRMM data. The selected locations to do the analyses are Riyadh, Hafar Albatin, Sharurah, and Yanbu. Figure 18 shows nine different wind resource monitoring stations. These stations were installed by KACARE and have different starting date of data collection. Also, KACARE is planning to install around 40 other monitoring masts as to date the country wind resource has not been fully characterized. Figure 19 shows a general picture of mesoscale modeling and that illustrates the annual average wind speed at 100 m AGL. As it can be seen, the annual average wind speed in most of KSA was in between 6 to 8 m/s.

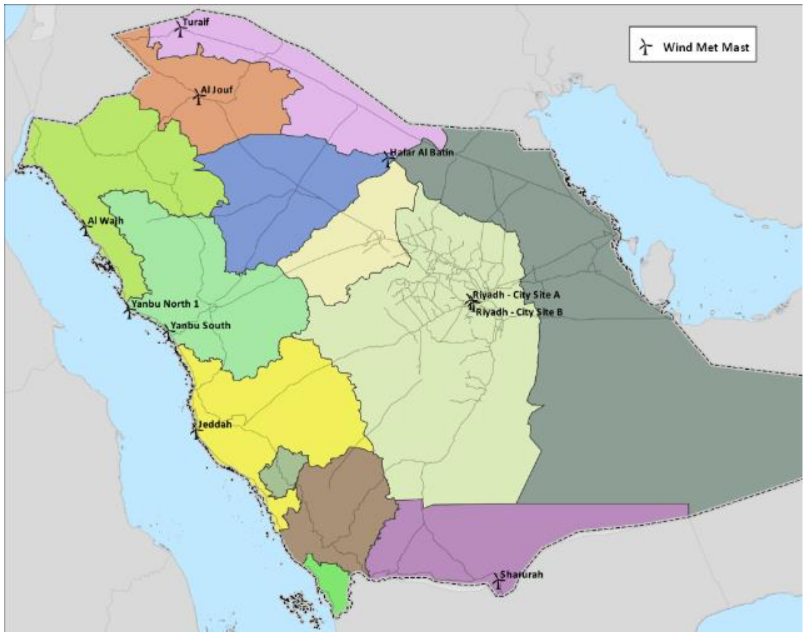


Fig. 18 Wind resource monitoring stations [29]

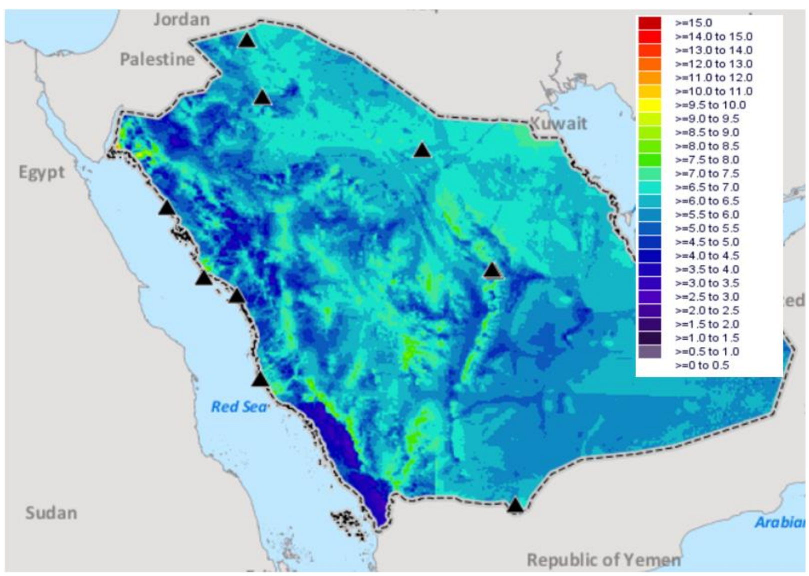


Fig. 19 Historical annual average wind speed at 100 m/s [29]

CHAPTER 3.

RENEWABLE ENERGY TECHNOLOGIES AND TYPES OF RE SYSTEMS

3.1 Renewable Energy Technologies

Renewable energy technologies enable users to generate electricity, create heat and fuel from renewable sources. Solar, hydro, wind, bioenergy, wave, and tidal energy-based technologies are all powered by the sun. Technologies of geothermal are powered by deep heat from the Earth's core. Bioenergy technologies allow users to transfer the solar energy stored in plants, wastes of food, farm forest, sewage, and algae into electricity, fuel, and heat, using a variety of approaches. By exploiting these technologies, users can heat and cool buildings, produce electricity, and to travel by sea, land etc. without producing dangerous greenhouse gases and other forms of pollution[52]. Since solar and wind energy technologies have been used in this project, brief descriptions of these effective technologies are presented in this section.

3.1.1 Wind Technologies

Wind energy plays an important role in any plan to exploit renewable energy resources. Historically, wind has been a source of energy for the then flourishing civilizations and now a days it is an obvious option for the generation of electricity. It has evolved dramatically during the last decades and at present the estimated wind energy share of global electricity production is about 4.0% based on the latest REN21 report [53].

For electricity generation, wind power is arguably the most developed renewable energy technology among other types of clean energy [54]. This is mainly due to the concessionary policy by many countries toward the industry of wind power. Though wind power has shown a great performance over the recent years, it is also creating environmental impacts, such as wind farm noise as well as threat to the wildlife and may spoil the view for the near neighborhoods. These impacts considered minor when compared with emission caused by fossil fuels, however its effect on humans should not be ignored due to its great performance and potential development in usage [55].

There are several challenges for the design of electricity production system (generator), the control of wind speed, and wind power intensity. These are important to be controlled in order to synchronize a generator of wind turbine to the grid, which is working at constant frequency as well as at a certain voltage and phase sequence. Two types of wind turbines can be recognized, and these are variable (VSWT) and fixed (FSWT) speed wind turbines [56]. In terms of efficiency and reliability, modern wind turbines have performed well compared to the 1970s-1980s wind turbines which were mostly constant speed having low output power. The power output has increased from few kilowatts up to 8MW for a single turbine due to the use of new technology, along with the higher hub height and larger sweep area of its blades. These modern turbines, either offshore or onshore are much larger in size and are used primarily in large utility grids.

Since the late 1990s, variable speed wind turbines are the most commonly used type for high power levels, mainly to add more flexibility to the system considering power quality, energy yield, and turbines audible noise. Also, wind turbines have different designs and configurations. The most widely used system of wind turbines is known as doubly fed induction generator (DFIG). It has two converters namely grid-side converter (GSC) and rotor-side converter (RSC) connected between grid and a wound rotor induction generator. This Type has more wider operating speed range which allows the turbine to capture more energy from wind [57].

3.1.1.1 Fixed speed wind energy conversion systems (WECS)

In a fixed speed WECS , fixed-speed wind turbines almost rotate at a constant speed, which is determined by the grid frequency, the gear ratio, and the generator's number of poles [56]. The maximum conversion efficiency in this system can be achieved only at a certain wind speed, and the efficiency of the system degrades at other level of wind speeds. In order to avoid the possible damage caused by high wind gusts, fixed speed turbines are protected by aerodynamic control of blades. The turbine that has such system (FSWT) generates highly fluctuating output power to the grid. This fluctuation cause disturbances to the power system. This type of turbine also requires a powerful mechanical design in order to absorb the high mechanical stresses. Even though there are different low cost and attractive solutions for some problems i.e. inrush current during start-up, reactive power demand from the turbine generators etc, such system cannot extract as much energy from the wind as a variable speed WECS [56].

3.1.1.2 Variable speed wind energy conversion systems

Over a wide range of wind speeds, the variable-speed wind turbines (VSWT) can achieve maximum energy conversion efficiency. The turbine in this system can continuously adjust its rotational speed according to the wind speed and in this way the stress on the mechanical structure will be reduced as well as the delivered electrical power becomes smoother. To make the speed of turbine adjustable, the generator of the wind turbine is normally connected to grid through a power converter system. This system enables the control of the generator speed that is mechanically coupled to the rotor (blades) of the wind turbine. The main advantages of this system include reduced mechanical stress, increased wind energy output, and improved power quality. However, the main drawbacks of the variable-speed turbine are the power losses caused by the use of power converters and the increased manufacturing cost. Nevertheless, the power losses and additional cost are compensated for by the higher energy production [58].

3.1.2 Photovoltaic Technology

Significant progress in reducing cost and rising the efficiency of PV cells has been made over the past years. The terrestrial uses of this technology are now globally widespread, particularly in providing energy for lighting, telecommunications, and other electrical appliances in remote areas where a more conventional power generation would be too costly. These applications range from ubiquitous solar calculators to the power stations of several megawatts [59].

Now a days, growing number of commercial, domestic, and industrial buildings have PV arrays providing part of their electricity needs. The photovoltaic or solar cell is the basic component of a PV power system. Module of a PV consists of separate solar cells connected electrically to increase their power output. So, in order to obtain more power, certain number of cells are normally connected together to form modules. To obtain even more output power, groups of modules are in turn mounted side-by-side and connected together either in series or parallel connection to form PV arrays [18].

Global solar PV installation has come from using different technologies, such as concentrated solar PV and thin film, and silicon technology. However, in the present PV industry the technology of crystalline silicon (c-Si) has more than 85% of the share, through modules and cells based on mono, poly, and multicrystalline wafer technology. The sustainable growth of the solar PV market and industry is phenomenal, with a considerable surge, on average over 40% during the last few (10 to 15) years, recorded globally. The silicon solar cell industry primarily depends on the semiconductor industry for its feedstock. Regarding the (thin film) solar cells, they have created a niche in building integrated markets and window-based applications. Good performance stability (25 years) and high/reasonable efficiency conversion of solar cells are two measures for any solar technology entering the market. Thin film and silicon solar PV technologies have created a substantial market size and have proved their potential. In terms of technology development, the PV solar cells are generally divided into three generations and these are: c-Si solar cells, thin film-based cells, and organic-inorganic hybrid solar cells, more details can be found in [60]. Latest researches regarding PV solar cells efficiency have published an extensive listing of the highest independently confirmed efficiencies for solar cells and modules [61].

3.2 Types of Renewable Energy Systems

Power systems of renewable energy are generally classified according to their component configurations, their operational and functional requirements, and how the equipment is connected to electrical loads and other power sources. Grid-connected and stand-alone systems are the two principal classifications. Renewable energy systems can be designed to generate AC and/or DC power service, can operate autonomously or interconnected with the utility grid, and different renewable energy sources can be connected with each other (Hybrid system) and with or without energy storage backup systems [62].

Grid-connected systems are designed to operate with the electric utility grid. The primary component in grid-connected systems depend on the type of renewable energy sources i.e. PV, solar thermal, wind, hydro, single or combined hybrid systems etc. Generally, the renewable energy system or microgrid system consists of distributed power sources connected to loads and it can operate in either grid-connected mode or off-grid mode and can maintain operation autonomously. Mainly, renewable energy sources like solar panels and wind turbines are the generation units. In the grid-connected mode, the microgrid control the power balance of demand and supply by selling power to the grid or purchasing power from the main grid. Figure 20 illustrates the renewable energy grid connected system using different types of renewable energy sources. In the stand-alone or off-grid mode, the microgrid can work separately from the grid to keep a reliable power supply to the connected loads [63,19]. The grid serves as the main backup system and using battery bank is optional when the microgrid system connected to the utility grid. On the other hand, diesel generator or battery bank can work as a backup system for the isolated microgrid (stand-alone system) as illustrated in Figure 21 which is illustrates the connection of renewable energy stand-alone system [20].

To generate electricity with high efficiency and reliability, a co-generation or hybrid systems are recommended and have proven their usability. These types of systems commonly contain two or more combined renewable energy systems and can be connected with typical power plants to reduce fuel consumption and meet load demands with high efficiency. Using more RE source that have enough resources can be more profitable than the system that has only one type of renewable energy source [20].

One of the main advantages of using Hybrid Renewable Energy System (HRES) is the reduction of power outages due to the insufficiency of any renewable energy resources. For example, when there is not enough solar irradiance during the day, wind resources might be high enough to generate power with the help of the main contributor (utility grid). This will keep the system work reliably, maintain less fuel consumption, and the excess electricity can provide an additional income and that depends on the renewable energy resources strength and availability.

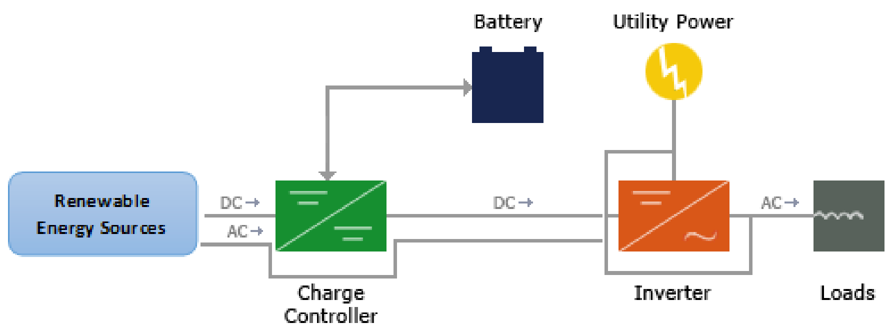


Fig. 20 Renewable energy Grid- connected System

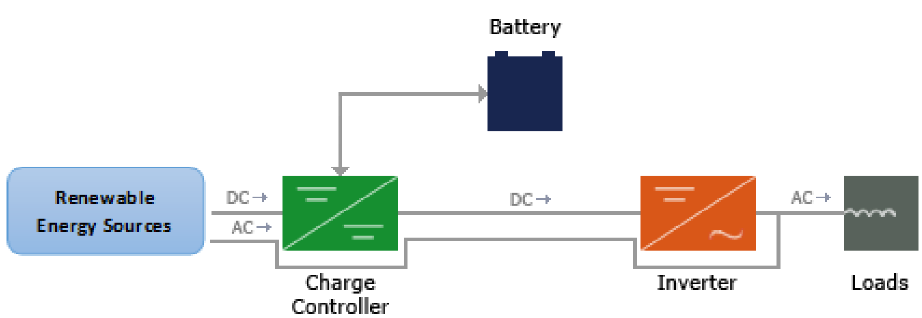


Fig. 21 Renewable energy stand-alone system

CHAPTER 4

TECHNO-ECONOMIC ANALYSIS OF A GRID-CONNECTED SOLAR PV-WIND HYBRID SYSTEM

The literature review and previous chapters showed the potential of solar and wind resources based on the RRMM data, which is provided by KACARE. Also, showed the need to investigate the potential of a large-scale grid-connected PV/Wind hybrid system, especially for the KSA's climate conditions. In this chapter, a resource assessment and techno-economic and analyzes of grid-connected solar/wind hybrid systems for different locations was carried out. In order to develop a hybrid grid-connected system model to analyze the power production and identify the best economic configuration, the National Renewable Energy Laboratory's (NREL) HOMER software was used. For the selected locations, the load applied was a hypothetical community load with a maximum daily consumption of 15 MWh/day. The peak of this load is expected to occur during August due to the high temperatures with 2.395 MW. The analyses of the grid-connected hybrid systems were performed by simulating each system's operation for 25 years—that is, the project lifetime. Capital costs, equipment replacement cost, operation and maintenance expenses, grid prices, and project lifetime were taken into consideration [21]. Furthermore, to get more accurate results, ground reflectance, ambient temperature, wind site altitude, and hub height were included in the computations. Based on system cost, amount and cost of energy production, energy buying from and selling to grid, lowest CO_2 emissions, best and optimal hybrid energy system among the selected locations was determined and further sensitivity analysis was carried out. Figure 22 depicts the flowchart of the techno-economic analysis of this hybrid grid-connected system.

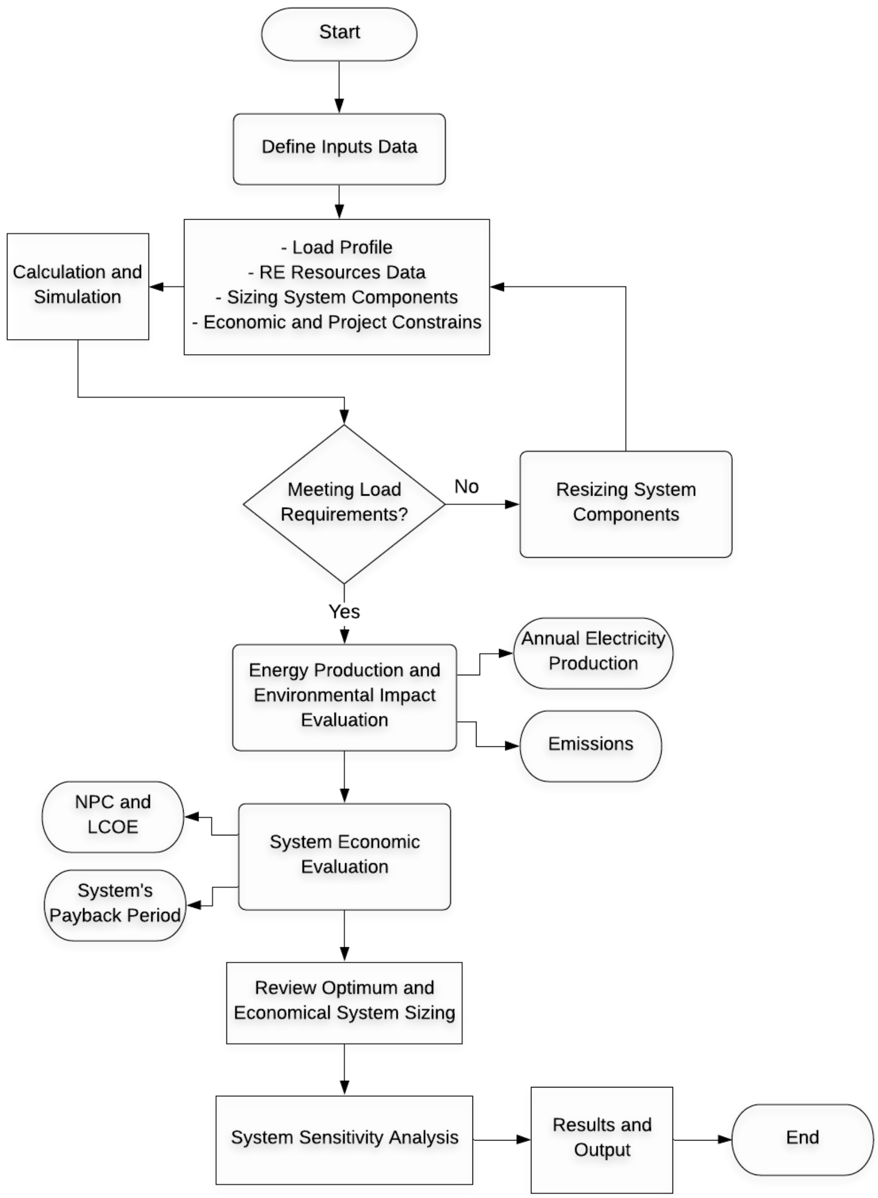


Fig. 22 System Flowchart

4.1 Resource Analysis

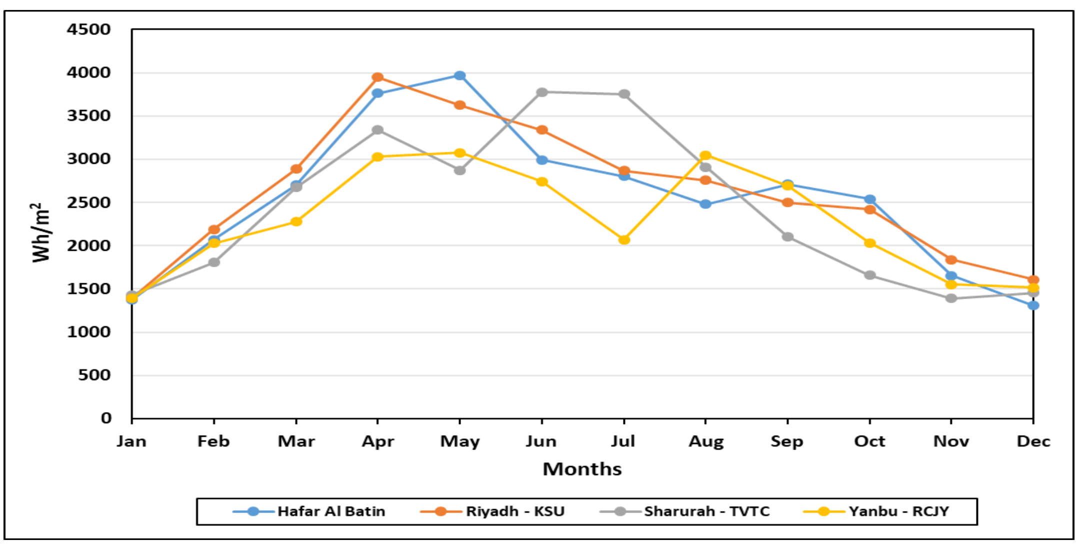
4.1.1 Solar Data

The analysis presented in this part was carried out using the KACARE's RRMM. To get an overview of the solar energy potential at the four selected cities in Table 1, the monthly average values of the GHI, DNI, and DHI were analyzed for all 12 months of 2015. This analysis aims to explore the availability of solar resources based on the data available from different sites. For this purpose, we downloaded the solar data for Hafar Albatin, Riyadh, Sharurah, and Yanbu from the Renewable Resource Atlas. As mentioned earlier Figure 14 in chapter 2 provides an overview of the stations installed across the country which were classified into the Tier 1 Research station, Tier 2 Mid-range stations, and Tier 3 Simple Stations. Sulaiman et al. [64] and Erica et al. [35] explained more about these types and the major equipment used for the Saudi solar resource network [21].

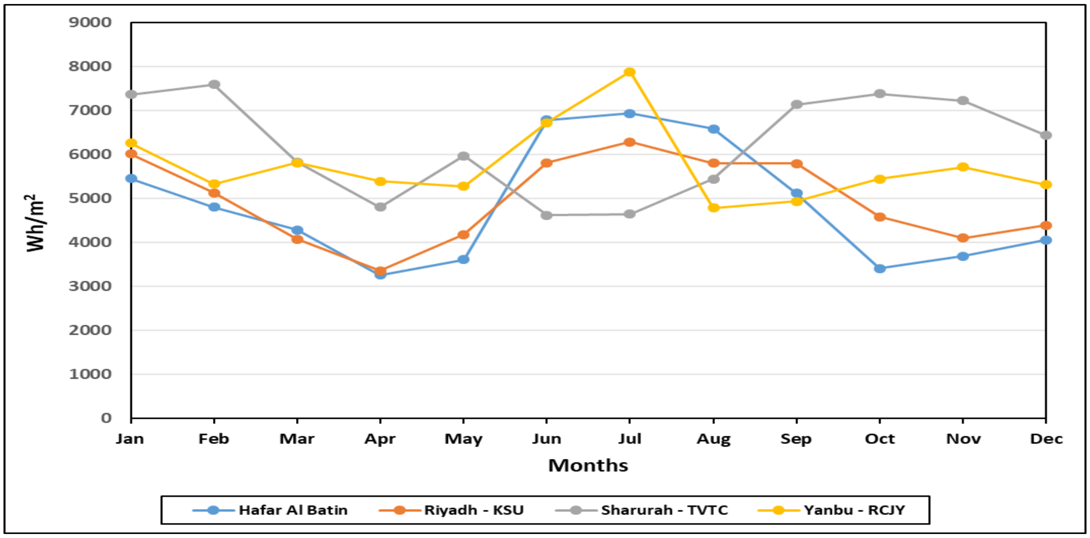
Table. 1 Solar monitoring stations details.

S. NO	Monitoring Sites	Tier	Longitude (E)	Latitude (N)	Operating Since
1	Hafar Albatin	2	45.9570	28.3320	6 October 2013
2	Riyadh	2	46.6163	24.7235	15 October 2014
3	Yanbu	1C	38.2046	24.9865	29 October 2014
4	Sharurah	2	47.0861	17.4758	3September 2013

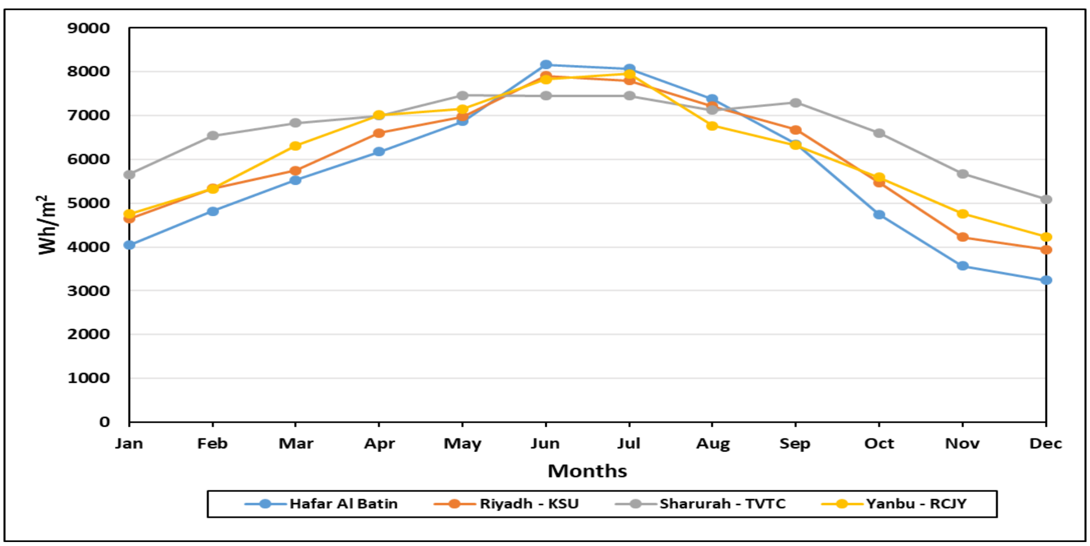
The DNI data are an important factor for Concentrating Solar Power (CSP) technologies. Figure 23 compares the measured values of the DNI for the four selected stations during 2015. This represents the average monthly data. The main selected cities were Hafar Albatin (Northeast region), Riyadh (middle of the country), Sharurah (South), and Yanbu (West coast). The maximum DNI occurred between June and July with approximately 7887 Wh/m^2 as the maximum for Yanbu, 6937.7 Wh/m^2 for Haver Albatin, and 6293 Wh/m^2 for Riyadh. The minimum DNI for Hafar Albatin and Riyadh was during April with less than 3500 Wh/m^2 and 4783.8 Wh/m^2 for Yanbu during August. It can be seen from the DNI line graph that when the longitude has the same or a similar value as explained in Table 1, DNI will follow the uniform pattern as shown for Hafar Albatin and Riyadh. The DHI is the scattered solar radiation, and it does not include the DNI since it is available from the entire sky. In Figure 23, the Hafear Albatin and Riyadh stations recorded the highest amount of DHI radiation in the first quarter of 2015, while Sharurah had the maximum DHI during July, and that for Yanbu during August [21].



(**a**) DHI



(**b**) DNI



(**c**) GHI

Fig. 23 Average Monthly DHI, DNI, and GHI at the selected stations.

GHI is the input data used in HOMER software since it is an important factor to photovoltaic installations, and it includes the DNI and DHI. In this part, we compared the GHI of the selected places using the data of the same year from January to December. The solar radiation started gradually increasing from the first quarter of the year and reached the maximum in June and July. Thereafter, it decreased from August until the minimum values occurred during December. We observed a uniform pattern for the GHI data from the line graph in Figure 23 with maximum values of 7400 to 8160 Wh/m^2 during the summer season and the minimally recorded values during winter, which were in between 3239 and 5088 Wh/m^2 for the sites.

In this study, we took different locations with different topographies into consideration to test and compare the performance of the solar monitoring stations in each city. We observed the minimum annual average daily total DNI at Hafar Albatin and the maximum at Sharurah, as it can be seen in Figure 24. For the DHI, we recorded the maximum annual average daily total in Riyadh by 2614.04 Wh/m^2. The maximum average daily total of GHI solar radiation was in Sharurah which was 6681.62 Wh/m^2, and the minimum was in Hafar Albatin with the value 5744.84 Wh/m^2 [21].

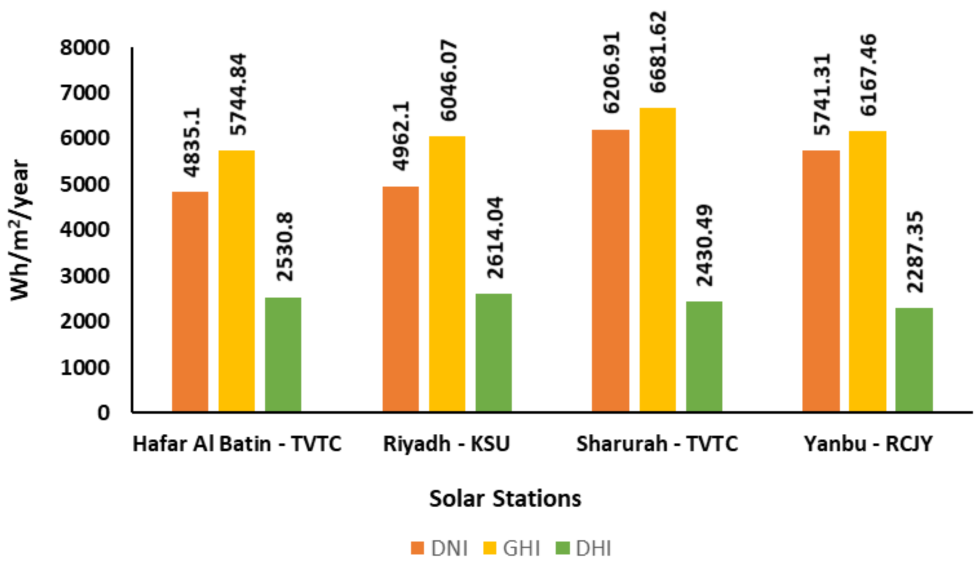


Fig. 24 Annual average daily total of DNI, GHI, and DHI.

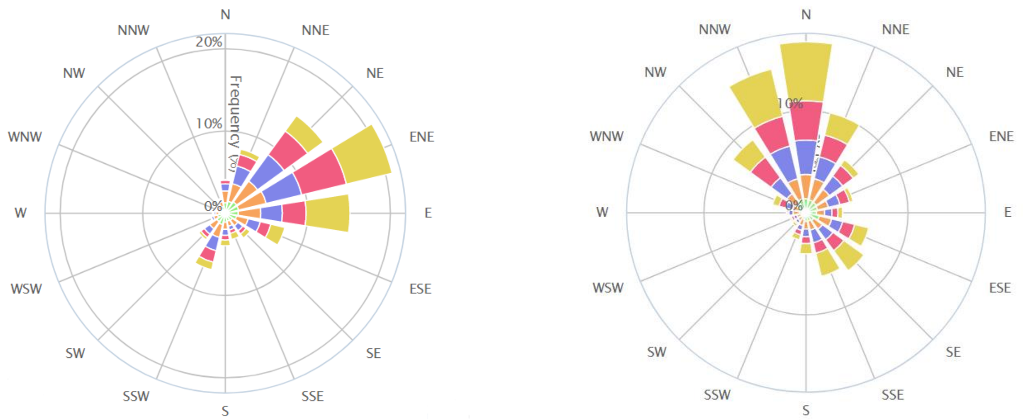
4.1.2 Wind Data

This part provides a brief description of the four locations considered in this study. The meteorological data were collected beginning in 2014 by the KACARE wind resource monitoring stations across the country. The measured parameters included temperature, relative humidity, pressure, wind speed, wind direction, and many other parameters at 40 m, 60 m, 80 m, 98 m, and 100 m above the ground surface. The measurements of the average monthly wind speed were made at 40 m, 60 m, 80 m, 98 m, and 100 m for each site, and the average wind directions were made at 37 m, 80 m, and 98 m. For this study, the details of the selected sites are summarized in Table 2. At all of these locations, the meteorological measurements were taken at different heights. The data used in this analysis covers 12 months of measurements stretching from January to December of 2015. The reason for choosing only one year is because we found some data missing for some of the months in 2014 and 2016. Figure 18 in chapter 2 shows the map of Saudi Arabia. The figure shows the locations of the measurement sites presented in Table 2 and the current locations of the other wind sites in the country.

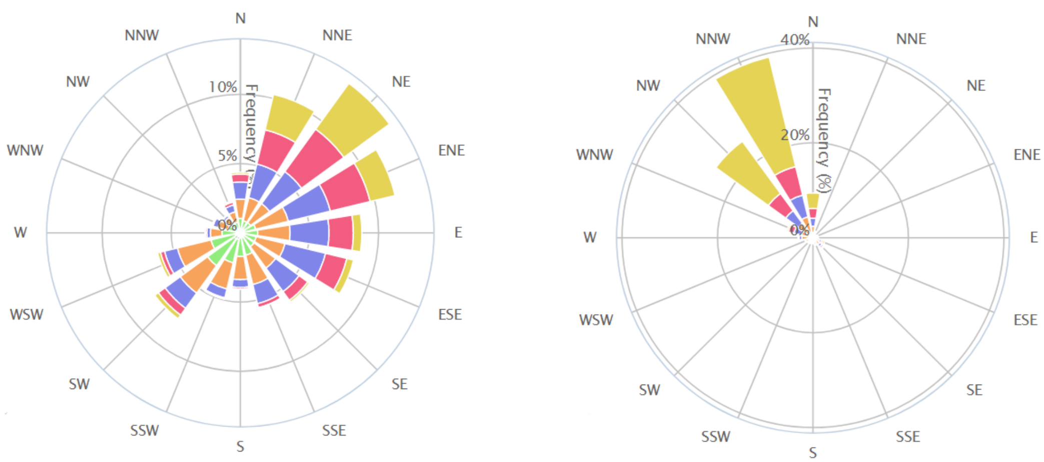
Table. 2 Wind monitoring stations details.

S. NO	Site	Longitude (E)	Latitude (N)	Elevation (m)	Data Collection Start
1	Riyadh	46.3527	24.5764	924	13 August 2014
2	Yanbu	37.4844	24.3420	18	18 August 2014
3	Sharurah	47.0731	17.3234	764	26 August 2014
4	Hafar Albatin	44.2031	28.2688	360	24 August 2014

One of the most important factors about wind farm projects is the wind direction. To achieve the optimum design of a wind power plant, the prevailing wind direction of the selected locations must be assessed. In this study, we applied the KACARE wind rose simulation for the locations under consideration to provide the diagrams at a height of 80 m above the ground. Each wind rose chart has 16 cardinal directions, as shown in Figure 25. These charts show the frequency and speed of the wind as it blows from each direction. Designers can make their decisions for a particular site by analyzing the rose plots. We can observe from these plots that the most prevailing wind direction for Sharurah and Riyadh was from the East-Northeast for about 21% of the time and from the Northeast for 13% of the time, respectively. The Hafar Albatin site recorded that the most wind direction was from the North for about 16% of the time, and 39% was from the North-Northwest direction for Yanbu, as seen in Figure 25. Hence, wind turbines can be installed upon these directions. Generally, modern wind energy conversion systems have different cut-in speeds that depends on the size of the installed wind turbine [21].



(**a**) Sharurah (**b**) Hafar Albatin



(**c**) Riyadh (**d**) Yanbu

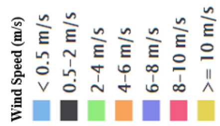


Fig. 25 Wind rose diagrams for the selected stations.

It is fundamental to analyze the wind energy regime before implementing any wind energy project since the cost of wind energy production is heavily dependent on the wind resources at these sites [65]. Speed critically influences the wind resources at a certain site. Accordingly, the average wind speed is important in assessing the wind energy potential at any site [66]. To describe the wind speed distribution, the literature shows several density functions that can be used. The Weibull and the Rayleigh functions are the two most common distributions. In this study, we used the Weibull distribution to do the wind distribution analysis for the selected sites. This type is characterized by two parameters, one is the scale parameter c (m/s), and the other is the shape parameter k (dimensionless). There are several methods for calculating these two parameters of the Weibull distribution for wind speed analysis [41,42]. We used the power density method (PDM) in this study to estimate the scale and shape parameters; it relates to the averaged data of wind speed. We then compared the results to the actual data, and we calculated the coefficient of determination (R^2) in order to examine how well the distribution functions fit the data set. Table 3 shows that R^2 was 97% and above for all Weibull distributions. These results illustrate that the fitted functions describe the observed values of wind speed reasonably well [21].

Table. 3 Annual estimated Weibull parameters.

Site	Mean (m/s)	Standard Deviation	Average WPD (W/m^2)	K	C (m/s)	R^2
Riyadh City Site A	6.30	3.27	292.02	2	7.11	0.976
Yanbu	8.84	4.70	833.78	1.95	9.98	0.980
Sharurah	7.07	3.78	426.20	1.95	7.98	0.981
Hafar Albatin	7.65	3.94	519.27	2.02	8.64	0.982

Figures 26 and 27 show the Weibull distribution, and Cumulative Distribution Function (CDF) at 80 m height for the selected sites. From these two graphs, we observed that the wind speed remained above 10 m/s for about 41% of the time at Yanbu, followed by 10 m/s for 27% at Hafar Albatin, 22% at Sharurah, and 14% at Riyadh. This also shows that the best location among these cities for wind energy production is Yanbu due to the high wind speed, as seen in Figures 28. The results also indicate that the city of Yanbu has a better potential for using wind energy than the other three locations in the provinces examined. In Table 3, we found the annual mean wind power density (per unit area P/A) for the selected locations to be about 833.78 W/m^2 at Yanbu, 426.20 W/m^2 at Sharurah, 292.02 W/m^2 at Riyadh, and 519.27 W/m^2 at Hafar Albatin for winds at a height of 80 m [21]. This indicates that the city of Yanbu is the most recommended place for wind energy among other locations.

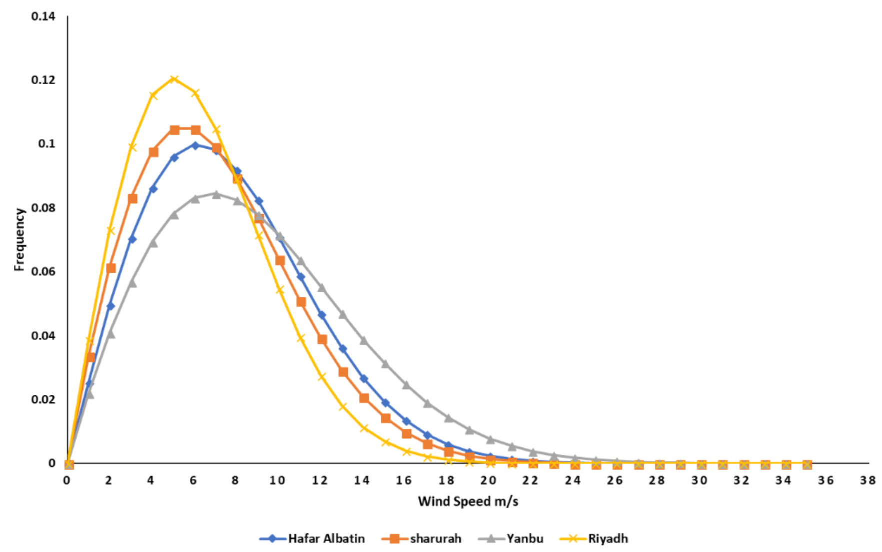


Fig. 26 Weibull distribution of the measured data at 80 m.

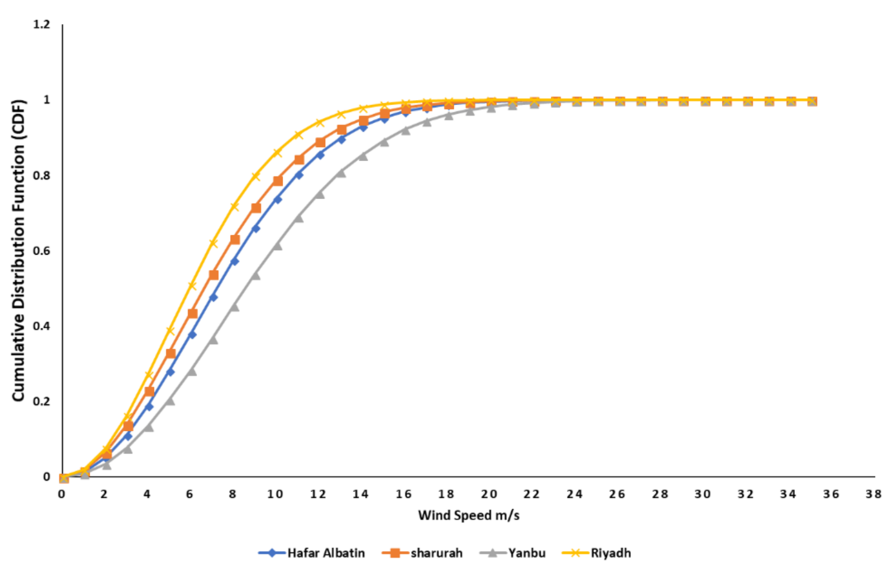


Fig. 27 Cumulative density of wind speed at 80 m.

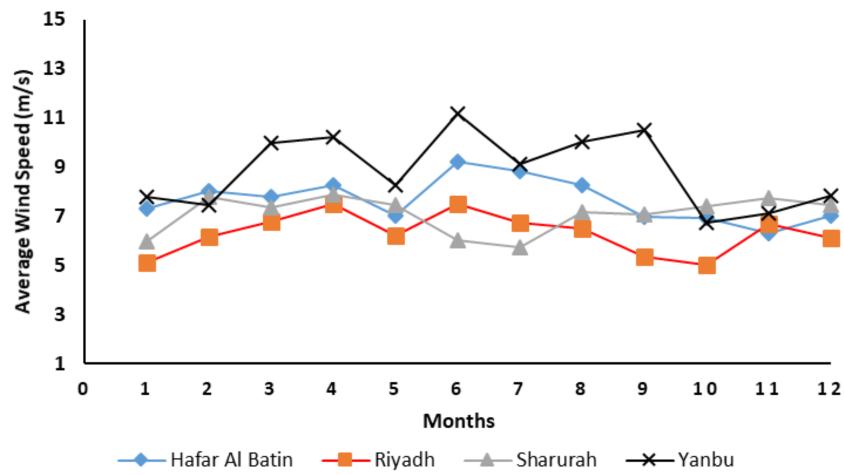


Fig. 28 Monthly mean wind speed in m/s.4.2 Design and System Specifications

4.2 Design and system specifications

4.2.1 Model Design

The hypothetical load considered in this study is a 15 MWh/day community load. This load is the AC primary electric load that the system must meet in order to avoid the unmet load. Beside the load, the system consists of four other components: The grid system, DC to AC converter, solar PV array, and 1 MW wind turbine as presented in Figure 30. An inverter is required by the grid-connected system to adapt the direct current DC produced by the PV array and feed it to the AC busbar where the load connected. Since this design has no backup system, the utility grid will serve as a reliable supplier to the load due to the electric intermittence caused by the renewable energy sources.

Figure 31 shows the profile of the monthly average load with a peak demand beginning in May through August and declining from September to the end of the year. This increase is mainly due to the high temperatures during the summer, which cause the significant usage of air conditioning in KSA. The average scaled power consumed per day is 15 MWh/day with a peak of 2.395 MW occurring in August [21].

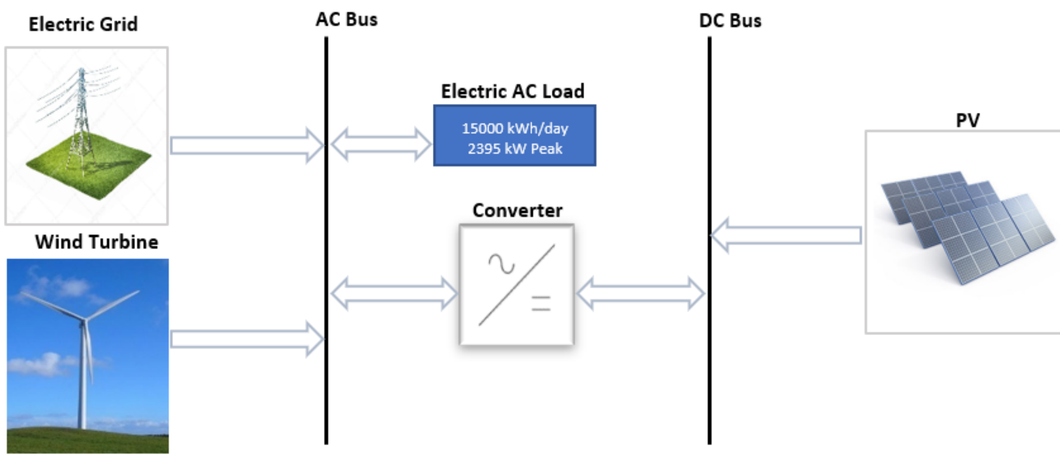


Fig. 29 Design configuration of Wind/PV grid-connected system.

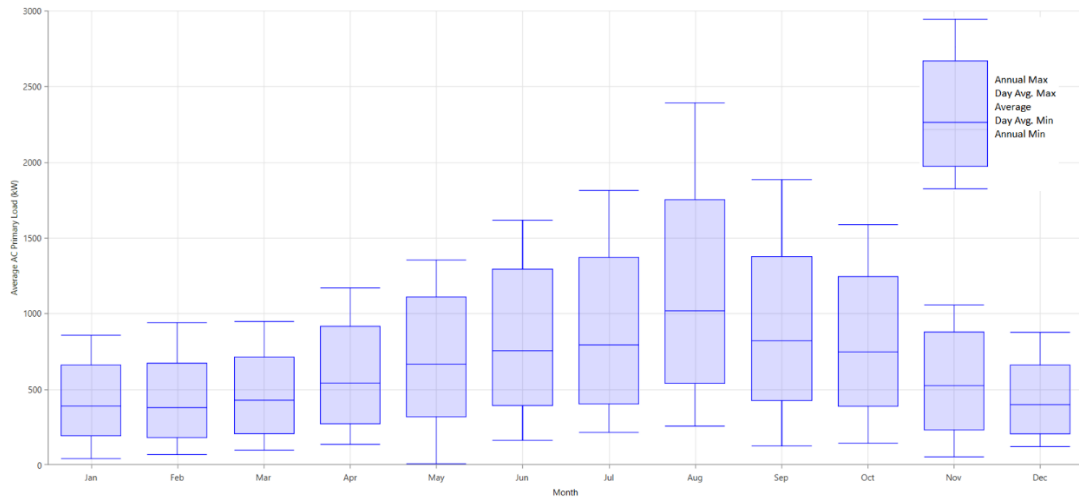


Fig. 30 The monthly average load profile.

4.2.2 System Components

4.2.2.1 Electric Grid

The utility grid is the most reliable system that can be used, whereas the solar PV/wind system depends on the availability of renewable energy resources. However, if the power produced by the solar PV/wind exceeds the load requirements, the excess electricity is sold in a certain tariff to the grid. Several researches have proven that the LCOE is reduced when the excess energy is used in this way [69]. The Renewable Energy Feed in Tariff (REFIT) is an agreement to accelerate the investment in renewable energy technology. In KSA, A.M. Ramli et al. [70] conducted a study on the analysis of renewable energy feed-in tariffs and concluded that applying fixed REFIT helps to enhance sustainability by eliminating the inflation effect in such a region. In 2017, SEC changed the residential and commercial rate of electricity to new prices. The two consumption categories of the residential loads are 1–6000 kWh and more than 6000 kWh, which have the rate charge of 0.048 $/kWh and 0.080 $/kWh, respectively. Accordingly, the new rates utilized to schedule fixed prices at different times during the day and month, as shown in Figure 31. This figure shows the grid schedule rate for the whole day and each row represents the hours of the day starting at 00.00. The rate includes peak, shoulder, and off-peak times, whereas the sellback electric charges are 0.070 $/kWh, 0.040 $/kWh, and 0.038 $/kWh, as shown in Figure 32 [21].

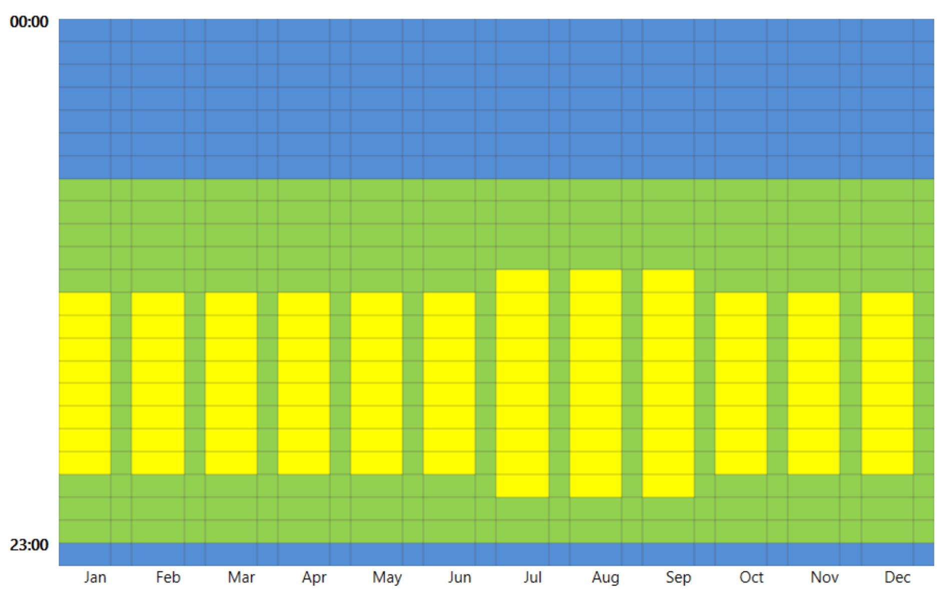


Fig. 31 Grid daily schedule rate for all months.

		Price $/kWh	Sellback $/kWh
Peak		0.0800	0.0700
Shoulder		0.0480	0.0400
Off-peak		0.0480	0.0380

Fig. 32 Defined rates during the day.

4.2.2.2 PV Modules and Wind Turbine

In this study, the hybrid solar PV/wind is a system integrated with the grid to reduce dependence on fossil fuels as a primary source of electricity. The size of a grid-connected RES depends on the system constraints. In the present design, the solar PV/wind hybrid system should be sized to meet at least 60% of the peak load demand, and this will identify the required output power from the hybrid grid-connected system. In HOMER, the PV output power can be calculated using equation (1)

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}} \right) \left[1 + \alpha_P \left(T_c - T_{c,STC} \right) \right] \quad (1)$$

where Y_{PV} is the capacity of PV array in [kW], f_{PV} refers to the derating factor in [%], $\bar{G}_T$ PV solar irradiation in [kW/m^2], $\bar{G}_{T,STC}$ is the incident radiation at standard test conditions and it is [1 kW/m^2], α_P is the Temp coefficient of power in [% /^{o}C], T_c PV cell Temp in current time step [^{o}C], and $T_{c,STC}$ the cell temperature under stander test conditions [25 ^{o}C].

It can be seen from Equation (1) that several factors, including solar irradiation and the cell temperature have the influence on the generated power from the PV. Table 4 presents the PV technical and financial input data and the inverter types. These types of PV and converters have shown a good performance in KSA [71].

The wind speeds have been described in the previous sections for all selected locations. The technical and estimated financial input data of the 1 MW wind turbine are presented in Table 4. Figure 33 shows the power curve of the considered wind turbine, which has the cut-in speed of 4 m/s, and the total output power of 1 MW can be obtained at a wind speed of 12 m/s to 20 m/s. The measurement of wind speed was taken at the height of 80 m and the approximate hub of the wind turbine is 80 m above the ground at which the rotor sits [72]. By knowing the hub height wind speed, the wind turbine power can be determined from the power curve. In HOMER software, the power curve is typically used to specify the performance of any wind turbine under conditions of standard temperature and pressure (STP). The power value shown by the power curve is multiplied by the air density ratio to adjust the actual conditions, as illustrated in equation (2)

$$P_{WTG} = \left(\frac{\rho}{\rho_0}\right).P_{WTG,STP} \quad (2)$$

where P_{WTG} is considered the actual output power of the wind turbine in kW, $P_{WTG,STP}$ is the power output of the wind turbine at STP in kW, ρ is the actual air density kg/m^3, and ρ_0 is the air density at STP, which is 1.225 kg/m^3 [21].

Table. 4 Components specifications.

Components	Parameters	Value	Unit
PV (CS6K-280M-T4-4BB)	Capacity	1	kW
	Lifetime	25	Year
	Capital	1640	$/kW
	Replacement	1640	$/kW
	O&M	10	$/yr
	Dual axis tracker	1000	$
	α_P	−0.50	%/ºC
	f_{PV}	80	%
	Efficiency	18	%
Converter	Capacity	1	kW
	Lifetime	15	Year
	Efficiency	95	%
	Capital	300	$
	Replacement	300	$
Wind Turbine	Initial Capacity	1,300,000.0	$
	Replacement	1,300,000.0	$
	O&M	1200	$/yr
	Lifetime	25	Year
	Hub Height	80	m
	Applied Losses	15	%
	Capacity	1	MW
Economical parameters	Project lifetime	25	Year
	Real Discount Rate	6	%
PV/Wind Size	PV	0.5	MW
	Wind Turbine	1	MW

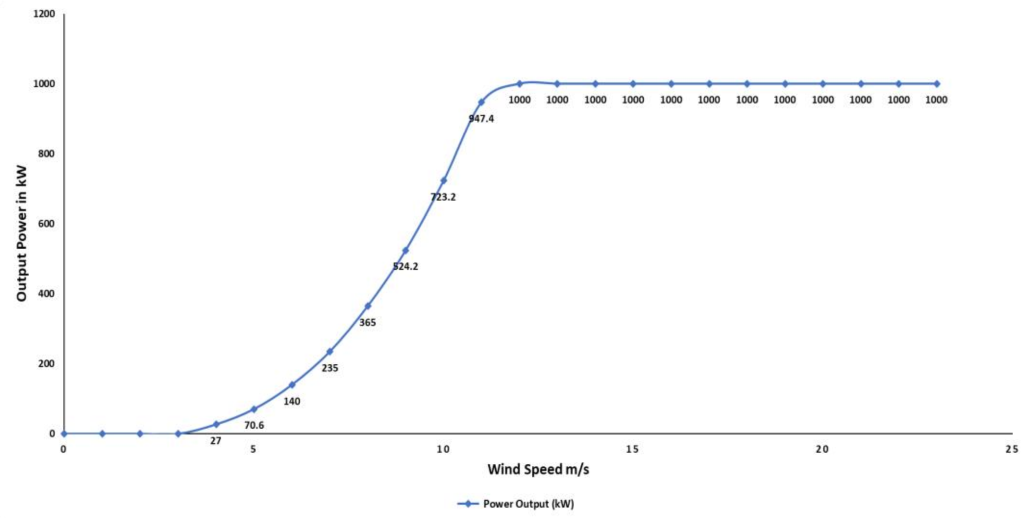


Fig. 33 Wind turbine power curve.

4.2.3 Economic Model

There are two main economic factors used to rank different system configurations. These are the net present cost (NPC), or the life-cycle cost and the levelized cost of energy (LCOE) [73]. NPC is defined as the present value of all system costs over the project's lifetime, minus the value of all revenues earned. Additionally, it can be calculated from Equation (3). The LCOE is the average cost in $/kWh of the actual consumed energy produced by the system and it can be calculated from equation (5)

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \tag{3}$$

where i is the annual interest rate, $C_{ann,tot}$ represents the system total annualized cost, R_{Proj} is the project lifetime in years, and the capital recovery factor (CRF) can be calculated using equation (4)

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{4}$$

i is the real discount rate and N refer to the number of years

$$LCOE = \frac{C_{ann,tot}}{R_{prim} + R_{tot,grid,sales}} \tag{5}$$

Where R_{prim} is the AC primary load in kWh/year and $R_{tot,grid,sales}$ is the total grid sales in kWh/year.

An alternative economic performance measure could be investigated by decision makers along with the NPC and the cost of energy. The Return on Investment (ROI) is the yearly cost savings relative to the initial or reference system. In HOMER software, the ROI can be calculated using Equation (6)

$$ROI = \frac{\sum_{i=0}^{R_{proj}} C_{i,ref} - C_i}{R_{proj}\left(C_{cap} - C_{cap,ref}\right)} \tag{6}$$

where $C_{i,ref}$ is the nominal annual cash flow for the base (reference) system; C_i is the nominal annual cash flow for current system; R_{proj} is the project lifetime in years; C_{cap} is the capital cost of the current system, and $C_{cap,ref}$ is the capital cost of the base (reference) system, which is the grid [21].

4.3 Simulation Results and Discussion

Performance of the grid-connected solar PV/wind hybrid system in the selected cities is discussed in this section. Technical and economic details along with electricity production for four different cases are compared and then the saved CO_2 emissions for the defined cases are considered.

4.3.1 System Electricity Production

Figure 34 illustrates the total annual electricity production from the grid, wind turbine, and solar PV systems in kWh/yr. The effect of renewable energy penetration on the consumption from the grid can be seen from the graph. At Yanbu city, the annual electricity production from the RE system represents almost 70% out of the total due to the high output power, specifically from the wind turbine, which represents 53%. This reduces the annual energy purchased from the grid to 1,978,631 kWh/yr, which represents only 30% out of the total annually consumed power. The wind energy production in Yanbu city was compared to a study presented by S.M. Shaahid et al. [47] and the capacity factor of the wind turbine were higher in this study due to the different size and hub height of the wind turbine. The yearly total renewable power output at Hafar Albatin is 3993.2 MWh/yr versus 2418.7 MWh/yr from the grid. At this city, wind energy production represents 62%, whereas the solar PV is around 17%, and the remaining power produced by the grid. Sharurah city has the highest solar irradiation among others. 19% of the annual electricity production comes from the PV system. However, the wind energy production and electricity purchased from the grid have almost the same amount, as illustrated in Figure 34. Riyadh city has recorded the highest electricity purchased from the grid due to the low renewable output power [21].

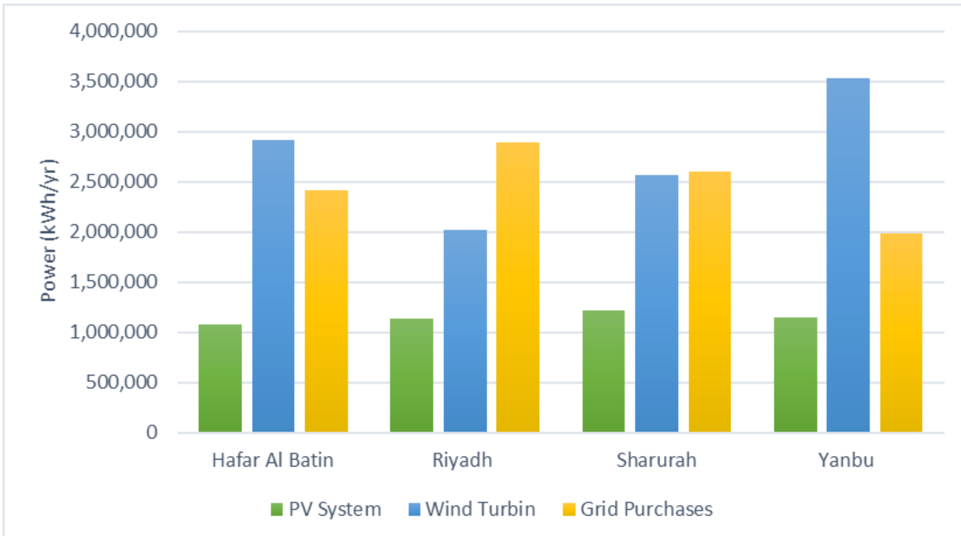
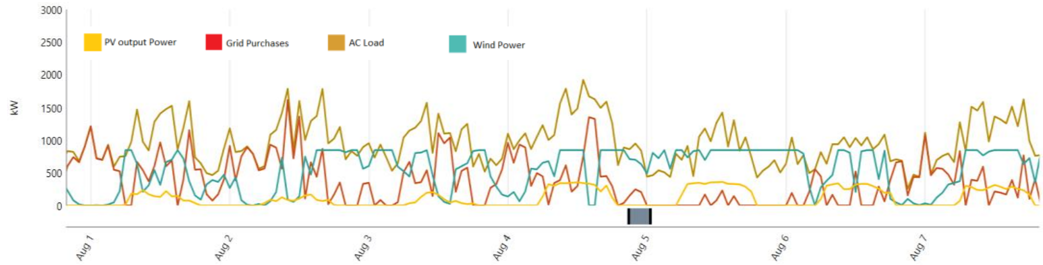
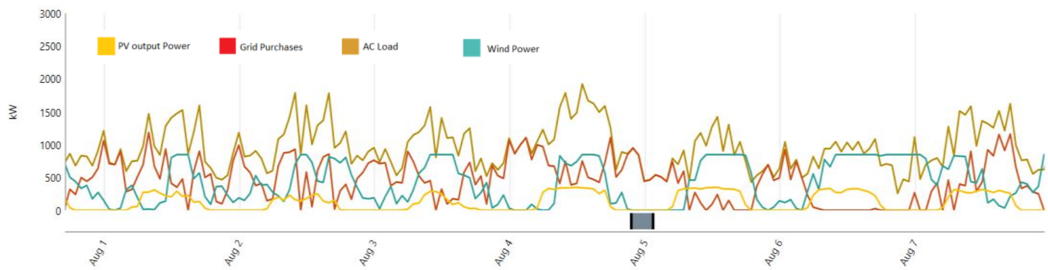


Fig. 34 Total annual electricity production from the grid, PV, and wind turbine.

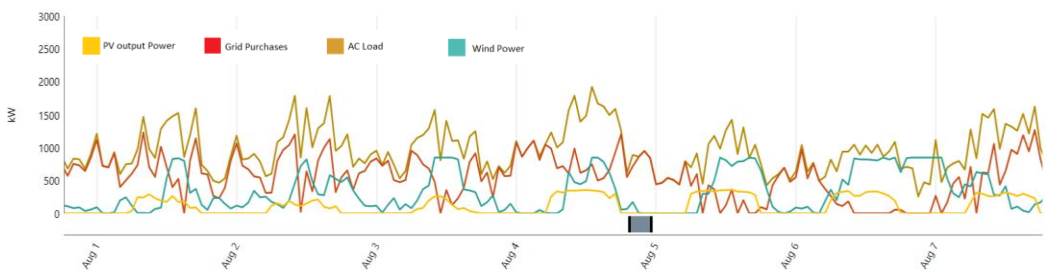
Figure 35 shows the time series analysis of the first week of August in all cities. As it can be seen from these graphs, all systems have the same load shape and different output power. As the output power produced by the hybrid system increases, the power consumed from the grid declines instantaneously. Additionally, the sum of the renewable output power and the grid power is equivalent to the total electrical load served, which indicates that the designed grid-connected system has met the electric load requirements with zero unmet power demand.



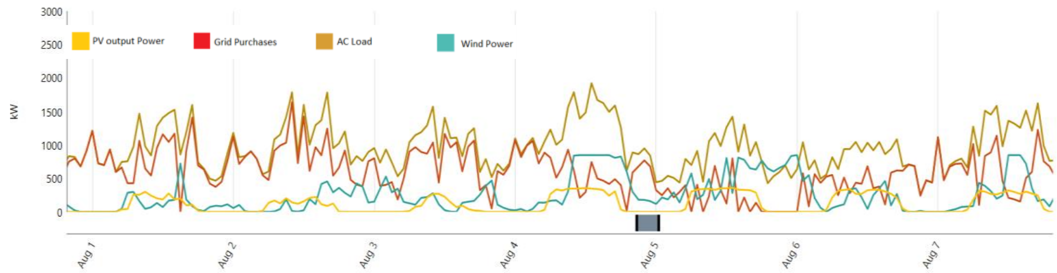
(**a**) Yanbu



(**b**) Hafar Albatin



(**c**) Sharurah



(**d**) Riyadh

Fig. 35 One-week generation of grid along with PV/wind hybrid system to maintain load demand

In KSA, the main source of electricity is fossil fuel-based power plants. As a consequence, the vast majority of CO_2 emissions are from the power sector. Figure 36 shows the amount of CO_2 emissions in kg/yr that can be saved if the renewable hybrid system is connected to the grid. The annual CO_2 emission produced by the grid system only (with no hybrid system) is 3,460,200 kg/yr, which means that the hybrid grid-connected system has contributed significantly to lower CO_2 emissions. As can be seen from the graph, the system performance at Yanbu city can reduce the CO_2 emissions by almost 63%, which equals to 2,209,705 kg/yr followed by Hafar Albatin, Sharurah, and Riyadh, respectively.

One of the most important indicators of renewable energy system productivity is the capacity factor. Additionally, it is considered the most effective parameter in analyzing renewable energy system performance due to the direct effect on the cost of generated power. It is defined as the ratio of the real energy output to the theoretical full energy output over a specific period of time [50]. The annual capacity factor and the annual energy output power of wind and solar are evaluated in Figures 34 and 37. For both solar and wind, several parameters were considered including the temperature, derating factor, tracking system, wake, turbine hub height, and about 15% generation losses of wind turbine in order to evaluate the production. Figure 37 summarizes the annual capacity factors for the four considered systems. The results clearly show that the annual capacity factor is significantly affected by the availability of renewable energy resources. As indicated in the figure, Yanbu city has the highest capacity factor for wind energy and Riyadh city has the lowest potential for installing wind turbines. On the other hand, there is no significant difference between the PV system capacity factors in all selected cities [21].

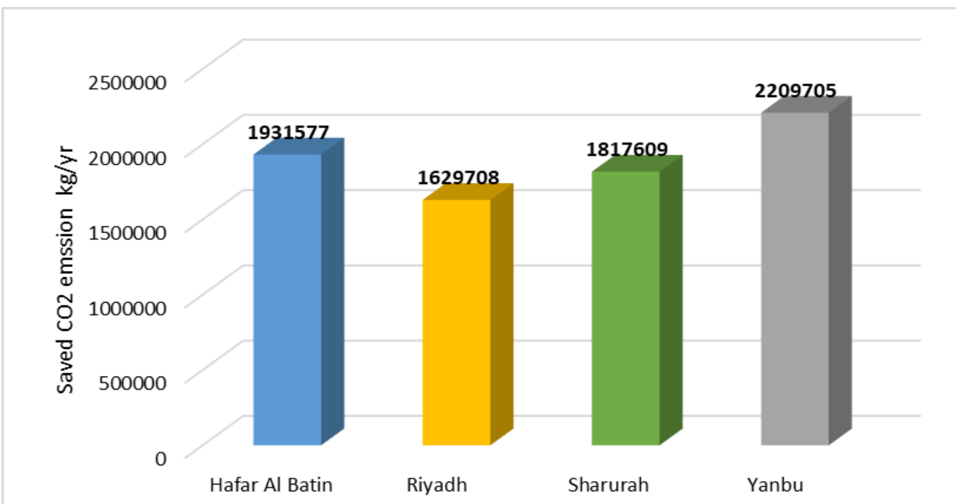


Fig. 36 Saved CO_2 emission by each system.

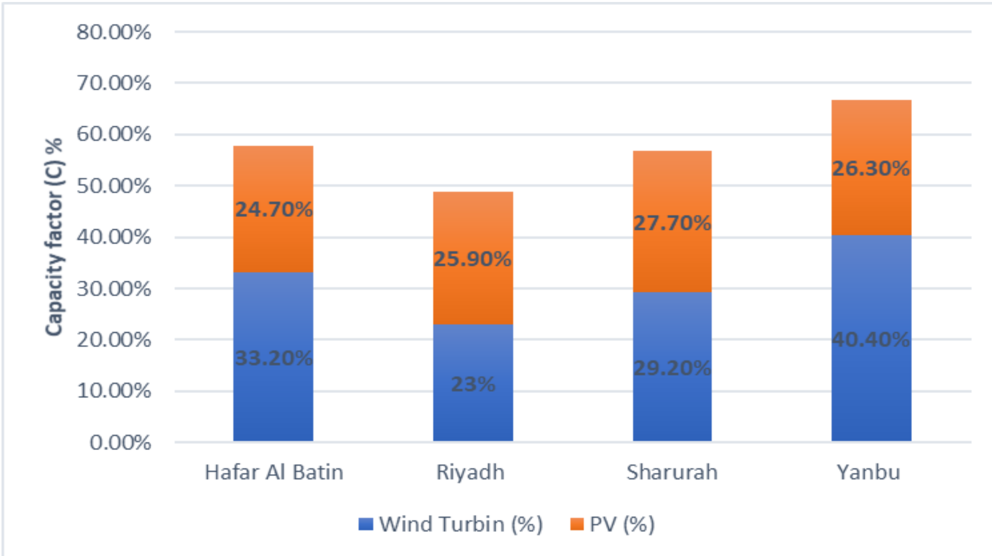


Fig. 37 Solar PV and wind capacity factor in each city.

4.3.2 Economic Analysis

Economic analysis was carried out considering Discounted Cash Flow (DCF) which is defined as the nominal cash flow discounted to year zero. In this study, the real discount rate considered for each system is 6%. Figure 38 shows a comparison of the cumulative discounted cash flow for all grid-connected systems considered throughout the projects lifetime compared with the base case. This method was used to estimate the attractiveness of an investment opportunity in such cases. A DCF was completed for all projects located at the selected cities and compared to the grid as a base case. Consequently, NPC for each system was found by summing up the yearly total discounted cash flows of the project lifetime. In Figure 38, the system at Yanbu city demonstrated the lowest NPC and LCOE of $3,080,182.00 and 0.03655 $/kWh, respectively. At Hafar Albatin city, the system NPC is $3,558,756.30 and has a LCOE of 0.04392 $/kWh. In Sharurah city, the system performed reasonably, even with a high NPC and LCOE. Based on the annual solar irradiation and the mean wind energy density, Riyadh city is not particularly suitable for the installation of large-scale hybrid grid-connected system. Additionally, the electric and economic analysis showed that using only the grid system in Riyadh city is the best economical option due to the high cost as shown in Figure 39 and low electricity production as discribed previously in Figures 34. However, Yanbu city has more appropriate renewable energy resources, specifically for utilization of wind turbine technology. The model at this city recorded the highest ROI of 7.5%, which makes it the most suitable place since it makes a profit during the project's lifetime. Thus, it is considered as the best city for wind energy development among all the others [21].

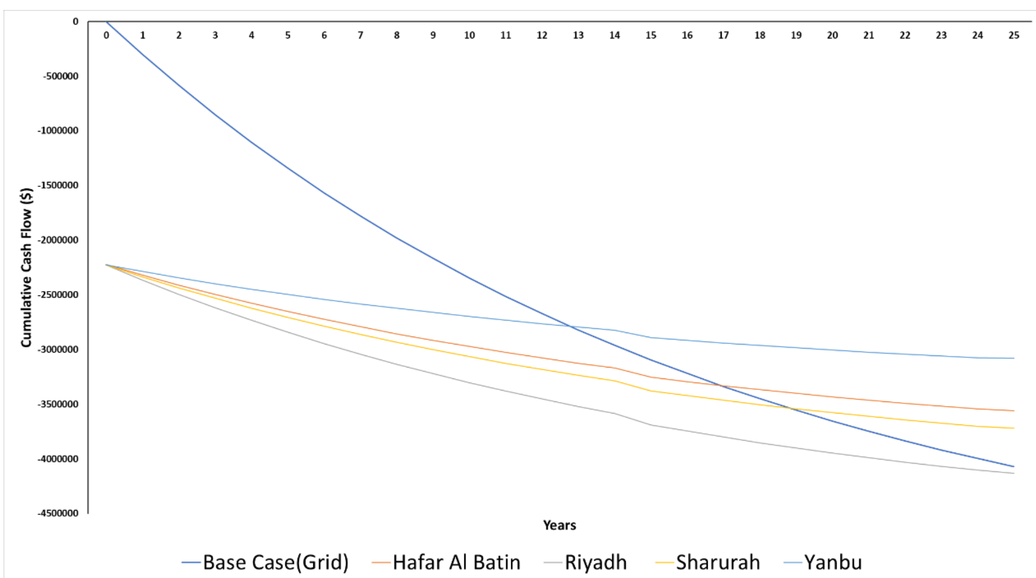


Fig. 38 Cumulative Discounted Cash Flow for all Systems and Base Case.

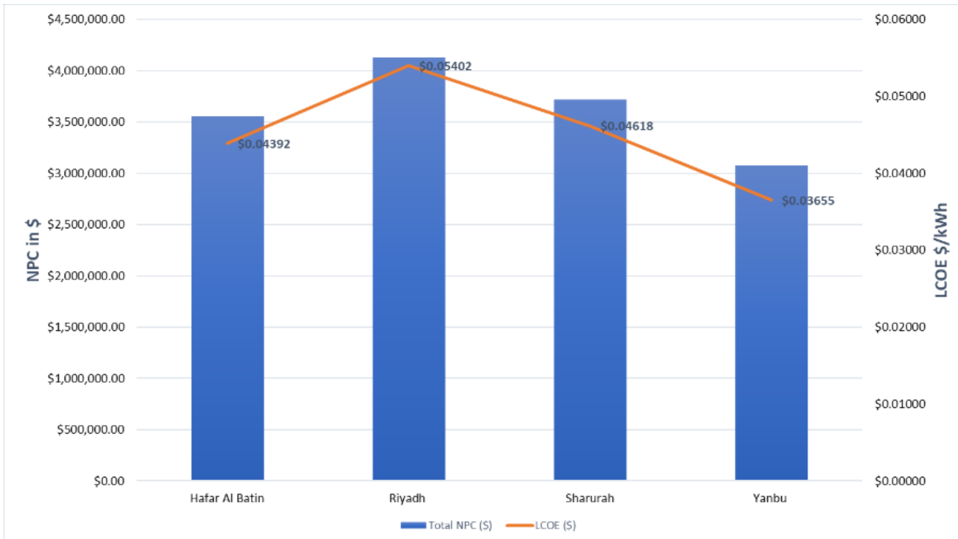


Fig. 39 Systems NPC and LCOE.

It is interesting to discuss the electricity purchasing and selling for each month during the year. The monthly power flow to and from the grid for the four systems under consideration is depicted in Figures 40 and 41. In the first four months of the year, the air temperature and the load demand are at their lowest. Consequently, all systems show the highest amount of power sold to the grid. More than 50% of the total annual energy sold to the grid for all systems occurred during this period. However, because of the high demand, in addition to the rising temperatures during most of the year, all systems become more reliant on the grid. Among all cities, the Yanbu city grid-connected system has the highest amount of energy sold to the grid and it is 1118 MWh/yr followed by Hafar Albatin, Sharurah, and Riyadh which are 863.5 MWh/yr, 824.6 MWh/yr, and 504.7 MWh/yr, respectively.

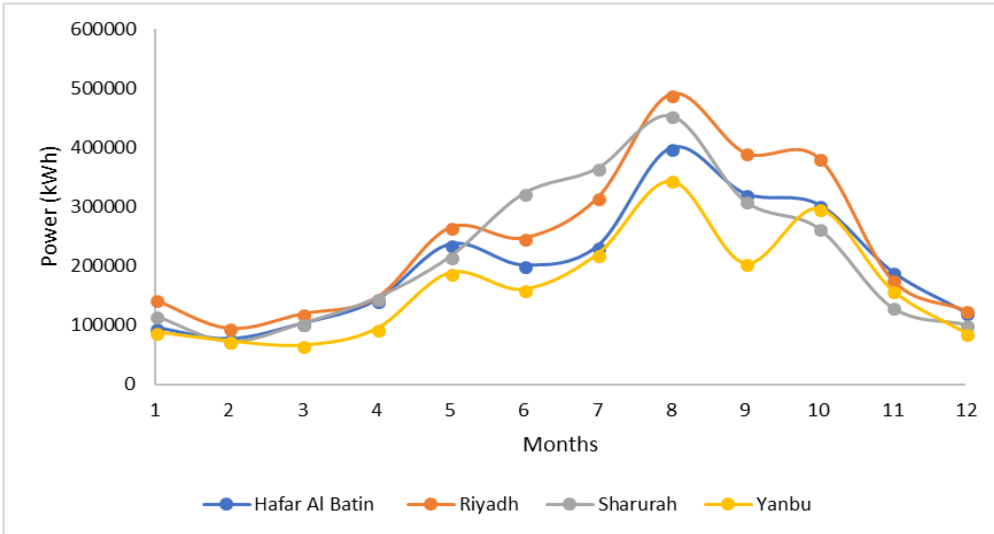


Fig. 40 Monthly energy purchased from grid.

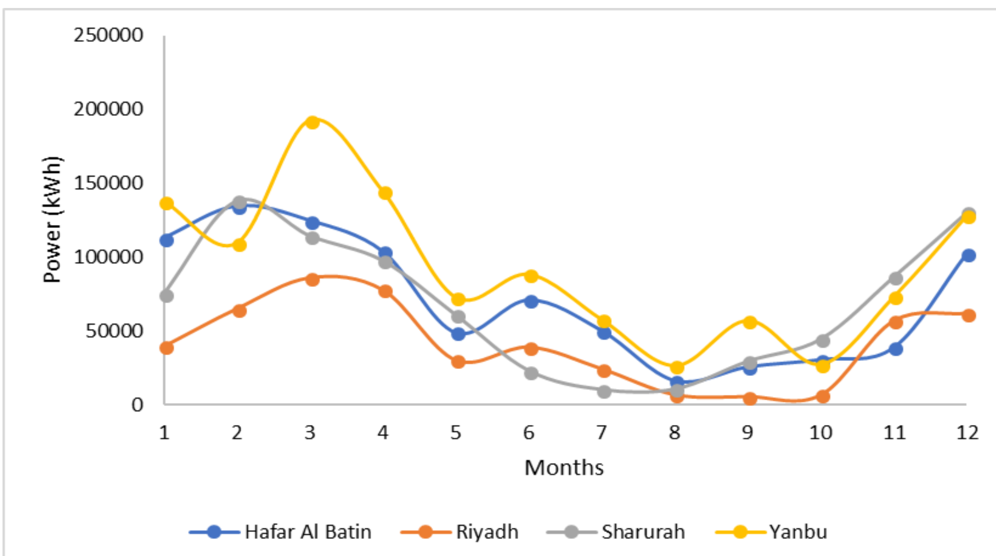


Fig. 41 Monthly energy sold to grid.

Figure 42 shows a comparison between the capital cost and the cost of the energy produced by PV/Wind system in each city. These results represent the energy cost at the grid price over the considered lifetime. In the designed system, the capital cost is part of the NPC. Since one model was applied at all selected locations, the capital costs are almost the same for each system. However, the costs of the energy produced over the project's lifetime are different, as illustrated in the graph. As depicted earlier in Figure 32 of section 4.2.2.1, the applied grid prices are 0.08 $/kWh during peak demand and 0.048 $/kWh at the shoulder and off-peak times. At Yanbu city, the total annual electricity produced by PV/Wind systems is around 4684.53 MWh/yr . The cost of this annual amount based on the grid prices exceeds 6.8 million dollars over the project's lifetime, as seen in Figure 42. The system capital costs at Yanbu city represent only 32% of the energy cost. The model at Hafar albatin city shows a total annual production of 3993.2 MWh/yr from the PV/Wind system. Over 25 years, the expected energy cost at the same city is almost 5.8 million dollars and the capital costs represent around 38% of this value. Sharurah and Riyadh show the lowest energy production with 3774.6 MWh/yr and 3157.5 MWh/yr, respectively [21].

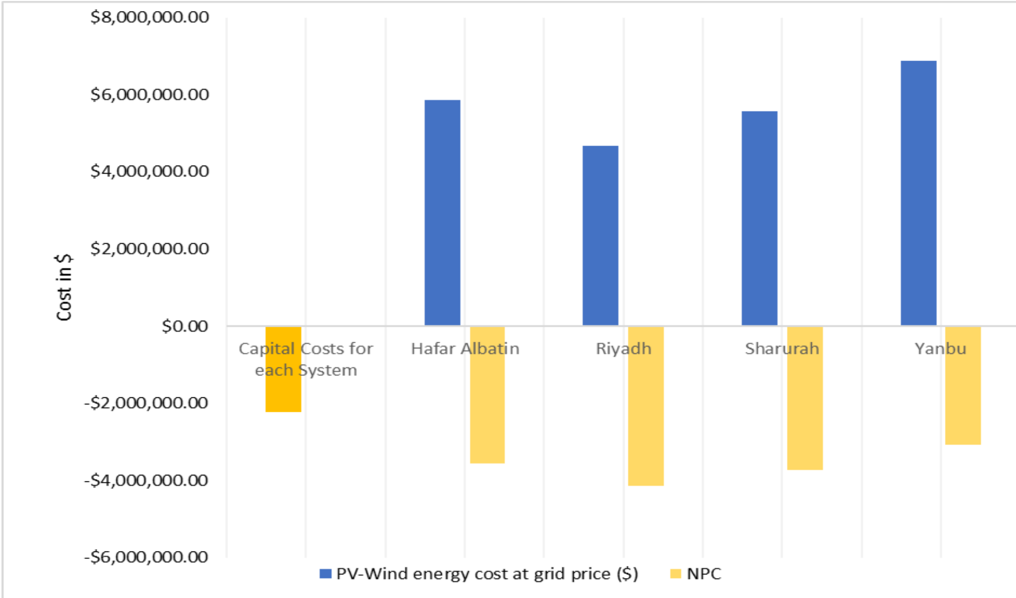


Fig. 42 Capital cost versus the total of energy produced by the PV/Wind system at the grid price.

Hybrid grid-connected system payback period represents the number of years that the system would take to recover. It shows the difference in investment costs between the base case system and the designed system. It also indicates that at what year the system's cash flow will switch from negative to positive. Grid system is the base case used in this study to do the comparison of all grid-connected systems. RE resource is one of the most important factors that contribute to bringing the payback period down and make such system cost-effective. The results in Figure 43 show that there is a decrease in payback period due to the RE penetration. Among all selected cities, Yanbu city has the lowest payback period followed by Hafar Albatin and Sharurah, while Riyadh city showed no profit throughout the project lifetime. Since Yanbu city has the highest RE penetration, it has the highest annual fuel saving with a payback period of 13 years followed by Hafar Albatin with 9 years and Sharurah with 7 years as illustrated in Figure44. The calculation of positive cash flow years or the systems payback period is carried out considering the kingdom current electricity tariff and the proposed sellback prices.

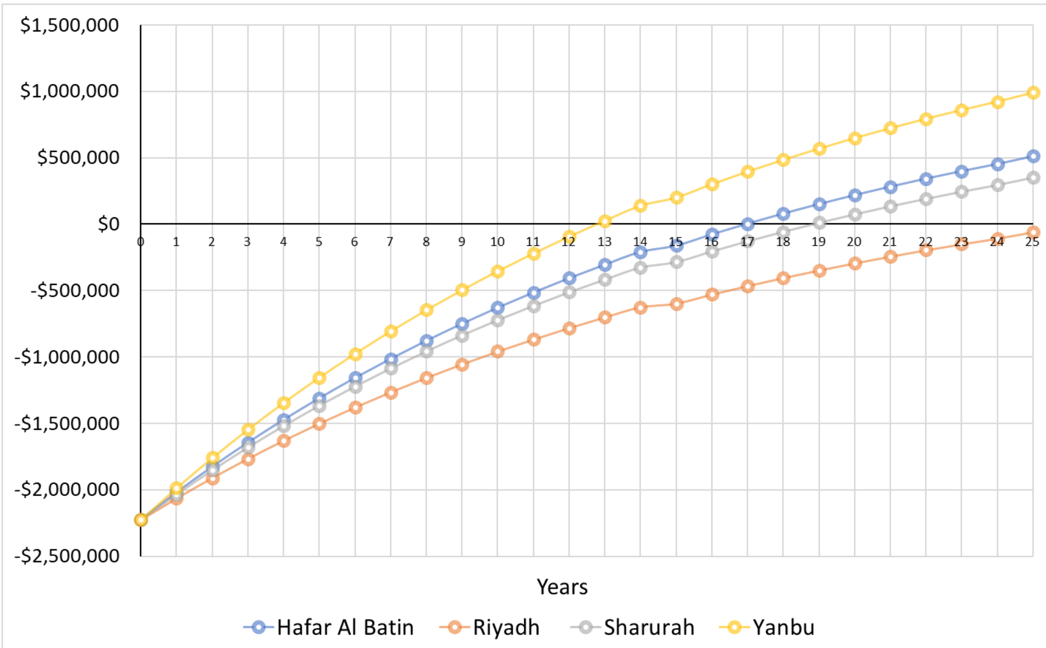


Fig. 43 Expected payback period for each system.

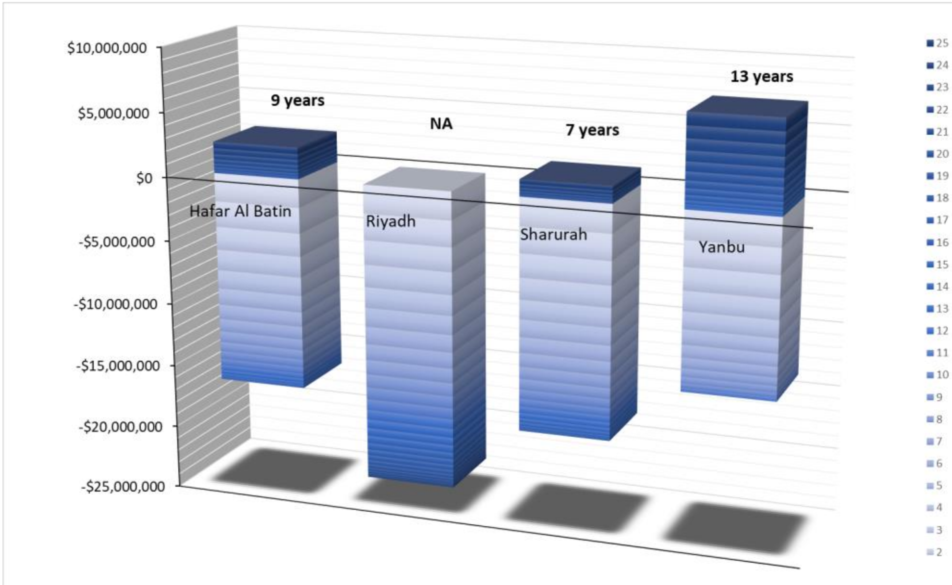


Fig. 44 Positive cash flow years.

4.4 System Sensitivity Analysis

Sensitivity analysis is important for such system to give a blueprint of the system reliability and determine how sensitive the outputs are to any changes in the system's variables. This included an interplay of different input parameters to investigate the changes that will affect the system performance. This analysis is useful to predict the effects and support decision making over the project lifetime. Since Yanbu city was the most recommended place among other cities based on the RE resources and power production, sensitivity analysis was performed to the system in this location. The electric load scaled average, power prices, wind and solar resources, net NPC and LCOE and other parameters were analyzed using surface plots.

Figure 45 illustrates the impacts of the grid prices and electric load changes on the NPC and COE. The surface plot shows the NPC ($) while the COE ($/kWh) is superimposed on the surface. The X axis represents the increasing range of load demand and Y axis shows the expected rise in purchased power prices from grid. As the electric load and power prices increase, the system's NPC and energy cost rise due to the insufficient renewable energy production that can meet the new load demands. These increases will make the system’s energy less economic and will increase the dependency on the conventional power plants. When the electric load raised from 15000 kWh/day to 20000 kWh/day, the NPC and COE increased by 42% and 12% respectively, while the increase in power prices from the first range (0.08 $/kWh, 0.048$/kWh) to the second range (0.084 $/kWh,0.0514 $/kWh), the NPC and COE increased by 3.4% and 2.2% respectively. This show that the changes in grid power prices have less impact on the system NPC and COE than the changes in load demand.

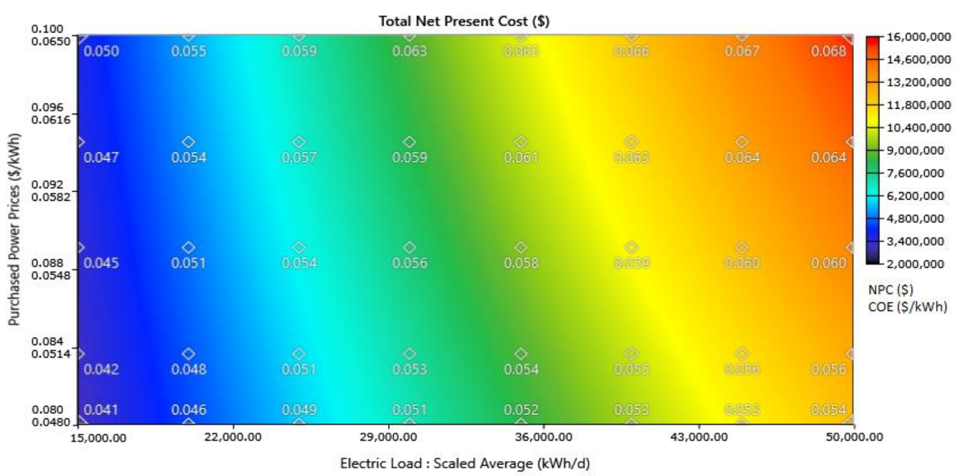


Fig. 45 Grid prices and electric load changes versus the NPC and COE.

When the power prices increase during the project lifetime, the RE electricity sellback rate may increase too. Therefore, it is important to investigate the economic effects of these changes. Figure 46 shows the impacts of the grid prices and electric load changes on the NPC and COE when the sellback rate ($/kWh) increasing linked with the power purchasing rate (power prices $/kWh). It should be noted here that whether the power prices linked to the sellback rates or not, the system's NPC and energy cost will be increased when the load demand increased. However, the increasing of energy cost and NPC will be slightly less when the sellback rates increase are linked with the utility grid prices, specifically when there are no significant changes in the load demands as illustrated in the surface plot in Figure 46.

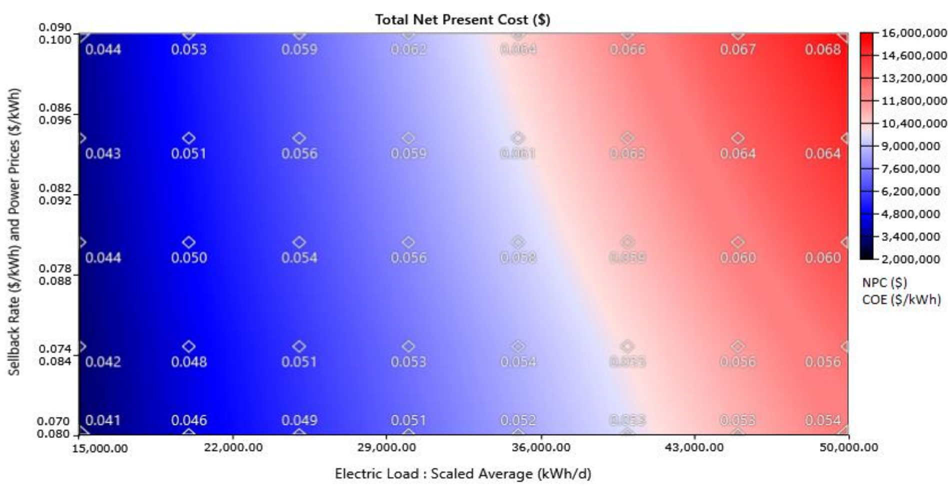
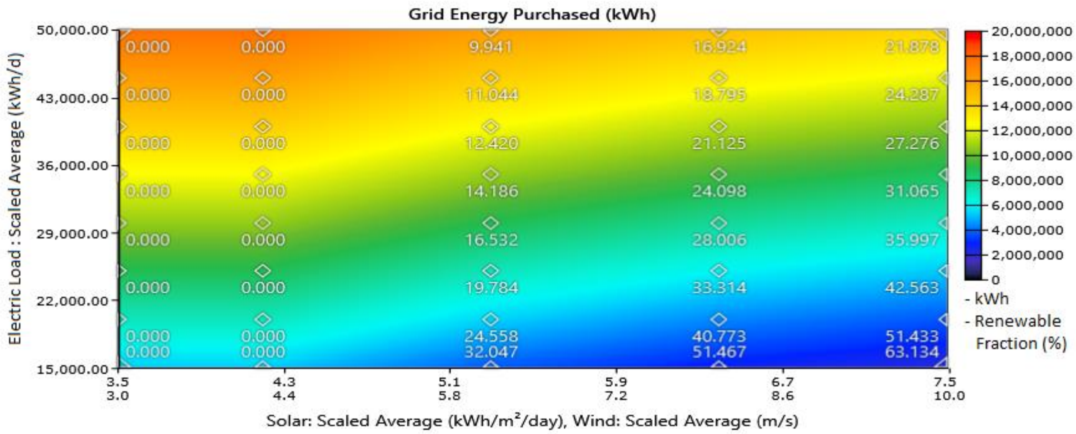
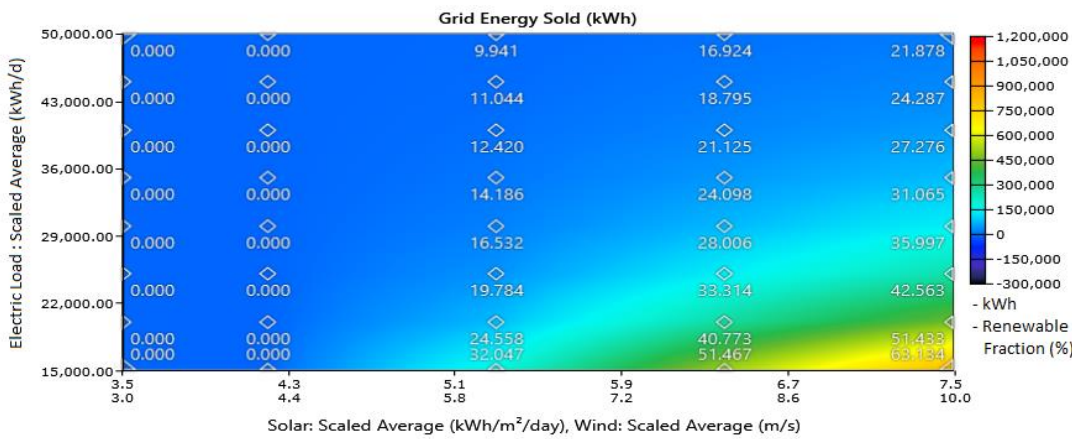


Fig. 46 Grid prices linked to sellback rate and electric load changes versus the NPC and COE.

Changes in RE resources and electric load have an impact on the system performance. Purchasing and sellback electricity to the grid are heavily dependent on the load requirements, RE size, and the potential of solar and wind resources. In this system, electricity supply comes from solar, wind, and grid purchases. Purchasing energy from the grid and CO_2 emissions can be decreased when the grid-connected system has highly efficient RE generation. Figure 47 illustrates the relations between renewable fraction, grid energy purchased, and grid energy sold, based on the changes in RE resources and electric load demands. The renewable fraction is the fraction of the energy dispatched to the electric demands that generated by the renewable power sources, and its value imposed on the surface as a percentage. The graphs showed that when RE resources are very low or there are not enough RE resources, the contribution of renewable energy power is zero, since it is not economically recommended. Hence selling energy to the grid will decrease significantly, while the energy purchase will be increased to maintain system's reliability and meet the required power demand. Also, electric load scaled average (kWh/d) has a significant impact on the renewable fraction as it can be seen from the energy purchased from and sold to the grid. When there are no big changes in load demand, the RE production will be affected by only the availability and potential of wind and solar resources. However, dramatical increase in load demand will reduce the contribution of RE power and raise the dependency on the conventional power plants. This is due to the fact that current RE sources have no capability to cover the new load requirements.



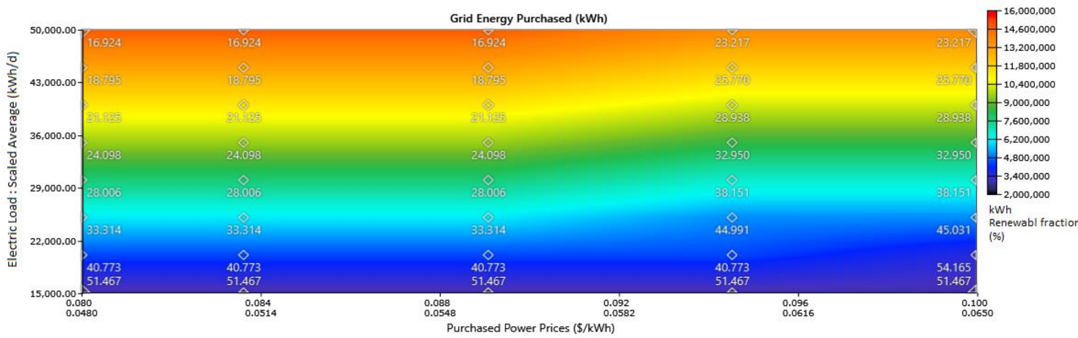
(a)



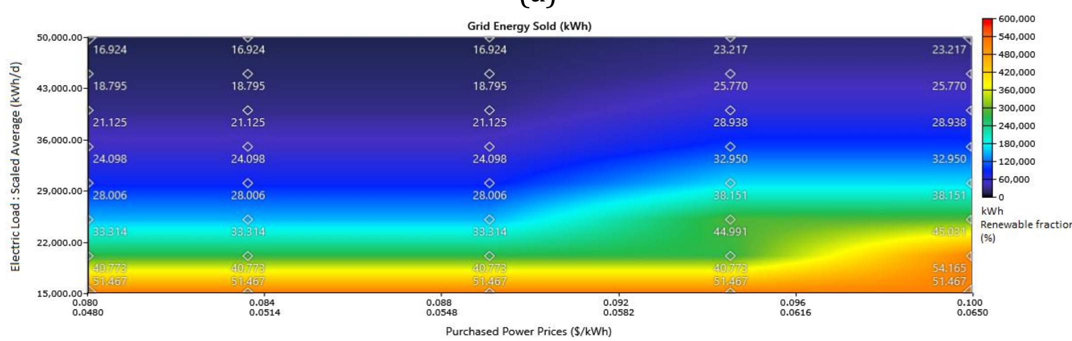
(b)

Fig. 47 Changes in RE resources and electric load versus renewable fraction, (a) grid energy purchased, and (b) grid energy sold.

Changes in power prices during the project lifetime is possible due to the oil price variations and that have also an economic impact on the system. Lacking enough RE sources while the load and power prices increase, may add more cost on the system rather than work effectively. Hence, it is important to investigate different configurations to understand the effects of increase in the utility grid prices. Figure 48 shows the effects of load demands and power prices increase on the renewable fraction, grid energy purchased, and grid energy sold. The X axis shows the expected rise in power prices purchased from grid and the Y axis represents the increasing range of electric load (kWh/d). It should be noted here that the power prices have three categories not two as shown in the scale (peak, shoulder, and off-peak times). The scale showed only two because shoulder and off-peak times have the same increasing range. The surface plots show the energy purchased from and sold to the grid. The renewable fraction is superimposed on the surface. From the first price rate on the scale (0.08, 0.048, 0.048) to the third electric price rate (0.090, 0.055, 0.055), power prices have no impact on the system size and the renewable contribution percentage showed no changes when the power prices increase. During these three different prices, PV system is not recommended because that added more cost on the system due to the low solar PV production (0.5MW) against the high load demand and power prices. Wind energy with the grid system is the best economic choice during the period of the first three power level of prices. When the load increased to 20000MW, the renewable fraction raised from 40.773% to 54.165% and that is because adding the 0.5MW to the grid connected system is more economic than using only the wind with the utility grid. This happened because of the high purchased power rate which is (0.1, 0.065, and 0.065 $/KWh) at that point. This scenario happened again when the electric load increased to 25000MW and the electricity rates were (0.095, 0.06, and 0.06). At this point, the renewable fraction increased from 33.134% to 44.991% and thereafter keep decreasing until reached its minimum (23.217%) across the highest value of electric load (50000MW). These changes showed that the cost caused by the increase in power prices rate can be decreased by adding more RE sources. That is why the solar PV (0.5MW) were recommended to be added to the grid connected system.



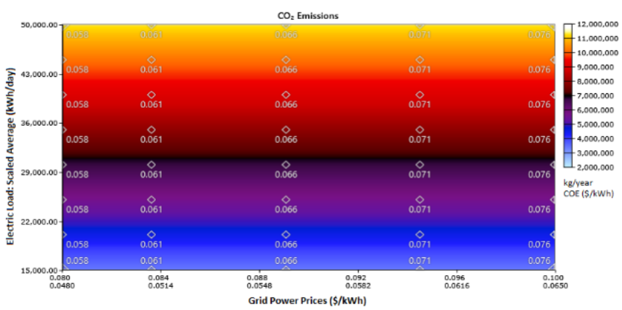
(a)



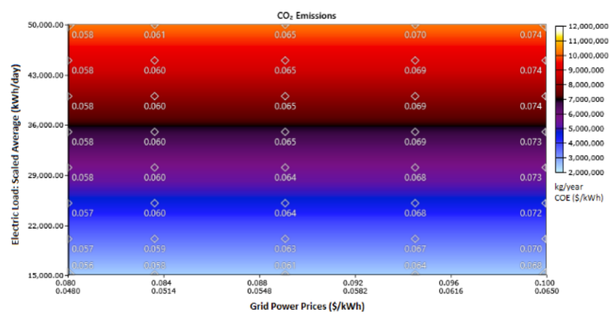
(b)

Fig. 48 Changes in grid prices versus renewable fraction, grid energy purchased, and grid energy sold.

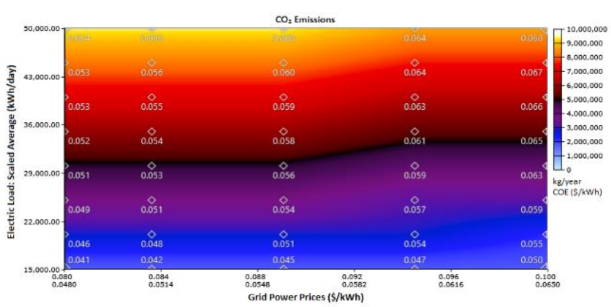
Environmental pollution and the high greenhouse gas emissions are the major disadvantages of the continued use of fossil fuels as primary energy sources. There is no doubt the pure RE systems have zero emission, but their NPC and COE are relatively high which make them uneconomical. However, increasing the contribution of RE sources to the total consumed energy will decrease the CO_2 emissions. RE resources play a significant role in reducing the environmental impact caused by burning fossil fuels and enhancing power production from renewable sources such as wind and solar. Figure 49 shows four graphs illustrating the Impacts of RE resources potential and increase in the load demand on the CO_2 emissions (kg/year) and COE($/kWh). Every graph simulated separately at different rang of solar and wind scaled average resources to investigate the possible impact. The surface plot shows the CO_2 in kg/year while the COE ($/kWh) is imposed on the surface. Graph (a), shows the possible CO_2 emission and energy cost at different load and power prices when the solar and wind scaled average is 4.5 kWh/m^2/day and 4 m/s, respectively. The CO_2 emission and cost of energy in this graph has the highest readings due to the very low contribution (around zero) of renewable sources. That showed the importance of solar and wind resources and lacking enough RE resources would increase the fossil fuels consumption which obviously affected the cost of energy. In graph (b), the solar and wind scaled average are higher (5.5 kWh/m^2/day and 6 m/s) and that showed more contribution of the RE sources due to the slight increase in RE resources which obviously decrease the CO_2 and the cost of energy. Graph (c) and (d) showed that higher RE resources will not only reduce the level of CO_2 emissions, but will also contribute to increasing the project's revenues. This can be determined from the changes in energy costs when the renewable resources increase. Solar and wind scaled average (6.5 kWh/m^2/day and 8m/s) in graph (c) is the closest scaled average to the current real data used to do the RE resource analysis in this study. This scaled average has been used to find the relation between the renewable energy fraction and the CO_2 emissions based on different load demands as described in Figure 50. From this figure, the increase in load demand will increase purchasing power from the grid and the energy sold to grid will be reduced, and this is mainly due to the low renewable penetrations. Consequently, the CO_2 emissions will keep increasing proportionally with the load demand and power generated by the conventional power plants. All sensitivity analysis scenarios showed how a variation of different inputs such as RE resources, RE output, and increasing in load demand and electricity prices can affect the performance of hybrid grid-connected system significantly.



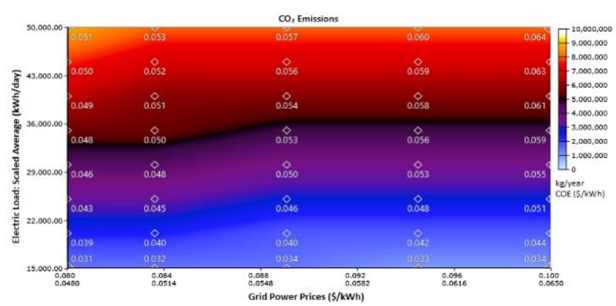
a) Solar and wind scaled average
(4.5 kWh/m²/day and 4m/s)



b) Solar and wind scaled average
(5.5 kWh/m²/day and 6m/s)



c) Solar and wind scaled average
(6.5 kWh/m²/day and 8m/s)



d) Solar and wind scaled average
(7.5 kWh/m²/day and 10 m/s)

Fig. 49 Impacts of RE resources potential and Load demand on the CO_2 emissions (kg/year) and COE ($/kWh).

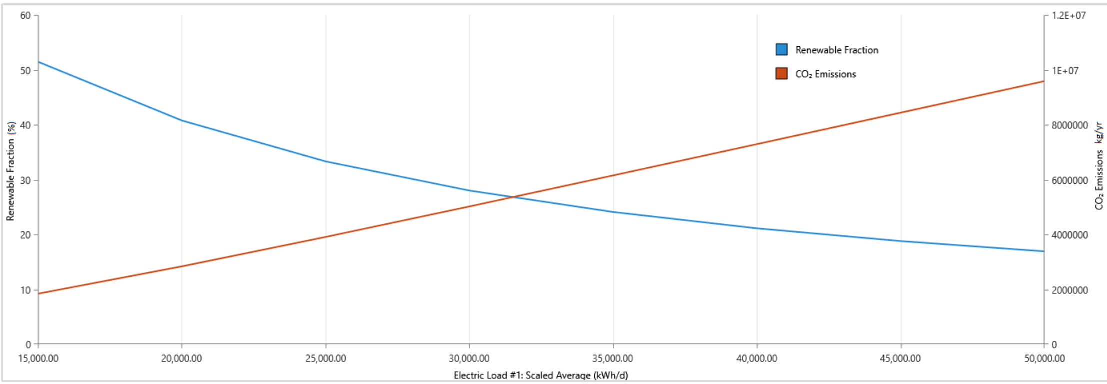


Fig. 50 Impact of Electric load increase on Renewable fraction and CO_2 emissions.

CHAPTER 5

RENEWABLE ENERGY INTEGRATION WITH UTILITY GRID

5.1 Conventional Operation and System Flexibility

5.1.1 Power System Operations

The vast majority of electric power systems are installed and designed to respond to any instantaneous changes in electricity demand requested by different loads i.e. residential, industrial, agriculture etc. The electricity load demand is a function of time of day, season, weather conditions etc., and there is considerable fluctuation in the amount of consumed electricity and hence its electricity demand pattern [74]. Figure 51 is the weekly peak load demand of the year 2017 in KSA. The data of this line graph were provided by the Electricity and Cogeneration Regulatory Authority (ECRA) and shows the weekly peak load for different provinces in KSA[27]. This Figure is a good example demonstrating different levels and the interconnected system patterns of the weekly electricity consumption. From this Figure, it can be observed that interconnected system curve is ramping up from the week number 13 up to the peak point at the week number 34 (61,402 MW). The total demand (interconnected system) then ramps down until it reaches around 35,019 MW during week 52. The load demand at the next year then will follow the uniform pattern considering the parameters that can have an impact on the amount of load demand i.e. temperature, number of populations, electricity bills etc. This example can be extended to any year, month, or week and that would be a different picture demonstrating complex load demand behavior.

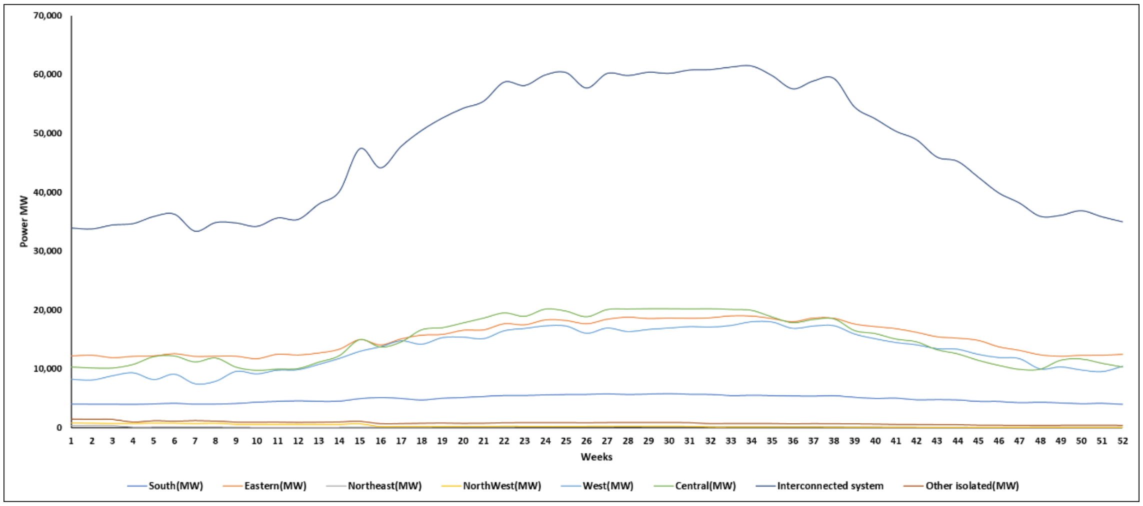


Fig. 51 The 2017 weekly peak load demand in KSA

To understand more about the variation in the amount of electricity used, Figure 52 is a weekly electrical demand from the electricity load used in previous chapter. The data for this weekly was extracted from the month of January to demonstrate different level of power consumption each day of the week. From this graph, it can be observed that demand curves for all days of the week are ramping up from 9 am up to the peak point at different times then ramps down until around 11:30 pm. Also, it can be seen that each day has different demand patterns requiring a certain amount of power.

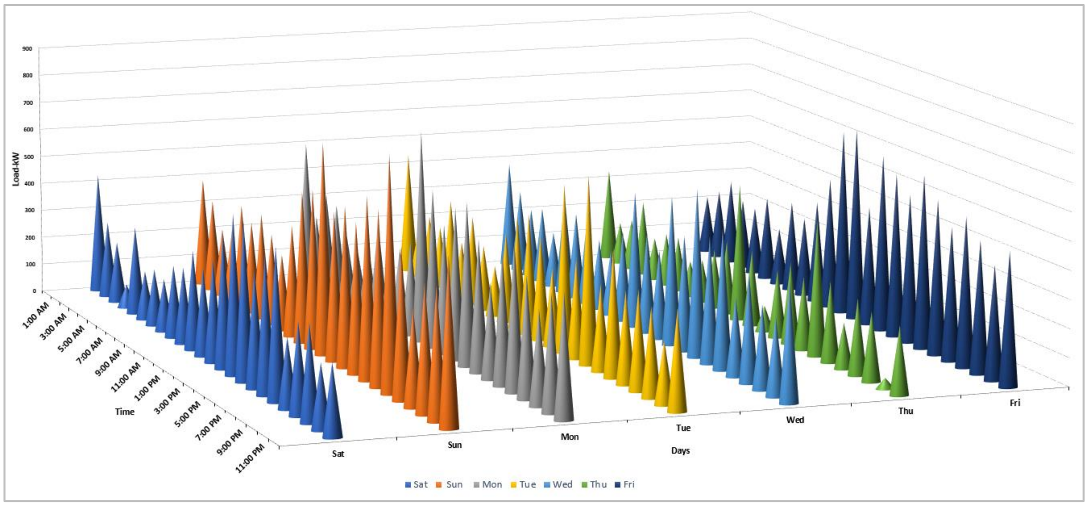


Fig. 52 Daily variation in load demand for one week

Further insight into the use of electricity and power system operation can be obtained throughout the Load Duration Curve (LDC). This curve shows the total number of hours a system is required to produce a power for a certain amount of load [75]. The area under the LDC curve shows the energy demanded by the designed system (consumed) and such a graph helps to understand the relationship between system capacity utilization and production capacity requirements in electric power generation. Figure 53 represents the LDC for the AC electric load used in this research (detailed in previous chapter, section 4.2.1).

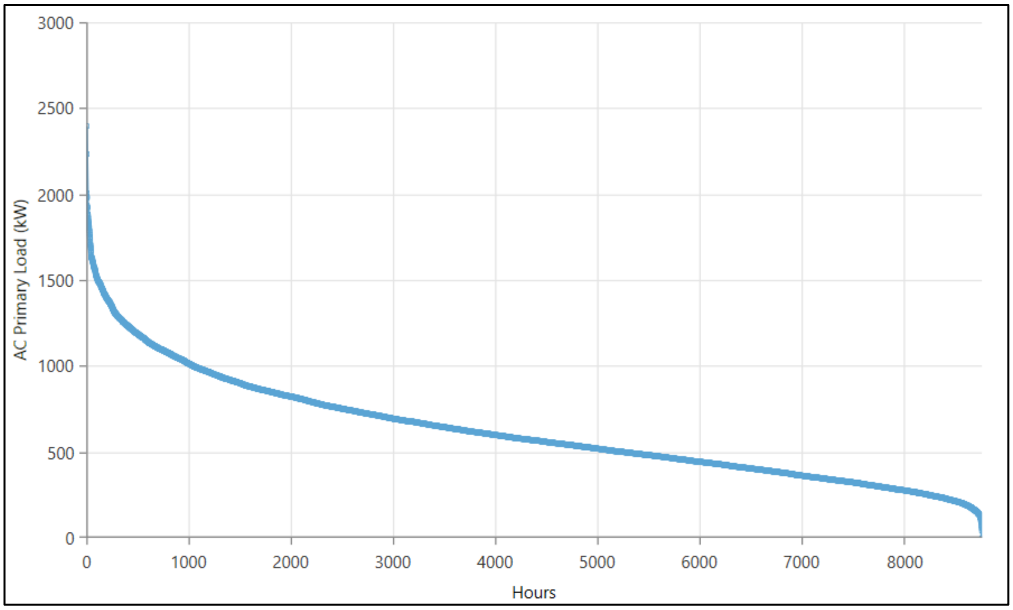


Fig. 53 AC Load duration curve

Because of the constantly changes in electricity demand, the electric systems could be affected. Control mechanisms have been developed to manage systems variability and uncertainty and increase electric system reliability [76]. Examining the timeframes of grid operation is helpful to understand the need for flexibility in power generation. These timeframes can be classified into three general timeframes which are regulation, load following, and the unit commitment as illustrated in the in Figure 54. This Figure shows a general power system load pattern for one day, with system load increasing during the afternoon time and lowering at night. This also, shows that demand must be satisfied with the power from generation at all time periods during the day.

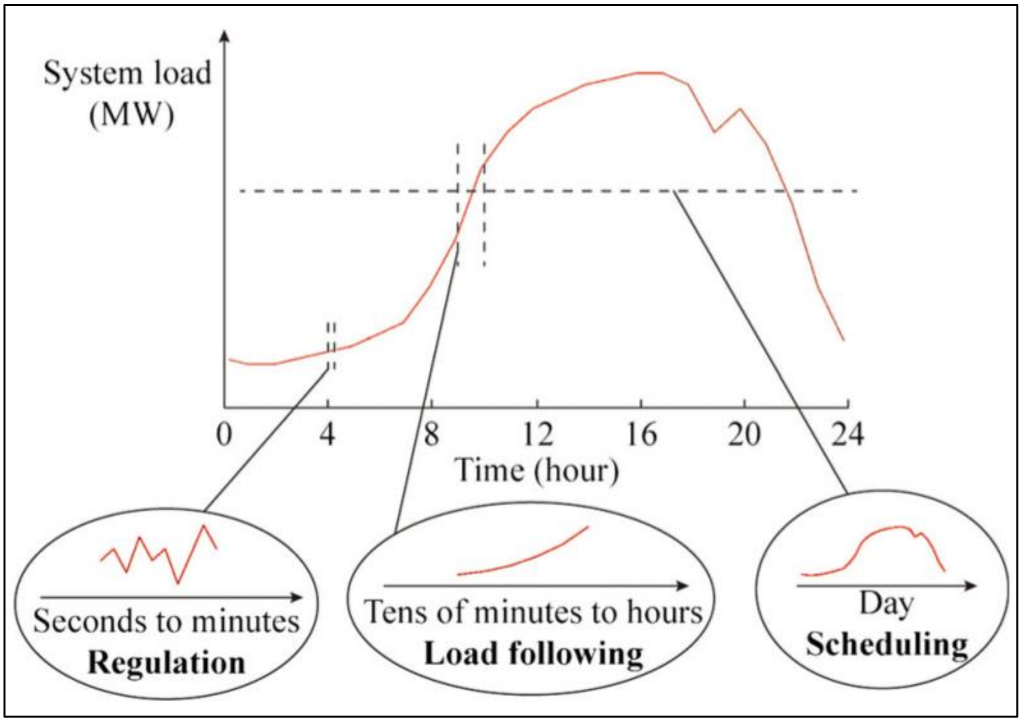


Fig. 54 Power system operation time-frames [77]

The fast response to load changes or disturbances is called regulation since the system regulating the AC power system frequency. The common range of regulation is typically in between seconds to 5 minutes of random variations in load or generation [78]. In power system, generators should be able to respond instantaneously to load changes that require different level of power in order to maintain proper AC power system frequency (primary response). Thereafter, the frequency should be corrected to its pre-event levels (before disturbances or load changes). This is referred to as the secondary response from generators [79]. In large power systems, Automatic Generator Controls (AGC) used to bring a signal to the generators in a certain system to return the frequency to its nominal value. Also, this balancing can be done by centralized control centers that can have communication system adjusting the dispatch set point. Due to the subsequent events that may occur, a tertiary response may be required in order to increase system reliability, specifically when the first and second responses have been depleted [78]. Several researches showed that solar and wind can provide fast regulation services during an abnormal event [80,81,82].

Following the general trending load pattern occurs throughout the day and typically ranges from few minutes (5–15 minutes) to few hours. To follow the fluctuation in demand over hours, the power from generation should be able to match the increase and decrease in load demand considering the power generation margin. This is commonly performed by economic dispatch and sometimes involves standby units or units that can be started and stopped in few minutes (combustion turbines). Since VRE generate power based on the availability of renewable resources, they are not considered a reliable source to follow load unless paired with energy storage system i.e. battery bank, thermal storage, hydrogen pumped hydroelectric storage etc. When ultra-high levels of VRE added into the power systems (grid) , the overall net load must be monitored in order to match the original system requirements [77].

Power system scheduling is the planning for power production to meet the daily load demand requirements considering the expected peak load. This often involves forecasting of the daily electricity demand and scheduling the expected required generation considering adequate reserve margins. Since scheduling is heavily dependent on forecasts of the power production output and availability, it is critical in power systems with ultra-high levels of VRE to forecast variable renewable resources [77,83].

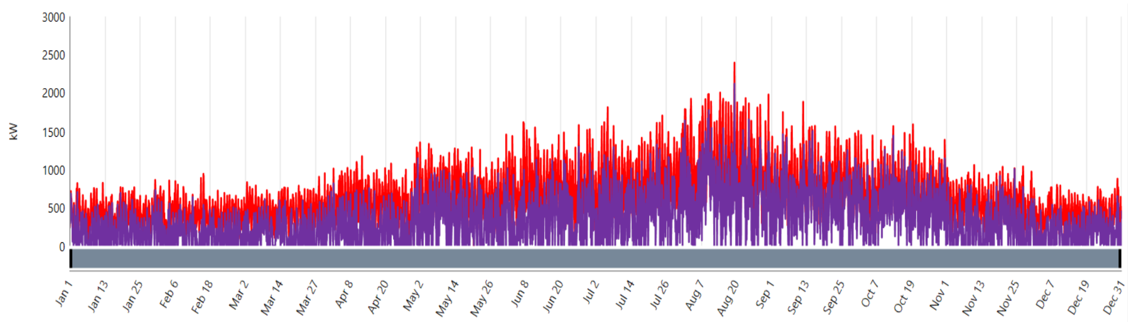
5.1.2 The Importance of Flexibility

Flexibility in power system is defined as the capability to adapt to dynamic and changing conditions (to reduce the cost in the system). In other words, system flexibility is the efficient use of existing resources from the supply side and then on the demand side in order to avoid implementing large new conventional power plants or building other big investments. The main challenges to be addressed near term include the fast deployment of VRE generation, fluctuations of fuel prices and uncertainty, and changes to policies and system standards.

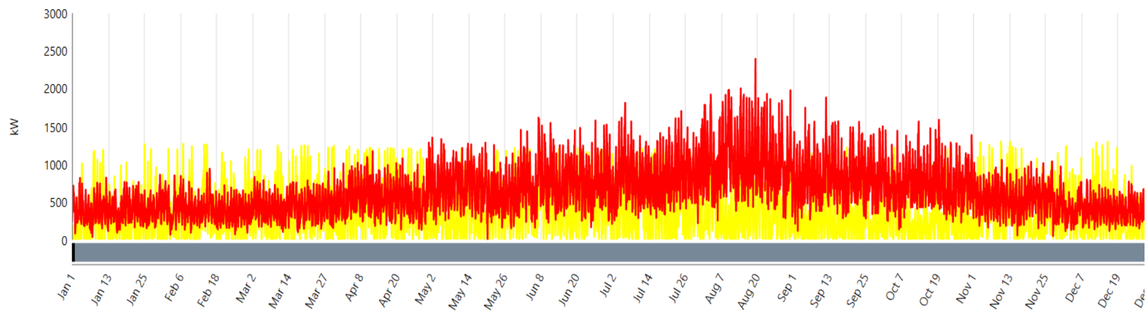
The ramps of large wind and solar electricity generation happen over few minutes to hours. The use of regulation units in power system to compensate for solar ramps is both costly and considered not necessary because regulation services is more costly than other technologies. To integrate higher levels of VRE sources such as wind and solar, grid operators who monitor the electricity systems need to have access to sufficient flexible sources of power generation that can provide the additional load following required by VRE resources [84].

To illustrate how VRE can increase the flexibility need, Figure 55 represents the annual load used in this study and demonstrates how variable RE output impacts the operation of power system. The figure introduces the concept of “grid purchases” which shows the electric demand that must be supplied by the conventional power plants if all of the RE is to be utilized. Red line in the graph represents the AC load demand, and shows the daily variability of demand on an hourly basis during the year and for two weeks in graph D. The yellow line shows the total RE output from solar and wind, and the purple color represents the demand-less-RE that must be supplied by the grid, assuming no curtailment of RE. The Figure (clearer in graph D) shows that the level of output power from the conventional generators must alter more rapidly and be turned to a lower level with wind and solar energy in the system. Other renewable energies may cause qualitatively similar impacts on the power system.

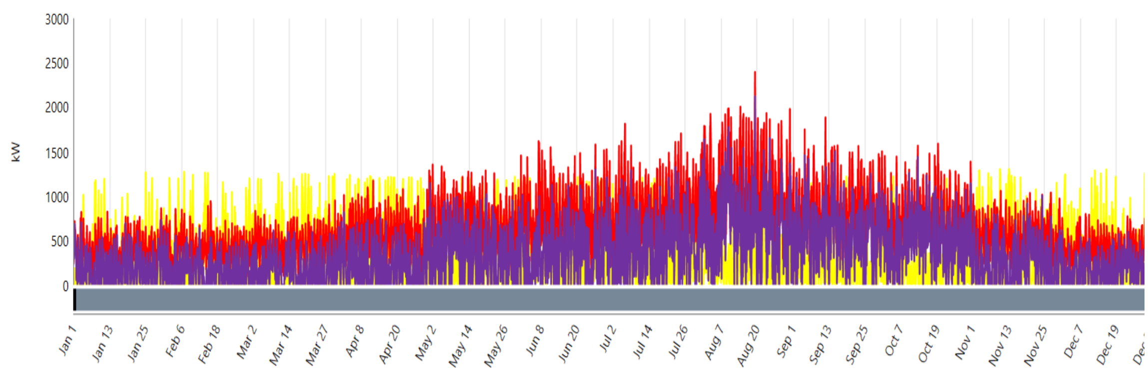
Beside enabling power supply to match electric demand during all times, the flexibility of power system can facilitate the transformation toward modern power systems by improving economic and financial conditions (or investment climates), lowering electricity prices, and reducing emissions. Curtailment of VRE reduces the system capacity factor and likely the revenue stream of a power plant which reduce the attractiveness of investments in new generation either renewable or conventional. Therefore, more flexible power systems can increase the confidence in revenue streams and decrease the risk of negative pricing and curtailment. Furthermore, power system flexibility can provide significant amounts of load following at little or no additional cost. Difficulty balancing demand and supply, significant renewable energy curtailments, negative market prices, and price volatility are some of signs of inflexibility [85].


kW
3000
2500
2000
1500
1000
500
0
Jan 1
Jan 13
Jan 25
Feb 6
Feb 18
Mar 2
Mar 14
Mar 27
Apr 8
Apr 20
May 2
May 14
May 26
Jun 8
Jun 20
Jul 2
Jul 14
Jul 26
Aug 7
Aug 20
Sep 1
Sep 13
Sep 25
Oct 7
Oct 19
Nov 1
Nov 13
Nov 25
Dec 7
Dec 19
Dec 31

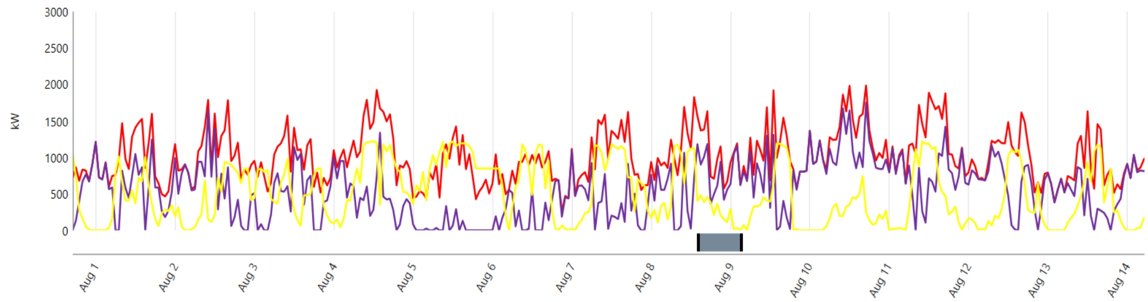
A


kW
3000
2500
2000
1500
1000
500
0
Jan 1
Jan 13
Jan 25
Feb 6
Feb 18
Mar 2
Mar 14
Mar 27
Apr 8
Apr 20
May 2
May 14
May 26
Jun 8
Jun 20
Jul 2
Jul 14
Jul 26
Aug 7
Aug 20
Sep 1
Sep 13
Sep 25
Oct 7
Oct 19
Nov 1
Nov 13
Nov 25
Dec 7
Dec 19

B


kW
3000
2500
2000
1500
1000
500
0
Jan 1
Jan 13
Jan 25
Feb 6
Feb 18
Mar 2
Mar 14
Mar 27
Apr 8
Apr 20
May 2
May 14
May 26
Jun 8
Jun 20
Jul 2
Jul 14
Jul 26
Aug 7
Aug 20
Sep 1
Sep 13
Sep 25
Oct 7
Oct 19
Nov 1
Nov 13
Nov 25
Dec 7
Dec 19

C



D

A- Load versus grid Purchases
B- Load versus RE output power
C- Load, Grid, and RE power
D- (Two weeks) Load, Grid, and RE power

Fig. 55 Electric Load versus the Production from Grid, PV, and Wind Turbine

5.1.3 Source of Flexibility

Planning for flexibility needs to take into account all possible sources. Both technical and institutional aspects of flexibility need to be considered and decision makers make the final decisions based on least-cost principles. To familiarize readers with the main characteristics of flexibility sources to be considered for flexibility planning, different types of flexibility are discussed. Figure 56 illustrates the impacts of VRE at different time scales and the relevant flexibility solutions to handle them. There are several impacts to integrate VRE into electric power systems (utility grid), specifically high levels of VRE. This graph discusses some of the possible operational impacts and shows a range of possible solutions. The solutions used for power system and RE challenges are always depend on the system type and location. Therefore, some power system solutions may or may not be applicable to certain situations.

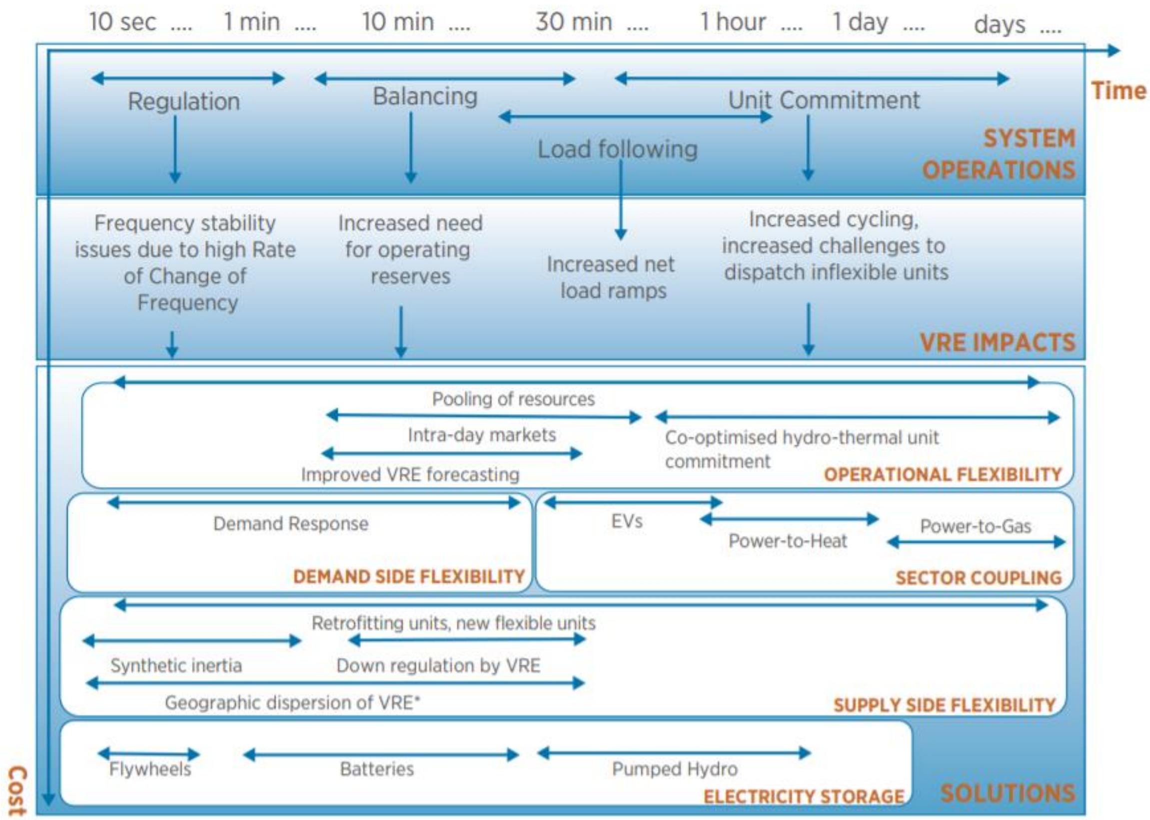


Fig. 56 VRE Impacts at various time scales and relevant flexibility solutions [84]

Technical flexibility is related closely to the system physical structure. It refers to the combination of different technologies that determine 1) the ability of power supply to follow fast changes in connected load, 2) the ability of connected load demand to follow rapid changes in power supply, 3) the ability of energy storage or backup system to balance mismatches between power supply and electric load demand at all-time scales, and 4) grid infrastructure capability to allow least-cost power supply to reach load demand anywhere in power system at all times [84].

Operational flexibility refers to how the power system assets are operated. This type of flexibility shows how power systems respond to any changes in electric load demand and generation. Changes in power generation and electric load demand must be constantly balanced in order to maintain power system reliability and stability. Therefore, flexibility is highly important for power systems that planned to integrate high levels of wind and solar, whose power outputs can be uncertain, variable, and creating a fluctuating supply. Sources of flexibility can be enhanced across a power system, including system markets and operations, demand-side resources, generation, and transmission networks. Having flexible system requires higher quality planning in order to optimize investments and ensure that power system requirements are met during both long and short periods of time [86].

Regarding system operations and markets, changes in it and practices can enhance flexibility, usually at lower economic costs than the other options that require some changes to the existing physical power system. Adjusting generation scheduling practices day ahead to allow variations near to real time allows operators to dispatch electricity based on improved forecasts of both variable renewable energy demand and output. This reduces the need for expensive generating capacity (reserves) and increase the probability of having more efficient and accurate market operation system.

In terms of the flexibility of demand and storage, management of demand side and demand response allow customers to participate in load control based on the signals of price. This mechanism includes the system operator control, smart metering and smart grid, time of use tariffs, and real time pricing. This process (demand response) can be relatively inexpensive. However, it requires rigorous regulations related to reliability, minimum magnitude, and response time. Storage technologies depend on the location and the system type. The most common storage technologies are pumped hydro, thermal storage, and battery bank. These technologies hold the produced energy during periods of excess generation from VRE and then use this energy when it is needed. Compared to storage technology to demand response and other options for flexibility, it has a higher capital cost.

Regarding flexible generation, conventional power generators (fossil fuels based power plants) and dispatchable or reliable RE such as geothermal or biomass plants enhance flexibility if they have the capability to rapidly ramp the output up or down to follow net load, start up and shut down quickly, and work efficiently at a lower minimum level during high level of variable renewable energy output power periods. Retrofitted and new small-scale distributed generation, as well as large scale power plants can supply flexible generation. Flexible transmission networks come after generation, interconnecting and extending transmission lines to neighboring networks can provide greater access for power system to a range of balancing resources. Aggregating generation assets via networks interconnection reduces net variability and improves system flexibility over the entire power system [86].

5.2 Grid Code Definition and Purpose

The grid codes refer to the operation of power system and energy market rules. In other word, instructions that illustrate the operational and technical characteristic requirements of power plants [87]. These codes are considered the guidelines to be followed by users and they enable network operators, generation system, suppliers and consumers to function more effectively. This ensures safe, secure, and economic electric system. Market codes, operating codes ,planning codes , and connection codes are some of the grid codes examples [88] .

Globally, power sector is accelerating the transition towards a sustainable energy since the renewable energy sources have been used to address some of the problems mentioned in the literature review. RES is considered a viable choice for integration with conventional power plants. In 2017, the estimated global renewable energy share of the generated power was 26.5% and solar power represented 1.9%, wind power 5.6%, bio-power 2.2%, and ocean ,CSP and geothermal power was 0.4% out of the total RE production as described in Figure 57. For power systems operation and integration, Variable Renewable Energy (VRE) generators pose more challenges. Therefore, grid codes are essential for the successful integration with conventional generation [88].

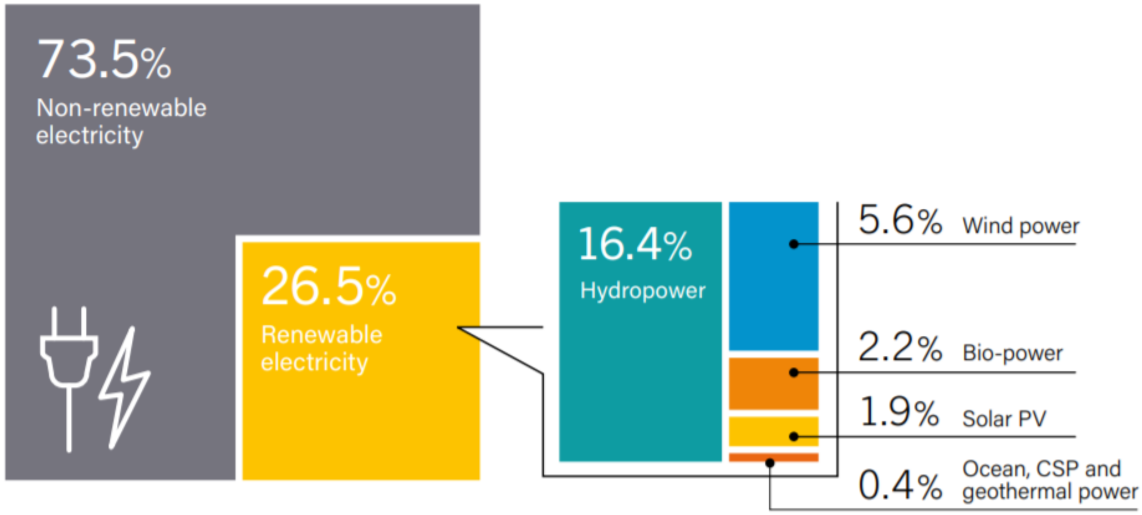


Fig. 57 Estimated RE share of global electricity production [89]

This section focuses on grid connection codes of VRE generators, specifically for wind and solar PV generators of any size. The grid connection code function that cover the VRE is to provide technical requirements for solar PV and wind plants during the integration with the utility grid. This helps to maintain system stability and reliability. Developing RE grid code should include different elements based on country's conditions. Many of the VRE generators connection requirements depend on the conditions and specific needs of the local power system. In order to develop the VRE grid code, several considerations should be taken into account. For example, size of the power system, distribution and flexibility of load and generation, energy planning, market size for VRE, characteristics of conventional generators, interconnection level, voltage levels, energy policy, and operational practices. All of these aspects are presented in Figure 58.

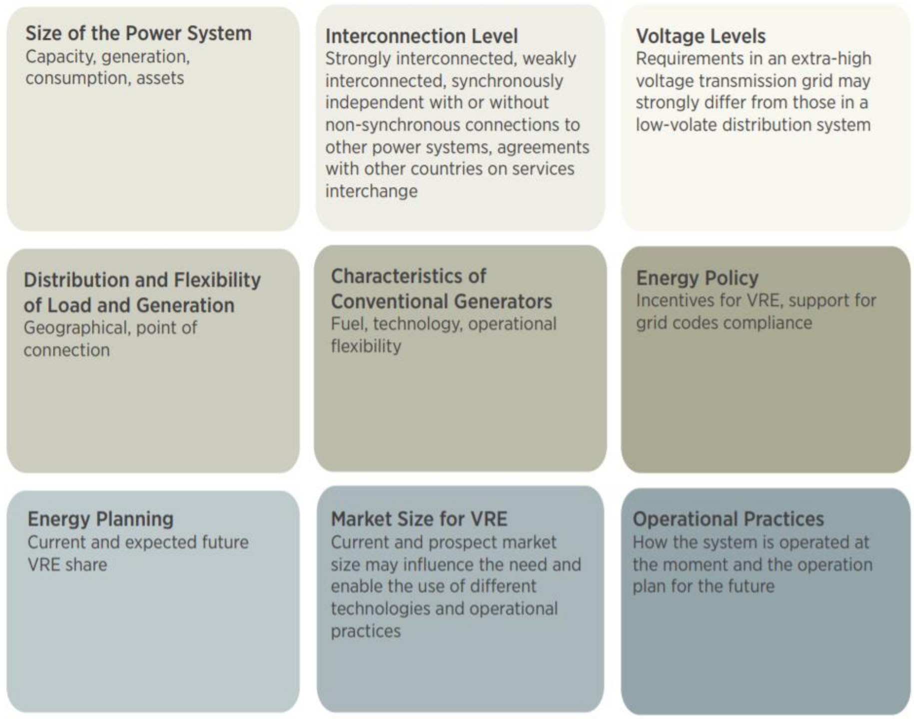


Fig. 58 Aspects of grid connected code development [88]

5.3 Grid Code for Renewable Energy

Nowadays, the renewable energy share of power generation in the total produced power is becoming more and more prominent. Due to the intermittent of electricity production, improvements are important for the power generation plants. Grid code requirements vary between countries and their severity usually depends on the robustness of power network as well as renewable power penetration level. The requirements of grid code have been a drive for the development of renewable energy, specifically solar and wind technologies. Manufacturers in these technologies sector are constantly trying to improve the electrical system control and design, in order to meet the new grid code requirements [57]. The discussions in this section will be focused on the important grid code requirements for solar and wind technologies in KSA and VRE grid code experiences from other countries

5.3.1 Grid Code Requirements for Solar Technologies

The Photovoltaic Power Plant's (PVPPs) high integration has started to affect the reliable service or system operation, and stability of utility grids. Therefore, many countries have established new requirements for grid integration of PVPPs in order to address the possible issues in system stability, reliability, and security of the power grid [90]. Due to successful regulations which have been implemented by the developed countries, the generation of renewable energy in the power grids has been increasing in the last decade. For example, countries like, China, Japan, Germany, United States which are leaders with respect to implementing PVPPs are also leading in developing grid codes. To prevent grid instability due to a high penetration of renewable energy technologies, there are directives for connecting generating plants to the grid. The mandatory and main requirements introduced by some of the developed countries are: Active power control, Automatic frequency response, Reactive power control, and Fault ride through capabilities.

5.3.1.1 Active power control

The frequency deviates from the nominal value when the grid is overpowered and this can result in machine damage, instability, load shedding, and even blackouts. Renewable generating unit (Solar energy) either CSP plant or Utility-Scale PV plant, should be able to control the output power in order to avoid possible network congestion. Therefore, the Transmission Service Provider (TSP) is responsible for required curtailment of power output from solar power plants and to maintain the network. The PV system uses a static inverter, while the CSP plants rotating synchronous generating unit. Therefore, different requirements may be applied since the operation of CSP technology is similar to that of a conventional generating plant.

Grid codes require at least two types of active power control: these are the ramp rate control and power curtailment. In addition, some countries ask for power reserve [91]. Some studies have shown that there are no barriers that may prevent large scale PV power plants to be compliant with such requirements. However, to implement the power sharing management system, a high cost may be envisaged specifically for PV plants (rather than CSP plants) [54].

5.3.1.2 Automatic frequency response

Any renewable energy generating unit, such as PV or CSP power plant, should be capable of reducing its power generation when the grid frequency exceeds a pre-set value. This will help to avoid risk of unstable system operation when the frequency increase over a certain value. In KSA, the grid frequency used is 60Hz, and all generating units must be capable of continuously supplying active power within the system frequency range 59.5 Hz to 60.5 Hz. The drop of active power should be adjustable within 2% and 8% and the normal set point should be at 4% [92].

In case the system frequency momentarily rises to 62.5 Hz or falls to 57.0 Hz, all generating units connected to utility grid should remain synchronized with the transmission system for the operating times stated in Table 5. This will allow the TSP to undertake measures to correct the situation. Each RE source should be capable of regulating its active power in the frequency range illustrated in Figure.

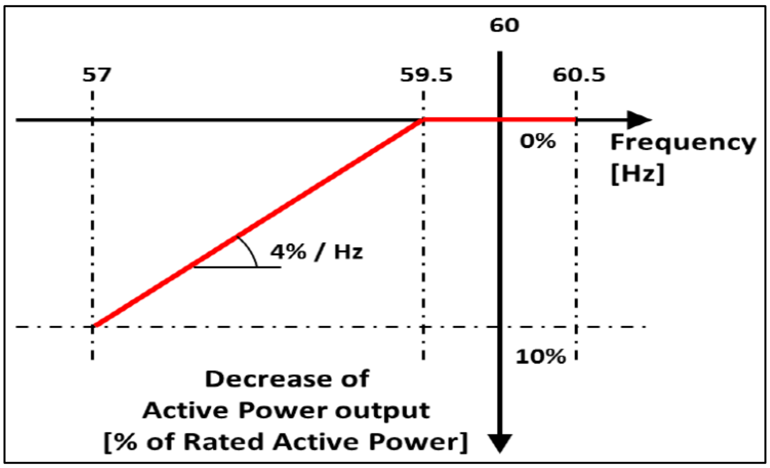


Fig. 59 Maximum Output Power Reduction Diagram [92]

Table. 5 frequency limits based on Saudi Arabia grid code [92]

Below Nominal Frequency (Hz)	Above Nominal Frequency (Hz)	Operation Requirement
58.8 – 60.0	60.0 – 60.5	Continuous
57.5 – 58.7	60.6 – 61.5	for a period of 30 minutes
57.0 – 57.4	61.6 – 62.5	for a period of 30 seconds

To illustrate more about the frequency limit, Table 6 shows the frequency limits in different international grid codes. For the countries that have a frequency of 50Hz, the extent areas of frequency operation have the same range between 47 and 52.0 to 53.0 Hz in international Grid Code (GC). In Germany, the frequency variation range for grid-connected solar PV stations is between 47.5 and 51.5 Hz. Otherwise, it must be disconnected immediately. The Malaysian grid-connected PV power plants have to operate continuously over the frequency changes within 52 to 47 Hz range. In the case of China, the normal operation range of frequency is from 49.5 to 50.2 Hz, however in case the frequency level decreased in the range of 48 and 49.5 Hz, the PV power plant connected to network should withstand this change for 10 minutes. Additionally, when the frequency is greater than 50.2 Hz, the solar PV power plant must remain connected for 2 minutes. If it exceeds 2 minutes, PVPP must shut down directly.

The frequency regulation in USA - PREPA, Spain, Germany, China, Malaysia and Japan GCs forces the fast shut down of PV power plants when the frequency reaches the upper limit, while the immediate disconnection for PV power plant station based on the GCs of US North American Electric Reliability Corporation (NERC) is only allowed after 0.16 s, Australia 2 s, and South Africa 4 s, if the frequency increased to upper limits. On the other hand, all countries GCs listed in the table require an instant trip in case the underfrequency limits is reached, except the codes of China and US NERC that require that PV power plants stay connected for a specific time before tripping.

Table. 6 The frequency limits in different international grid codes [90,91]

Country Grid Code	Nominal Frequency, Hz	Frequency limits, Hz	Maximum Duration
United States—Puerto Rico Electric Power Authority	60	f > 62.5 61.5 < f < 62.5 57.5 < f < 61.5 56.5 < f < 57.5 f < 56.5	Immediate disconnection 30 s Continuous operation 10 s Immediate disconnection
United States—North American Electric Reliability Corporation	60	> 61.5 61 < f ≤ 61.5 58.5 < f ≤ 61 57.0 < f ≤ 58.5 f ≤57	0.16 s 300 s Continuous operation 300 s 0.16 s
Japan- Western	60	f > 61.8 58 < f < 61.8 f < 58	Immediate disconnection Continuous operation Immediate disconnection
Germany	50	f > 51.5 47.5 < f < 51.5 f < 47.5	Instant disconnection No trip (continuous) Immediate disconnection
China	50	f > 52 50.2 < f < 52 49.5 < f < 50.2 48 < f < 49.5 f < 48	Immediate disconnection 2 min Continuous operation 10 min Depend on the inverter
Spain	50	> 51.5 47.5 < f < 51.5 48 < f < 47.5 f < 47.5	Immediate disconnection Continuous operation 3 s Immediate disconnection
Malaysia	50	f > 52 47 < f < 52 f < 47	Immediate disconnection Continuous operation Immediate disconnection

5.3.1.3 Reactive power control

It is known that the utility grid voltage is directly proportional to the reactive power. Generally, decreasing reactive power causes the network voltage to drop, and increasing it results in a voltage rise. Therefore, conventional power plants should overcome the deviation of grid voltage by injecting the appropriate amount of reactive power on the grid [93]. In the last decade, modern GCs require RE generators to contribute in grid stability to prevent the instability of utility grid. Therefore, PVPPs are required to control the reactive power production to contribute towards the stability of grid voltage, especially during grid faults, to assist fast grid-voltage recovery. This can be achieved either by a specific power factor that controls the reactive power based on the amount of active power or by voltage control at the PV power plant connection point to the network. At the Point of Common Coupling (PCC), the power factor's value can deviate from unity and range from 0.95 under-excited to 0.95 over-excited. A target value of the reactive power supply to individual PVPP can be assigned by the network operator through a predefined scheme or real-time communication [94]. Capacitor banks are examples of energy buffers, which are available in the inverters of PV systems connected to the utility grid, and they are used to support reactive power production from grid-connected PV systems. However, an increase of PV installation system costs can be expected.

CSP power plants can fulfil the minimum power factor and the reactive power control. This is because of their electricity generating units used by synchronous generators equipped with excitation system that capable to provide the required reactive power [95]. Therefore, the amount of reactive power that can be delivered to the grid network mainly depends on the generator size and relevant excitation system as for the traditional power plants.

5.3.1.4 Fault ride through capabilities

Renewable energy generating units can be distinguished by GC in two different categories: all renewable energy generating units and the ones based on synchronous generators. These two categories are required to contribute with different kind of dynamic support according to their capability. Since the CSP could be considered in all respects as traditional power plants, they should have the capability to meet the requirements set for the conventional generating units, while all other renewable energy generating units, such as PV power plants, must meet specific requirements. As an example, when the network fault occurred, with consequent voltage drop, the grid-connected PV power plant has to remain connected to the grid for a certain time specified by the GC. Furthermore, it shall feed-in the same active power as soon as the fault is cleared [54].

The voltage drop that shall be ride and through by any PV generating power plant is specified by gird code (Voltage through capability) as shown in the Figure 60. On the diagram, the area A represents the normal voltage profile at the point of common coupling (PCC), where the PV power plant works continuously. The PV Power Plant has to withstand voltage dip and remain connected for a period of time (t_0 to t_1) when the voltage profile at PCC is in area B. Otherwise, it has to be disconnected. In the case that the PV power plant's voltage profile is in area C, it is not mandatory for PV power plant to stay connected unless the voltage is recovered to V_1 within time t_2 after fault occurrence. If this happened, then it is mandatory for PV power plants to remain under continuous operation without disconnection.

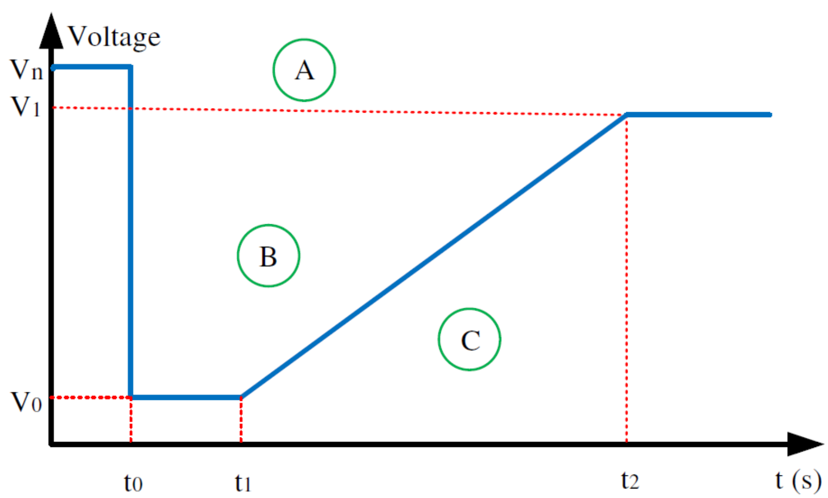


Fig. 60 General curve for fault ride through requirements [90]

Based on the standards and characteristics of the national grid, the values of t_1, t_2, V_1 and V_0, are different from one grid code to another. Generally, modern grid codes that include Low-Voltage Ride Through (LVRT) are like that in Figure 60, even though their features can vary from one country to another considering the requirements of power company operator and the reliability of the national grid. As an example, the German grid code required that each PV power plant should remain connected to the network within 0.15 s when the voltage at PCC drops to 0 of the rated voltage. Within this period, no tripping-off operation is allowed. If the voltage could recover 90% of the predistributed value at the connection point within 1.5 seconds, the PV power plant shall remain under continuous operation with no tripping off. In the case of Italy, the grid code requires that the PV power plants should withstand grid-faults with a voltage drop to 0 for 0.2 s. After voltage drop occurrence, the voltage restoration should reach to 90% of its nominal value during the next 1.0 s. The Chinese grid code stipulates that during voltage sag down to 20%, PV power plants must remain connected up to 0.625 s and the voltage should be restored to 90% of the voltage level available within 2 s. Figure 61 summarizes the parameters and shows the comparison of LVRT requirements for other countries grid codes with respect to the integration of PV power plants to the utility grid.

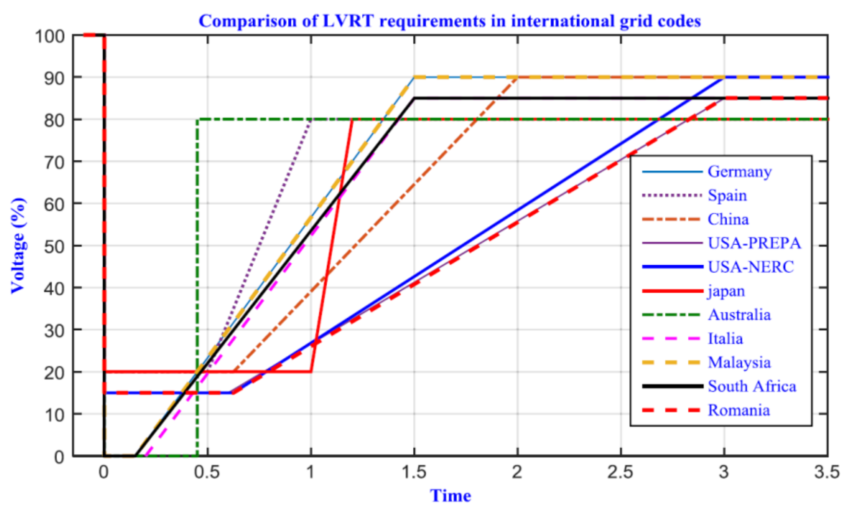


Fig. 61 Comparison of LVRT Requirement in International Grid Codes [90]

In order to maintain the network stability and avoid critical situations that may occurred because of the overvoltage, some modern grid codes require that PV power plants should stay connected to the system when the overvoltage occurs for a certain time. This is named as High-Voltage Ride Through (HVRT) capability requirements. Commonly, voltage swell grid fault is rarely happened compared with voltage sag. However, when the grid voltage swell occurs, modern grid codes require the HVRT capability to be applied. Figure 62 compares the requirements of HVRT given by different countries. As it can be seen from the graph that most exhausting HVRT requirements in international grid codes are limited at 130% of nominal voltage except the Puerto Rico Electric Power Authority (PREPA), which requires PV power plants to withstand an overvoltage up to 140% of nominal voltage within 1 s.

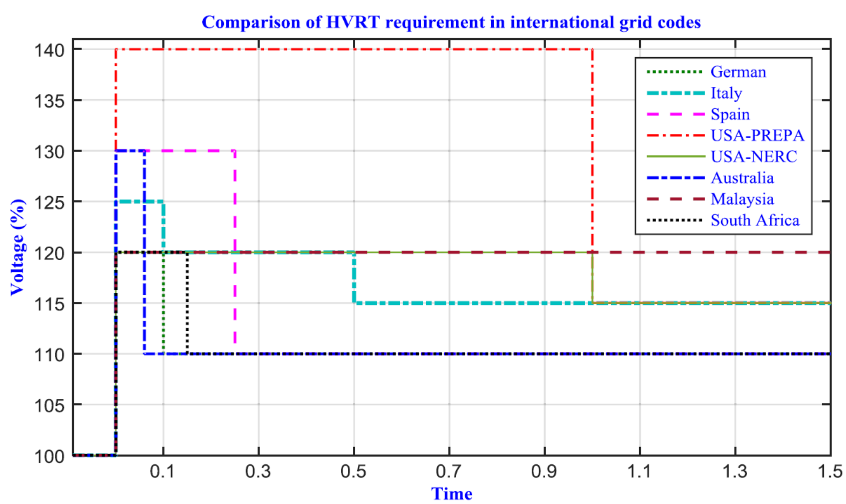


Fig. 62 Comparison of HVRT Requirement in International Grid Codes [90]

5.3.2 Grid Code Requirements for Wind Technologies

Wind variability plays a significant role in any feasibility studies of wind farm projects either grid connected or standalone systems [96]. Therefore, power system studies must take wind variability into account in order to alleviate the negative impact of intermittency and wind variability on power system reliability, in addition to promote the economic viability of wind energy. In general, grid connected wind farms are expected to support the grid and to provide additional services much like conventional power plants (e.g., frequency regulation and dynamic voltage control, active power control, and low voltage ride through (LVRT))[57].

The requirements are different from country to country and their severity. They commonly depend on the level of wind power penetration as well as on the national or regional power network robustness. The requirements of grid code have been a drive for the development of wind energy technologies. Wind energy sector manufacturers are constantly trying to improve wind turbines, mainly in the area of electrical system design and wind turbine control, in order to meet the latest grid code requirements and that may require additional cost. Thus, grid codes for interconnection and operation of wind generation as well as demand of technical requirements should be enacted by system operator to maintain the stable operation of the system according to operating condition.

Some of the various codes and requirements introduced by the developed countries are: Active power regulation, Reactive power regulation, Fault ride through capability, Communications and notifications

5.3.2.1 Active power control (APC)

Active power control can be defined as the ability of wind turbine or wind power plants to regulate the output of their active power to a defined level and at a defined ramp rate (e.g., in the case of active power curtailment requests by Transmission System Operators (TSOs)). The purpose of these requirements is to prevent overloading of transmission lines, to ensure a stable frequency in the system, and to minimize the effect of wind turbines dynamic operation on the grid (e.g., during extreme wind conditions, at startup/shutdown). Also, during faults, the capability of any wind turbine or wind farms to control their active power is important for transient stability. As long as the power is controlled effectively when a fault occurs, the turbine can be prevented from over speeding [57].

It is interesting to explain the motivation for wind energy to provide APC by presenting current requirements of frequency support by some transmissions systems operators (TSOs). There are two main motivations for why active power control should be provided by wind turbines. Firstly, regulation is necessary for maintaining frequency of grid and as wind penetration increases it can provide key support in maintaining the required balance. Secondly, the potential to rise the profitability of wind power plants by enabling participation in ancillary service markets [79]. In the last decade, different studies demonstrate that providing regulation is important for wind power plants to increase their own profits [97].

In countries and regions with relatively large levels of wind penetration and relatively isolated grids, participation in regulation of grid frequency by wind plants and wind turbines is crucial. A report issued by Project UpWind [98] mentioned that replacing conventional power generation sources with a large scale of wind power lacking the capability of active power control can potentially have notable impacts on grid frequency stability. This effect is very noticeable on island grids that have low levels of interconnectivity to other grids, like many of the Greek isles [99].

The need of participation in grid frequency regulation by wind turbines or wind farms is reflected in the regulations and requirements put on wind plants by TSOs in regions with relatively isolated grids or high levels of wind penetration. For example, the Irish grid code requires that in the event of a frequency deviation, wind power plants should have active power curtailment capabilities and outline specific active power generation set-points as a function of available power [100]. Further, a minimum response rate for individual turbines of 1% of rated power per second is specified by this code. Elsewhere, Denmark's TSOs Eltra and Elkraft require that wind power plants should be able to track reference power levels generated by the system operator and track a reserve power offset. In the case of Canada, Hydro-Quebec requires that 10 MW and above wind power plants must have the ability to modify their active power output for at least 10s in response to grid frequency deviations greater than 0.5 Hz. Additionally, the TSO Red Electrica in Spain mandates wind power plants respond to the deviations of frequency with proportional control of active power output within a specified range of percentages of rated power.

5.3.2.2 Reactive power control

Reactive power control concerns the stability of voltage. The voltage levels in a power system must be maintained constant because the utility and consumers equipment are designed to operate at specific voltage levels [57]. To maintain the overall system voltage stably, compensators of reactive power should be equipped sufficiently and controlled continuously according to the variation of reactive power demand. The characteristics of reactive power consumption of entire power system can be changed significantly according to unpredictable changes of wind generation and it may not be entirely compensated due to decrease of conventional power generation if the wind penetration is increased. Therefore, wind turbines are required to have the compensation capability of reactive power as well as the related equipment [101].

To formulate the reactive power control requirements for Wind Power Plants (WPPs), the technical characteristics of individual wind turbine should be considered. Before 2000, fixed-speed wind turbines (FSWTs) were widely installed and it was noticed that the induction generator equipped with this type of wind turbine can absorb reactive power from the power grid. Because of that, the power system reliability can be decreased, particularly when grid faults occur. Moreover, FSWT can hardly control the output reactive power. As a result, such wind turbines cannot contribute to the stabilization of grid voltage automatically. During last two decades, DFIG has been a dominant type in industry. As explained in chapter 3, DFIG is equipped with DC-link capacitor, grid side converter, and rotor side converter. Hence, it is possible that by controlling rotor side converter, generator in DFIG can be excited without absorbing reactive power from power grid. Furthermore, for voltage stabilization, the installed converters and capacitor can be used to provide reactive power [101].

5.3.2.3 Fault ride through capability

Mainly, voltage faults on wind turbine terminals are caused by the short circuits that can occur in different locations of the power system in a number of different ways including line-to-line and line-to-ground faults. Such faults can be nonsymmetrical or symmetrical depending on the fault scenario [102]. Usually during a fault, the system voltage decreases under a certain level and the wind generators are disconnected immediately to prevent the damage of its equipment and system. Wind generator trip and the loss of generation, however, can disturb the power system recovery and cause additional frequency problems as the wind penetration increases over a certain level [103]. Therefore, grid codes of developed countries require wind generator and wind farm to maintain the operation during the fault and continue normal operation immediately after a fault is cleared. This will help to prevent these undesired trips of large wind generation due to under voltage and unstable operation. This regulation is called Low Voltage Ride Through (LVRT) or Fault Ride through (FRT) and applied to both high and low voltage conditions. Most grid codes request wind generators to provide these FRT capabilities considering the additional requirements. FRT regulations of various countries are presented in section 5.3.1.4 of this chapter. All these requirements have a lot in common defining the fault duration, residual voltage, and voltage recovery to maintain the operation of wind generation. Since DFIG is the most widely used system of wind turbines, latest studies showed Low voltage ride-through capability improvement methods for DFIG based wind power plant [104,105,106].

5.3.2.4 Communications and notifications

It is common that the large-scale wind power plants are normally connected to power transmission networks so that the generated power can be delivered to load centers in remote locations, and small-scale wind farms can meet local demands through the integration into power distribution networks. Due to intermittency and high variability, operations of wind farm become a great challenge to power systems. Therefore, communication systems are extremely important technologies, which enable the accommodation of distributed RE production and play a significant role in operating, monitoring, and protecting both power systems and RE generators.

Communication systems are essential infrastructure that transmit the collected and measured information and control signals between power systems and wind farms. Robust communication systems can better explore the wind potentials and facilitate farm controls. Lack of powerful communication systems could compromise the system controllability and observability, which would negatively impact system reliability and security[107].

Figure 63 shows a scheme of grid integration to the Bulk Power System (BPS) and summarized in an illustrative way the information and energy flow, generation system, transmission system, distribution system. A modern power system is composed of communication networks and high-power equipment as illustrated in the graph. Energy flows through grid to meet electric load demand, while the system's information flows through the communication system to monitor the status of system, control the dynamic energy flows in the utility grid, and transfer the collected information across the power grid.

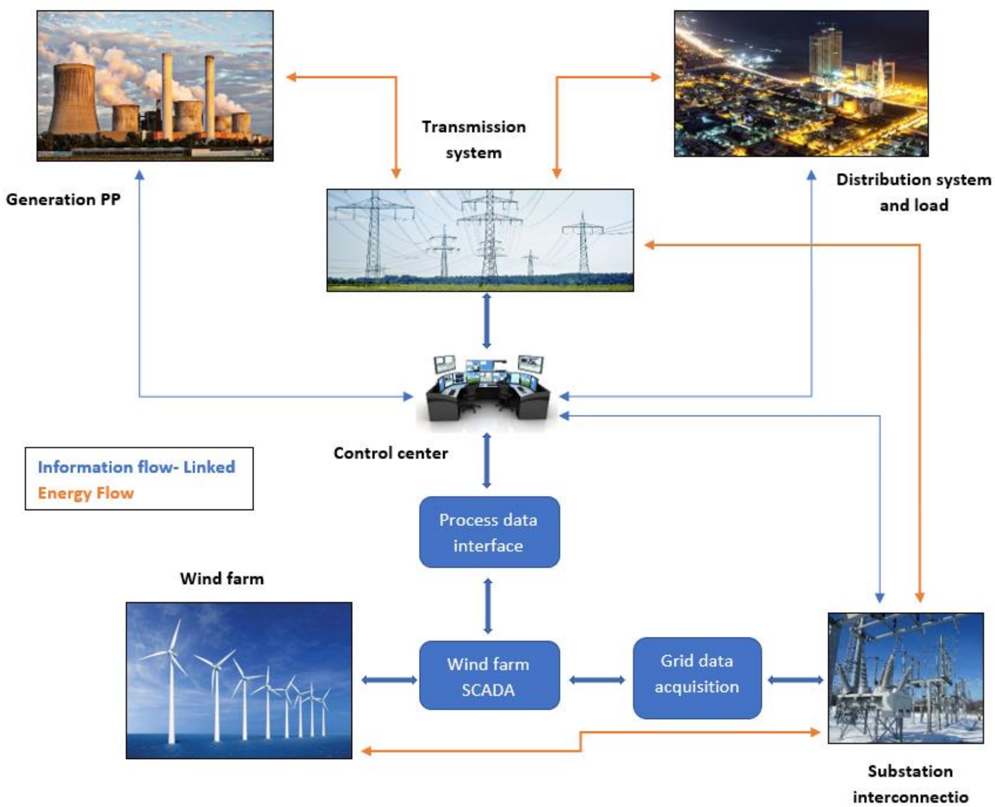


Fig. 63 Grid-connected wind farm

An example from developed countries' grid codes is that wind energy power plants should be equipped with control system which ensures the remote and independent control of each wind turbine included according to the depicted requirements of grid code. Based on these grid codes, for each wind farm this function should ensure that regulating orders to the wind farm's total output power are met in the connection point. Also, the predictions should be updated for certain time periods continuously to ensure the reliable market operation of power system [108].

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

This research work investigated the contribution of hybrid renewable energy system to utility grid with the aim of contributing to the development of renewable energy in the KSA and enhance sustainability and the role of renewable energy. It started with an overview of the global climate change and its impact followed by discussing the current status of KSA's power generation and the possible increase in the demand for electricity over the next 15 years. This study also Investigated the potential of the renewable energy resources (solar and wind) in four different locations in KSA using the installed resource monitoring stations' data. Furthermore, the performance of grid-connected HRES and its contribution to the KSA's electricity production was examined using simulation and optimization. Also, the study compared the effects of solar and wind energy technologies on the electricity generation and demand curve considering technical, economic, and environmental feasibility. Sensitivity analysis were done to give a blueprint of the system reliability and determine how sensitive the outputs are to any changes in the system's variables. Additionally, this study explored the developed countries' mandatory codes for grid-connected renewable energy systems in order to build up the RE sector in KSA. The following are the findings and contributions of this study:

The study showed that global average temperature, sea level, arctic sea ice, carbon dioxide concentration, ozone hole, and other observed changes are the key indicators of climate change and like many countries, KSA will also be notably affected. Therefore, the transition to renewable energy sources is needed in the near future not only in developed countries but also in developing countries in order to meet the climate target and maintaining the global temperature within the preindustrial levels.

Chapters 1 and 2, illustrated that the power sector of KSA relies heavily on fossil fuels for electric power generation and the rapid population and high economic growth forced the government to take quick action to expand or build new power plants in order to meet new loads. However, this will keep the KSA among the top CO_2 emitting countries since electricity and heat generation are the two-fuel combustion-based sectors that produced two-thirds of global CO_2 emissions. Besides that, continued dependence on fossil fuel as the primary energy source will cause fuel depletion, environmental pollution, and have an extremely negative impact on human health. Therefore, transition to sustainability in KSA must be enhanced and the huge potential for renewable (solar and Wind) resources must be exploited. PV, CSP, and wind energy are the most effective RE technologies in such region, respectively.

In this study, solar PV and wind energy resources for four different locations have been used to do the analysis of the designed hybrid grid connected system. Also, these two effective technologies have been described and presented in chapter 3 along with a description of renewable energy system types, component configurations, their operational and functional requirements, and how the equipment is connected to electrical loads and other power sources. Grid-connected system was the suitable type used since energy intermittency is not an issue in such region.

In chapter 4, a resource assessment and techno-economic analyzes of grid-connected solar/wind hybrid systems for the selected locations was carried out. The results of the assessment of RE resources showed that for solar resources, GHI values are high at all of our selected sites with relatively low variability. Due to the effect of pollution, dust, and clouds, DNI levels were more variable. The highest annual average daily total of GHI and DNI of solar radiation was in the city of Sharurah by 6681.62 Wh/m^2 and 6206.91 Wh/m^2, respectively. For wind energy resources, the frequency analysis showed that the availability of wind speeds above 10 m/s was 41% of the time at Yanbu followed by 27% at Hafar Albatin, 22% at Sharurah, and 14% at Riyadh at 80 m elevation for the entire year. In addition, the annual mean wind power density for Yanbu city was the highest with 833.78 W/m^2 at the height of 80 m, which indicates that this location is the best for wind energy production.

The effects of changing renewable energy resources on the power generation are analyzed. Four different grid-connected hybrid systems having the same components and capital costs are considered. Since every location has a different wind speed and solar radiation intensity over the year, different configurations of power generation at each location are expected to meet the same load demand requirements. The simulation results showed that the solar and wind resources potential at Yanbu city, leads to the minimum NPC of $3,558,756.30 and LCOE of $0.03655 followed by Hafar Albatin, Sharurah, and Riyadh with $0.04392, $0.04618, and $0.05402, Respectively. The system's capacity factors at each location also show that Yanbu city has the highest renewable energy output power, particularly the power from the wind turbine that represents 53% out of the total annual generation with an approximate total RE (solar and wind) capacity factor of 66.7%. The systems performance at Hafar Albatin and Sharurah shows reasonable power production and lower CO_2 emissions even though the systems have high NPC and LCOE. However, the solar PV and wind turbine capacity factors at Riyadh city are low compared to other systems. Therefore, it is not economically viable in this location.

Among all cities, Yanbu city grid-connected system has the highest amount of energy sold to the grid and it is 1118 MWh/yr followed by Hafar Albatin, Sharurah, and Riyadh with 863.5 MWh/yr, 824.6 MWh/yr, and 504.7 MWh/yr, respectively. After the comparison between the capital cost and the cost of the energy produced by PV/Wind system in each location, Yanbu city has the total annual electricity produced by PV/Wind systems which is 4684.53 MWh/yr and the cost of this annual amount based on the grid prices exceeds 6.8 million dollars over the project's lifetime. Because of that, this city showed the lowest payback period and the highest annual fuel saving with a payback period of 13 years. The calculation of positive cash flow years or the systems payback period is carried out considering the KSA's current electricity tariff and the proposed sellback prices.

All sensitivity analysis scenarios performed in this research showed that there are several factors that impact the performance of RE sources and integration to the power systems. Potential of RE resources, power output, and increasing in load demand and electricity prices are the main factors which have significant impact on system's power production, NPC and LCOE. The results in this part showed that, as the electric load and power prices increase, the system's NPC and energy cost rise due to the insufficient renewable energy production, that can meet the new load demands. These increases will make the system's energy less economic and will increase the dependency on the conventional power plants. The sensitivity analysis for grid prices and electric load changes showed that, the changes in grid power prices have less impact on the system's NPC and COE than the changes in load demand.

Furthermore, the impacts of the grid prices and electric load changes on the NPC and COE were analyzed, when the electricity sellback rate ($/kWh) increasing linked with the power purchasing rate. The result showed that, the increasing of energy cost and NPC will be slightly less when the sellback rates increase are linked with the utility grid prices, specifically when there are no significant changes in the load demands. In terms of Purchasing and sellback electricity to the grid, load requirements, RE size, and the potential of solar and wind resources have significant impact on that. The results showed that when RE resources are very low or there are not enough RE resources, the contribution of renewable energy power is zero since it is not economically recommended. Therefore, purchased energy from grid will be increased to maintain system's reliability and to meet the required power demand.

During the project lifetime, changes in power prices is possible due to the oil price variations and that have also an economic impact on the system. These changes showed that the cost caused by the increase in power prices rate can be decreased by adding more RE sources. The sensitivity analysis results also showed the importance of solar and wind resources, and lacking enough RE resources would increase the fossil fuels consumption which obviously affected the cost of energy. This section showed the importance of doing sensitivity analysis and enhancing system flexibility for such a system in order to avoid any additional expenses or negative impacts during the project's lifetime.

Chapter 5 presented the power system operation and the importance of system flexibility to facilitate the integration of renewable energy to utility grid. Also, the grid code requirements for solar and wind technologies have been presented. This part showed that electric demand must be satisfied with the power from generation at all time periods during the day to manage systems variability and uncertainty and increase electric system reliability.

Furthermore, flexibility in power system (capability to adapt to dynamic and changing conditions) is very important in order to avoid system instability and implementing new large conventional power plants or building other big investments. Several impacts to integrate VRE into electric power systems (utility grid), specifically high levels of VRE have been presented in this chapter along with the possible solutions. Beside the power system operation and the importance of system flexibility, renewable energy grid codes are the guidelines followed by users and they enable network operators, generation system, suppliers and consumers to function more effectively. Grid connection codes requirements of VRE generators, specifically for wind and solar PV have been discussed to enhance renewable energy and sustainability in KSA. Based on the developed countries grid codes, different codes can be added to the current KSA's grid code in order to form the infrastructure for RE systems and bring knowledge to the power system operators from other experienced countries.

Regarding the active power control, renewable generating unit (Solar energy) either CSP plant or Utility-Scale PV plant should be able to control the output power (ramp rate control and power curtailment) in order to avoid possible network congestion. Also, in the event of a frequency deviation, wind farms or wind turbines should have active power curtailment capabilities and outline specific active power generation set-points as a function of available power. Additionally, large wind power plants must have the ability to modify their active power output for at least 10s in response to grid frequency deviations greater than 0.5 Hz. In terms of automatic frequency response, any RE generating unit should be capable of reducing its power generation when the grid frequency exceeds a pre-set value. In case underfrequency limits is reached, RE generating units should stay connected for a specific time before tripping. For the Reactive power control, RE power plants are required to control the reactive power production to contribute towards the stability of grid voltage, especially during grid faults, to assist fast grid-voltage recovery. Regarding the Fault ride through capabilities, when the network fault occurred, with consequent voltage drop, the grid-connected RE system has to remain connected to the grid for a certain time specified by the grid code. Furthermore, it must feed-in the same active power as soon as the fault is cleared. Concerning the system communication and notification, RE power plants ,particularly wind farms or wind turbines should be equipped with control system which ensures the remote and independent control of each wind turbine included according to the depicted requirements of grid code. Also, the predictions should be updated for certain time periods continuously to ensure the reliable market operation of power system.

The analyses presented in this study can have a strong influence on the selection of technology and location of solar and wind energy power plants in KSA. Additionally, the proposed system design and techno-economic analysis could be applied to any location worldwide to improve the performance of grid-connected hybrid solar/wind considering the variation of the components' costs, load profile, and the sites' metrological conditions. We should note that using long-term data analysis would help to understand the inter-annual variability of renewable energy resources that limit this study. Therefore, continuing the operations of renewable energy monitoring stations is needed to gather data for long-term forecasting.

6.2 Future Work

This thesis is inspired by the climate and environmental issues, development of renewable energy and enhance sustainability, and renewable energy sources targets set by many countries .Its main objective is to enhance transition toward RE, specifically the deployment of grid-connected hybrid systems. This thesis narrates how this objective was attained. However, some issues still need to be tackled which can be considered as future work. The current scope of research can be expanded to include country cases that have similar challenges, for example, oil-based developing economies. Also, more renewable sources such as biomass, geothermal, and hydropower can be added and integrated to support utility grids based on country's conditions. Moreover, with large amounts of renewable energy penetration, the economic impact of renewable power curtailment and/or demand shedding compared to energy storage can be studied. This will help decision makers to select the suitable ways to store the excess power produced by renewable energy sources and compare the feasibility of the stored energy to the control of electricity production and power curtailment. Also, regarding REFIT, further analysis could be carried out to observe its impact on the economic performance of the hybrid grid-connected systems as it can play a significant role in renewable energy sources economic viability.

REFERENCES

[1] S. Müller, A. Marmion and M. Beerepoot , " Renewable energy markets and prospects by region,". 2011. Available online: http://www.iea.org/publications/freepublications/publication/Renew_Regions.pdf (accessed on 20 March 2018).

[2] K. Presley, Jr. Wesseh and B. Lin, "Can African countries efficiently build their

economies on renewable energy ?," *Renew. Sustain. Energy Rev*, vol. 54, pp. 161–173, 2016.

[3] G. Schwerho and M. Sy, "Financing renewable energy in Africa – Key challenge of the sustainable development goals ," *Renew. Sustain. Energy Rev*,vol. 75, pp. 393–401, 2017.

[4] K. Alkhathlan and M. Javid, "Carbon emissions and oil consumption in Saudi Arabia," *Renew. Sustain. Energy Rev*, vol. 48, pp. 105–111, 2015.

[5] M. Aljebrin, "Revisiting electricity consumption function : the case of Saudi Arabia," *Bus. Econ. J*, vol. 5, pp. 1–7, 2014.

[6] Y. Z. Alharthi, M. K. Siddiki, and G. M. Chaudhry, "The new vision and the contribution of solar power in the Kingdom of Saudi Arabia electricity production," *Proc. 9th Annual IEEE Green Technologies Conference (GreenTech)*, pp. 83–88, 2017

[7] B. Fattouh, "Summer Again: The swing in oil demand in Saudi Arabia," Available online:https://www.oxfordenergy.org/publications/summer-again-the-swing-in-oil-demand-in-saudi-arabia/ (accessed on 10 October 2018).

[8] W. Matar, F. Murphy, A.Pierru, B. Rioux "Lowering Saudi Arabia's fuel consumption and energy system costs without increasing end consumer prices," *Energy Econ*, vol. 49, pp. 558–569,2015

[9] A. H. Almasoud and H. M. Gandayh, "Future of solar energy in Saudi Arabia," *J. King Saud Univ. - Eng. Sci*, vol. 27, pp. 153–157, 2015.

[10] BP Statistical Review of World Energy 2016. Available online:

http://oilproduction.net/files/especial-BP/bp-statistical-review-of-world-energy-2016-full-report.pdf (accessed on 15 March 2018).

[11] M. A. M. Ramli, A. Hiendro, and Y. A. Al-turki, "Techno-economic energy analysis of wind / solar hybrid system : Case study for western coastal area of Saudi Arabia," *Renew. Energy*, vol. 91, pp. 374–385, 2016.

[12] A. Al-Sharafi, A. Z. Sahin, T. Ayar, and B. S. Yilbas, "Techno-economic analysis and optimization of solar and wind energy systems for power generation and hydrogen production in Saudi Arabia," *Renew. Sustain. Energy Rev*, vol. 69, pp. 33–49, 2017.

[13] H. Al Garni, A. Kassem, A. Awasthi, D. Komljenovic, and K. Al-haddad, "A multicriteria decision making approach for evaluating renewable power generation sources in Saudi Arabia," *Sustain. Energy Technol,* vol. 16, pp. 137–150, 2016.

[14] S. Munawwar and H. Ghedira, "2013 ISES solar world congress a review of renewable energy and solar industry growth in the GCC region," *Energy Procedia*, vol. 57, pp. 3191–3202, 2014.

[15] A. M. Eltamaly, "Pairing between sites and wind turbines for Saudi Arabia sites," *Arab. J. Sci. Eng*, vol. 39, pp. 6225–6233, 2014.

[16] J. Bates and N.Hill "The role of physics in renewable energy RD & D," Available online: https://www.iop.org/publications/iop/archive/file_52050.pdf (accessed on 20 March 2019).

[17] Y. Z. Alharthi, M. K. Siddiki, G. M. Chaudhry, S. Muaddi, and A. Alahmed, "Performance of solar resource monitoring stations in hot climate regions," *Proc. IEEE 44th Photovolt. Spec. Conf.*, pp. 1110–1115, 2017.

[18] Y. Z. Alharthi, A. Alahmed, M. Ibliha, G. M. Chaudhry, and M. K. Siddiki, "Design , simulation and financial analysis of a fixed array commercial pv system in the city of Abu Dhabi-UAE," *Proc. IEEE 43th Photovolt. Spec. Conf* ,pp. 3292–3295, 2016.

[19] Y. Z. Alharthi, M. K. Siddiki, and G. M. Chaudhry, "Economic analysis and environmental impacts of a hybrid PV system in arid climate considering different types of solar trackers," *Smart Grid Renew. Energy*, vol. 09, pp. 199–214, 2018.

[20] Y. Z. Alharthi, M. K. Siddiki, and G. M. Chaudhry, "Techno-Economic analysis of hybrid PV / Wind system connected to utility grid," *Proc. 2019 IEEE Texas Power Energy Conf.*, pp. 1–6, 2019.

[21] Y. Z. Alharthi, M. K. Siddiki, and G. M. Chaudhry, "Resource assessment and techno-economic analysis of a grid-connected solar PV-Wind hybrid system for different locations in Saudi Arabia," *Sustainability*, *10*, 3690, 2018

[22] NASA "Glubal cliamte change." Available online: https://climate.nasa.gov/causes/. (accessed on 20 July 2018).

[23] Intergovernmental Panel on Climate Change IPCC, "Climate Change 2014 Synthesis Report." Available online: https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wc

over.pdf (accessed on 30 July 2018).

[24] International Energy Agency (IEA) "CO_2 Emissions from fuel combustion 2017," *IEA*, Book, ISBN: 978-92-64-27819-6, 2017.

[25] KSA General Authority of Statistics "Total population in KSA," . Available Online: https://www.stats.gov.sa/en. (accessed on 10 Oct 2018).

[26] Organization of petroleum exporting countries (OPEC) "Saudi Arabia facts and figures ." Available online: https://www.opec.org/opec_web/en/about_us/169.htm. (accessed on 18 May 2018).

[27] The Electricity & Cogeneration Regulatory Authority "Data And Statistics." [Online]. Available: https://ecra.gov.sa/en-us/dataandstatistics/pages/DataAndStatistics.aspx (accessed on 12 Nov 2018).

[28] I. Ozturk and A. Acaravci, "CO_2 emissions , energy consumption and economic growth in Turkey," *Renew. Sustain. Energy Rev*, vol. 14, pp. 3220–3225, 2010.

[29] KACAR, "Renewable resource atlas." Available online: https://rratlas.kacare.gov.sa/RRMMPublicPortal/?q=en/Solar. (accessed on 15 Dec 2018).

[30] S. Alyahya and M. A. Irfan, "Role of Saudi universities in achieving the solar potential 2030 target," *Energy Policy*, vol. 91, pp. 325–328, 2016.

[31] A. Al-Ghabban, "Saudi Arabia's renewable energy strategy and solar energy deployment roadmap," King Abdullah City for Atomic and Renewable Energy

(K.A.CARE), 2013.

[32] International Renewable Energy Agency ,"Renewable energy target setting," Available online: https://www.irena.org/publications/2015/Jun/Renewable-Energy-Target-Setting (accessed on 15 Jan 2019).

[33] B. Hashem, "Geothermal development roadmap for the kingdom of saudi arabia," Available online: http://digitallib.oit.edu/digital/collection/geoheat/id/11484/ (accessed on 15 Jun 2018).

[34] M. S. M. Khan and Z. Kaneesamkandi "Biodegradable waste to biogas : Renewable energy option for the Kingdom of Saudi Arabia," *International Journal of Innovation and Applied Studies,* vol. 4,pp. 101–113, 2013.

[35] E. Zell, S. Gasim, S. Wilcox , S. Katamoura, T. Stoffel , H. Shibli, J. Engel, M. Al Subie , "Assessment of solar radiation resources in Saudi Arabia," *Sol. Energy*, vol. 119, pp. 422–438, 2015.

[36] A. Hepbasli and Z. Alsuhaibani, "A key review on present status and future directions of solar energy studies and applications in Saudi Arabia," *Renew. Sustain. Energy Rev*, vol. 15, pp. 5021–5050, 2011.

[37] M. A. M. Ramli, A. Hiendro, K. Sedraoui, and S. Twaha, "Optimal sizing of grid-connected photovoltaic energy system in Saudi Arabia," *Renew. Energy*, vol. 75, pp. 489–495, 2015.

[38] M. A. M. Ramli, S. Twaha, K. Ishaque, and Y. A. Al-Turki, "A review on maximum power point tracking for photovoltaic systems with and without

shading conditions," *Renew. Sustain. Energy Rev.*, vol. 67, pp. 144–159, 2017.

[39] A. F. Almarshoud, "Performance of solar resources in Saudi Arabia," *Renew. Sustain. Energy Rev*, vol. 66, pp. 694–701, 2016

[40] M. A. M. Ramli, E. Prasetyono, R. W. Wicaksana, N. A. Windarko, K. Sedraoui, and Y. A. Al-Turki, "On the investigation of photovoltaic output power reduction due to dust accumulation and weather conditions," *Renew. Energy*, vol. 99, pp. 836–844, 2016.

[41] S. Rehman and A. Ahmad, "Assessment of wind energy potential for coastal locations of the Kingdom of Saudi Arabia," *Energy*, vol. 29, pp. 1105–1115, 2004.

[42] S. Rehman, T. O. Halawani, and M. Mohandes, "Wind power cost assessment at twenty locations in the Kingdom of Saudi Arabia," *Renew. Energy*, vol. 28, pp. 573–583, 2003.

[43] N. M. Al-Abbadi, "Wind energy resource assessment for five locations in Saudi Arabia," *Renew. Energy*, vol. 30, pp. 1489–1499, 2005.

[44] A. M. Eltamaly and H. M. Farh, "Wind energy assessment for five locations in Saudi Arabia," *J. Renew. Sustain. Energy*, vol. 4, 022702, 2012.

[45] M. A. Baseer, J. P. Meyer, M. M. Alam, and S. Rehman, "Wind speed and power characteristics for Jubail industrial city, Saudi Arabia," *Renew. Sustain. Energy Rev*, vol. 52, pp. 1193–1204, 2015.

[46] M. A. Baseer, J. P. Meyer, S. Rehman, and M. M. Alam, "Wind power characteristics of seven data collection sites in Jubail, Saudi Arabia using

Weibull parameters," *Renew. Energy*, vol. 102, pp. 35–49, 2017.

[47] S. M. Shaahid, L. M. Al-Hadhrami, and M. K. Rahman, "Economic feasibility of development of wind power plants in coastal locations of Saudi Arabia - A review," *Renew. Sustain. Energy Rev*, vol. 19, pp. 589–597, 2013.

[48] D. Solyali, M. Altunç, S. Tolun, and Z. Aslan, "Wind resource assessment of Northern Cyprus," *Renew. Sustain. Energy Rev*, vol. 55, pp. 180–187, 2016.

[49] F. Fazelpour, E. Markarian, and N. Soltani, "Wind energy potential and economic assessment of four locations in Sistan and Balouchestan province in Iran," *Renew. Energy*, vol. 109, pp. 646–667, 2017.

[50] A. Dabbaghiyan, F. Fazelpour, M. D. Abnavi, and M. A. Rosen, "Evaluation of wind energy potential in province of Bushehr, Iran," *Renew. Sustain. Energy Rev*, vol. 55, pp. 455–466, 2016.

[51] A. Allouhi *et al.*, "Evaluation of wind energy potential in Morocco ' s coastal regions," *Renew. Sustain. Energy Rev*, vol. 72, no. November 2016, pp. 311–324, 2017.

[52] British Columbia sustainable energy association, "Renewable energy technologies" Available online: https://www.bcsea.org/learn/get-the-facts/renewable-energy-technologies. (accessed on 16 Nov 2018).

[53] REN21, Renewable global status report. Available online: https://www.ren21.net/reports/global-status-report/ (accessed on 16 Feb 2019).

[54] D. Solyalı, "An investigation into integration of renewable energy source for

electricity generation a case study of Cyprus," Ph.D. dissertation, The University of Bath, 2013.

[55] D. Y. C. Leung and Y. Yang, "Wind energy development and its environmental impact : A review," *Renew. Sustain. Energy Rev*, vol. 16, pp. 1031–1039, 2012.

[56] Y. Amirat, M. Benbouzid, B. Bensaker, R. Wamkeue, and H. Mangel, "The state of the art of generators for wind energy conversion systems", *Proceedings of ICEM'06*, September 2006.

[57] C. Sourkounis and P. Tourou, "Grid code requirements for wind power integration in Europe," *Conf. Pap. Energy*, vol. 2013, pp. 1–9, 2013.

[58] B. Wu, Y. Lang, N. Zargari, and S. Kouro, "Power conversion and control of wind energy systems," *Wiley IEEE press*, Book, ISBN: 978-1-118-02898-8, 2011.

[59] P. B. Deb *et al.*, "Application of solar energy conversion in a street lighting system," *International Journal of Scientific & Engineering Research*, vol. 7, no. 4, pp. 57–61, 2016.

[60] S. Sundaram, D. Benson, and T.K. Mallick "Production solar photovoltaic technology production," *ELSEVIER,* Book, ISBN 978-0-12-802953-4, 2016.

[61] M. A. Green, Y. Hishikawa, E. D. Dunlop, D. H. Levi, J. H. Ebinger, M. Yoshita, A. W.Y. Ho-Baillie, "Solar cell efficiency tables (Version 53)," *Prog Photovolt Res Appl*,vol. 27, pp. 3–12, 2019.

[62] S. C. Bhatia, "Advanced renewable energy systems," *ELSEVIER,* Book, ISBN 978-1-78242-269-3, 2014.

[63] A. Asrari, A. Ghasemi, and M. H. Javidi, “Economic evaluation of hybrid renewable energy systems for rural electrification in Iran - A case study,” *Renew. Sustain. Energy Rev*, vol. 16, pp. 3123–3130, 2012.

[64] S. Alyahya and M. A. Irfan, “Analysis from the new solar radiation Atlas for Saudi Arabia,” *Sol. Energy*, vol. 130, pp. 116–127, 2015.

[65] H. Saleh, A. Abou El-Azm Aly, and S. Abdel-Hady, “Assessment of different methods used to estimate Weibull distribution parameters for wind speed in Zafarana wind farm, Suez Gulf, Egypt,” *Energy*, vol. 44, pp. 710–719, 2012.

[66] H. Saleh, A. Abou El-Azm Aly, and S. Abdel-Hady, “Assessment of different methods used to estimate Weibull distribution parameters for wind speed in Zafarana wind farm, Suez Gulf, Egypt,” *Energy*, vol. 44, pp. 710–719, 2012.

[67] P. K. Chaurasiya, S. Ahmed, and V. Warudkar, “Comparative analysis of Weibull parameters for wind data measured from met-mast and remote sensing techniques,” *Renew. Energy*, vol. 115, pp. 1153–1165, 2018.

[68] P. K. Chaurasiya, S. Ahmed, and V. Warudkar, “Study of different parameters estimation methods of Weibull distribution to determine wind power density using ground based Doppler SODAR instrument,” *Alexandria Eng. J*, vol. 57,pp. 2299-2311, 2017.

[69] M. S. Ismail, M. Moghavvemi, T. M. I. Mahlia, K. M. Muttaqi, and S. Moghavvemi, “Effective utilization of excess energy in standalone hybrid renewable energy systems for improving comfort ability and reducing cost of energy: A review and analysis,” *Renew. Sustain. Energy Rev*, vol. 42, pp. 726–734, 2015.

[70] M. A. M. Ramli and S. Twaha, “Analysis of renewable energy feed-in tariffs in selected regions of the globe: Lessons for Saudi Arabia,” *Renew. Sustain. Energy Rev*, vol. 45, pp. 649–661, 2015.

[71] H. Z. Al Garni, A. Awasthi, and M. A. M. Ramli, “Optimal design and analysis of grid-connected photovoltaic under different tracking systems using HOMER,” *Energy Convers. Manag.*, vol. 155, pp. 42–57, 2018.

[72] WinWinDWWD-1 D60 1MW Turbine-Models. Available online: https://en.wind-turbine-models.com/turbines/486-winwind-wwd-1-d60 (accessed on 20 May 2018).

[73] A. Jamalaiah, C. P. Raju, and R. Srinivasarao, “Optimization and operation of a renewable energy based pv-fc-micro grid using homer,” *Proc. Int. Conf. Inven. Commun. Comput. Technol. ICICCT,* pp. 450–455, 2017.

[74] R. H. Cherrelle Eid, E Koliou, M Valles, J Reneses, “ Time-based pricing and electricity demand response_ Existing barriers and next steps,” *Util. Policy*, vol. 40, pp. 15–25, 2016.

[75] A. Coester, M. W. Hofkes, E. Papyrakis, “An optimal mix of conventional power systems in the presence of renewable energy_ A new design for the German electricity market.” *Energy Pllicy*, vol. 116,pp. 312-322, 2018.

[76] National Renewable Energy Laboratory (NREL), “ The importance of flexible electricity supply,” DOE/GO-102011-3201, 2011

[77] B. Kroposki, “Integrating high levels of variable renewable energy into electric power systems,” *J. Mod. Power Syst. Clean Energy*, vol. 5, pp. 831–837, 2017.

[78] E. Ela, M. Milligan, and B. Kirby, "Operating reserves and variable generation," *Technical Report NREL*/TP-5500-51978 , 2011 Availabe online: https://www.nrel.gov/docs/fy11osti/51978.pdf (accessed on 16 Mar 2019).

[79] J. Aho, A. Buckspan, J. Laks, P. Fleming, Y. Jeong, F. Dunne, M. Churchfield, L. Pao, K. Johnson., "A tutorial of wind turbine control for supporting grid frequency through active power control," *Proc. 2012 American Control Conf*, pp. 3120–3131, 2012.

[80] V. Gevorgian and B. O. Neill, "Demonstration of active power controls by utility-scale pv power plant in an island grid preprint," *Conference Paper NREL*/CP-5D00-67255, 2017.

[81] M. Morjaria, V. Chadliev, N. Milam, and C. Milan, "Demonstration of essential reliability services by a 300-MW solar photovoltaic power plant," T*echnical Report NREL*/TP-5D00-67799, 2017 Availabe online: https://www.nrel.gov/docs/fy17osti/67799.pdf (accessed on 12 May 2019).

[82] A. Nelson *et al.*, "Hawaiian electric advanced inverter grid support function laboratory validation and analysis," T*echnical Report NREL*/TP-5D00-67485, 2016. Availabe online: https://www.nrel.gov/docs/fy17osti/67485.pdf (accessed on 30 May 2019).

[83] S. M. Nosratabadi, R. Hooshmand, and E. Gholipour, "A comprehensive review on microgrid and virtual power plant concepts employed for distributed energy resources scheduling in power systems," *Renew. Sustain. Energy Rev*, vol. 67, pp. 341–363, 2017.

[84] IRENA, "Power System Flexibility for the Energy Transition, Part 1: Overview for policy makers," Abu Dhabi, ISBN 978-92-9260-089-1, 2018

[85] NREL "Flexibility in 21 st century power systems." NREL/TP-6A20-61721, 2014 Avilable online: https://www.nrel.gov/docs/fy14osti/61721.pdf (accessed on 30 Jun 2019).

[86] NREL,"Sources of operational flexibility," NREL/FS-6A20-63039, 2015. Available online: https://www.nrel.gov/docs/fy15osti/63039.pdf (accessed on 15 Jun 2019).

[87] P. R. Jayasree, A. Krishnan, A. S. Menon, M. Paul, and R. Rajin, "Renewable energy integration," *Int. J. Appl. Eng. Res*, vol. 10, pp. 332–337, 2015.

[88] T. Ackermann, N. Martensen, T. Brown, P.-P. Schierhorn, F. G. Boshell, and M. Ayuso, "Scaling up variable renewable power: The role of grid codes," *IRENA report,* ISBN 978-92-95111-85-1,2016.

[89] REN21,"Renewables global status report," *Report*, ISBN 978-3-9818911-3-3, 2018.

[90] A. Q. Al-Shetwi and M. Z. Sujod, "Grid-connected photovoltaic power plants: A review of the recent integration requirements in modern grid codes," *Int. J. Energy Res*, vol. 42, pp. 1849–1865, 2018.

[91] A. Cabrera-tobar, E. Bullich-massagué, M. Aragüés-peñalba, and O. Gomis-bellmunt, "Review of advanced grid requirements for the integration of large scale photovoltaic power plants in the transmission system," *Renew. Sustain. Energy Rev*, vol. 62, pp. 971–987, 2016.

[92] The Electricity & Cogeneration Regulatory Authority (ECRA), "The Saudi Arabian grid code," Available online: https://ecra.gov.sa/en-us/Pages/default.aspx (accessed on 15 Dec 2018).

[93] M. Castilla, J. Miret, A. Camacho, J. Matas, and L. G. De Vicuña, "Voltage support control strategies for static synchronous compensators under unbalanced voltage sags," vol. 61, pp. 808–820, 2014.

[94] W. Xiao, "Photovoltaic Power system: modeling, design, and control*,"* *Wiley,* Book , ISBN 9781119280361, 2017

[95] S. S. Murthy, "12 - Renewable energy generators and control," in *Electric Renewable Energy Systems*, pp. 237–289, 2016

[96] O. A. Dabar, M. O. Awaleh, D. Kirk-Davidoff, J. Olauson, L. Söder, and S. I. Awaleh, "Wind resource assessment and economic analysis for electricity generation in three locations of the Republic of Djibouti," *Energy*, vol. 185, pp. 884–894, 2019.

[97] J. S. González and R. Lacal-Arántegui, "A review of regulatory framework for wind energy in European Union countries: Current state and expected developments," *Renewable and Sustainable Energy Reviews*, vol. 56, pp. 588–602, 2016.

[98] A. Daniela, A. Hansen, "Electrical grid evaluation of power control with different electrical and control concept of wind farm Part 2 – Large systems," *DTU Library,* Avilable online: https://orbit.dtu.dk/files/5246113/UpWind%20part%202.pdf (accessed on

15 Apr 2019).

[99] N. IoannisKougias , SándorSzabó, AlexandrosNikitas, "Sustainable energy modelling of non-interconnected Mediterranean islands ," *Reneabl Energy,* vol. 133, pp. 930–940, 2019.

[100] E. V. Mc Garrigle, J. P. Deane, and P. G. Leahy, "How much wind energy will be curtailed on the 2020 Irish power system?," *Renewable Energy*, vol. 55. pp. 544–553, 2013.

[101] X. Liu, Z. Xu, and K. P. Wong, "Recent advancement on technical requirements for grid integration of wind power," *J. Mod. Power Syst. Clean Energy,* vol. 1, pp. 216–222, 2013.

[102] V. Gevorgian, M. Singh, and E. Muljadi, "Symmetrical and unsymmetrical fault currents of a wind power plant," *IEEE Power and Energy Society General Meeting*, pp. 1-8, 2012.

[103] R. Li, H. Geng, and G. Yang, "Fault ride-through of renewable energy conversion systems during voltage recovery," *J. Mod. Power Syst. Clean Energy*, vol. 4, pp. 28–39, 2016.

[104] S. A. Q. M. Amer Saeeda, Hafiz Mehroz Khana, Arslan Ashrafb, "Analyzing effectiveness of LVRT techniques for DFIG wind turbine system and implementation of hybrid combination with control schemes," *Renew. Sustain. Energy Rev*, vol. 81, pp. 2487–2501, 2018.

[105] A. R. Ann, P. Kaliannan, and U. Subramaniam, "Improved fault ride through capability of DFIG based wind turbines using synchronous reference frame

control based dynamic voltage restorer," *ISA Trans*, vol. 70, pp. 465–474, 2017.

[106] M. E. Hossain, "Low voltage ride-through capability improvement methods for DFIG based wind farm," *J. Electr. Syst. Inf. Technol*, vol. 5, pp. 550–561, 2018.

[107] F. R. Yu, P. Choudhury, and B. C. Hydro, "Communication systems for grid integration of renewable energy resources," *IEEE Network* , vol. 25, pp. 22–29, 2011.

[108] T. M. Letcher, "Wind energy engineering a handbook for onshore and offshore wind turbines," *ELSEVIER*, Handbook, ISBN: 978-0-12-809451-8, 2017.

VITA

Yahya Z. ALharthi was born on July 1986 in Saudi Arabia. He received his Bachelor of Engineering degree in Electrical Engineering- in the field of Power System and Electrical Machines in 2011 from Riyadh College of Technology, Saudi Arabia. He got his Master of Science degree in electrical engineering in 2015 from the University of Missouri-Kansas City (UMKC), USA.

Yahya pursued a PhD degree at the University of Missouri-Kansas City, USA. During his studies at UMKC, he received several awards from his school, Saudi Arabian Cultural Mission (SACM) and Embassy of Saudi Arabia in USA. From 2007 to 2013, he worked in Saudi Electricity Company (SEC) as an Electrical Technician and Electrical Engineer. He authored and co-authored more than 10 conference and journal papers during his PhD study. Also, he is a student member in the Institute of Electrical and Electronics Engineers (IEEE). He served as a reviewer for MDPI Applied Sciences and Energies journal, IET Renewable Power Generation journals, and Texas Power and Energy Conference (TPEC).

His research interests include design, performance and economic analysis of grid-connected renewable energy systems, renewable energy resources and technologies, and power system planning. Upon completion of his PhD degree requirements, he plans to continue his career in higher education institution and to pursue his research interests.

Journal Publication

1. Y. Z. Alharthi, M. K. Siddiki, and G. M. Chaudhry, "Resource assessment and techno-economic analysis of a grid-connected solar PV-Wind hybrid system for different locations in Saudi Arabia," *Sustainability*, *10*, 3690, 2018
2. Y. Z. Alharthi, M. K. Siddiki, and G. M. Chaudhry, "Economic analysis and environmental impacts of a hybrid PV system in arid climate considering different types of solar trackers," *Smart Grid Renew. Energy*, vol. 09, pp. 199–214, 2018.
3. Y. Z. Alharthi, M. K. Siddiki, and G. M. Chaudhry, "Techno-economic and sensitivity analysis of solar PV-wind hybrid system connected to utility grid," (***Under review***)

Peer reviewed Conference Proceedings

1. Y. Z. Alharthi, A. Alahmed, M. Ibliha, G. M. Chaudhry, and M. K. Siddiki, "Design , simulation and financial analysis of a fixed array commercial pv system in the city of Abu Dhabi-UAE," Proc. IEEE 43th Photovolt. Spec. Conf ,pp. 3292–3295, 2016.
2. Y. Z. Alharthi, M. K. Siddiki, and G. M. Chaudhry, "The new vision and the contribution of solar power in the Kingdom of Saudi Arabia electricity production," *Proc. 9th Annual IEEE Green Technologies Conference (GreenTech),* pp. 83–88, 2017
3. Y. Z. Alharthi, M. K. Siddiki, G. M. Chaudhry, S. Muaddi, and A. Alahmed, "Performance of solar resource monitoring stations in hot climate regions," *Proc. IEEE 44th Photovolt. Spec. Conf.*, pp. 1110–1115, 2017.

4. Y. Z. Alharthi, M. K. Siddiki, and G. M. Chaudhry, "Techno-Economic analysis of hybrid PV / Wind system connected to utility grid," *Proc. 2019 IEEE Texas Power Energy Conf.*, pp. 1–6, 2019.
5. Y. Z. Alharthi, M. K. Siddiki and G. M. Chaudhry , " Renewable Energy Hybrid Grid-Connected System Sensitivity Analysis, Integration, and System Flexibility," *The 2019 IEEE International Symposium on Technology and Society (ISTAS).* ***(Proceedings)***
6. Y. Z. Alharthi, M. K. Siddiki and G. M. Chaudhry , "Importance of Sensitivity Analysis for Hybrid Grid-Connected System," *2019 IEEE 46th Photovoltaic Specialists Conference (PVSC)*, ***(Accepted)***