Solar Power Integration in the Kingdom of Saudi Arabia

Naif Faiz Albagami

School of Engineering
University of Edinburgh

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Abstract

Power systems around the globe are undergoing a transition from their traditional form to a modern version, able to host new and different types of generation. This is driven by policies related to renewables and climate change. The electricity system in the Kingdom of Saudi Arabia (KSA) has not been thoroughly discussed in the literature, which makes it difficult to understand the nature of the transition in the biggest network in the Middle East. The focus of this thesis is on providing a better understanding of the challenges in the KSA in deploying renewable generation.

In order to deploy renewables in the KSA system, it is important to have a full understanding of the following: (1) the electricity system in the KSA; (2) the resources available; and since this thesis focuses on solar resources, it is further important to analyse (3) the integration of renewables. This thesis presents the historical development of the KSA electricity system in relation to such aspects as geography, social context and climate, while examining grid and load. Data is gathered from related entities in the Kingdom to construct a validated test network for the KSA. This allows for the creation of a credible realistic network with time series demand and generation data, all of which is described by this thesis.

This work assesses the available resources, specifically those of solar energy, by considering two different technologies: photovoltaic (PV) and concentrating solar power (CSP). This helps to propose various suitable locations for solar power plants following an in-depth examination using a high-resolution ground-measurement dataset. Time series data of solar power is then employed through multi-objective optimisation to identify candidate solar generation systems considering technical and financial trade-offs. A range of scenarios of these different technologies are used to assess solar power plants' integration into the KSA electricity system using an economic dispatch model. This approach illustrates the value of renewables integration in terms of potential fuel and operational cost savings.

Declaration of originality

I hereby declare that the research presented in this thesis unless otherwise stated or referenced are my own work and it was composed in the Institute for Energy Systems, School of Engineering at The University of Edinburgh.

Naif F. Albagami

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Abbreviations

AC	Alternating Current
ANM	Active Network Management
BOE	Barrels of Oil Equivalent
BP	British Petroleum
BSRN	Baseline Surface Radiation Network
CCGT	Combined Cycle Gas Turbine
CF	Capacity Factor
CHP	Combined Heat and Power
COA	Central Operating Area
COP	Conference of Parties
COV	Coefficient of Variation
DC	Direct Voltage
DER	Distributed Energy Resources
DG	Distributed Generation
DHI	Diffuse Horizontal Irradiance
DNI	Direct normal irradiance
DR	Demand Response
DSM	Demand-Side Management
DSR	Demand-Side Response
ECRA	the Electricity and Co-Generation Authority
ECMWF	European Centre for Medium-range Weather Forecasts
ED	Economic Dispatch
EOA	Eastern operating Area
GA	Genetic Algorithm
GCC	Gulf Cooperation Council
GHG	Greenhouse Gases
GHI	Global Horizontal Irradiance
GCCIA	Gulf Cooperation Council Interconnection Authority
GOES	Geostationary Operational Environmental Satellites
GWh	Giga Watt hour
KSA	Kingdom of Saudi Arabia
HTF	Heat Transfer Fluids
HVAC	Heating, Ventilating and Air-Conditioning
HVDC	High Voltage Direct Current
IEA	International Energy Institute
IRENA	International Renewable Energy Agency
IPPs	Independent Power Producers
IWPPs	Independent Water and Power Producers
K.A.CARE	King Abdullah City for Atomic and Renewable Energy
KASCT	King Abdulaziz City for Science and Technology
KAUST	King Abdullah University for Science and Technology
KFUPM	King Fahad University of Petroleum and Minerals
kW	Kilowatt
kWh	Kilowatt-hour
LEAP	Long Range Energy Alternatives Planning

MAAC	Monitoring Atmospheric Composition and Climate
MEIMR	Ministry of Energy, Industry and Mineral Resources
MENA	Middle East and North Africa
MEPA	Saudi Meteorological and Environmental protection Agency
MERRA	Modern-Era Retrospective Analysis for Research and Application
MIP	Mixed Integer Programming
MWh	Mega Watt hour
NAERC	North American Electric Reliability Corporation
NEEP	National Energy Efficiency Program
NREL	National Renewable Energy Laboratory
NETC	National Electricity Transmission Company
OCGT	Open Cycle Gas Turbine
OPF	Optimal Power Flow
RES	Renewable Energy Sources
RRMM	Renewable Resource Monitoring and Mapping
SAM	System Advisor Modelling
SAMA	Saudi Arabian Monetary Authority
SBC	Saudi Building Code
SCECOs	Saudi Consolidated Electricity Companies
SEC	Saudi Electricity Company
SEEC	Saudi Energy Efficiency Centre
SEGS	Solar Electricity Generating System
SMP	System Marginal Price
SOA	Southern Operating Area
SR	Saudi Riyal
SSI	Solar Surface Irradiance
ST	Steam Turbine
SUNY	State University of New York
SWCC	Saline Water Conversion Corporation
TES	Thermal Energy Storage
TOU	Time-of-Use
UC	Unit Commitment
UNFCCC	United Nations Framework Convention on Climate Change
WCRP	World Climate Research Program
WMO	World Meteorological Organisation
WOA	Western Operating Area

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Chapter 1 **Introduction**

1.1 Background

Energy is required to power the world around us. It is hard to imagine buildings, schools and facilities without lighting. Transportation systems, social systems and many aspects of life today are dependent on energy in order for the world as we know it to function properly. However, high economic and population growth is driving significant demand for electricity. Many countries around the world rely on fossil fuel energy and, apart from the environmental issues entailed in this, it is also not a sustainable path in the long-term. In recent years, the international community has decided to tackle this by implementing new policies toward a sustainable and low emissions power system.

The Kingdom of Saudi Arabia (KSA) has been blessed with an abundance of energy resources and the electricity in the country is generated from fossil fuel resources in the form of domestically produced oil and gas. The KSA has become a leading user of desalination and this drives its growing demand for electricity. If not addressed, these factors will lead the country to be a net oil importer by 2038, as some observers suggest [1]. In this regard, the KSA is rich in solar resources that could play a pivotal role in the short-term in providing a share of energy. This is a very promising technology that is spreading in many countries around the world, such as the USA, Germany, UK and China.

Solar power has not so far been utilised in the Kingdom because of the availability of heavily-subsidised hydrocarbon resources. However, many advantages can be gained from developing solar power in the country. Firstly, solar power is sustainable and available all year round in the KSA, which has limited clouds and rain. Secondly, the operational cost of the current technologies used in the power system is much higher than solar technologies and solar power can significantly lower carbon emissions. In order to employ solar technologies, solar resources should be assessed to understand the quantity and evaluate solar intensity for deployment. It is important to then study different solar technologies to find out about if solar power plants are suitable for investing in and finally to integrate them into the system.

The electricity system in the Kingdom has been run vertically, with tariffs set by the government and relying on subsidies from the government. The usage of electricity in the KSA is among the highest per capita in the world. There is a need to study the electricity system in the KSA to evaluate power generation and consumption and better understand the current and future infrastructure needs.

While there are notable analyses of solar power integration in a range of western systems (e.g. [2], [3]), there is as yet no systematic study for the KSA.

1.2 Thesis Objectives and Scope

The overall aim of this thesis is to identify the role that solar power could play in KSA. The objectives of this work are as follows:

- To provide an overall picture of the Saudi electricity system to gain an understanding of energy challenges in the country and the drivers of electricity consumption.
- Explore the nature of demand and assess the load components, regional and seasonal effects over the years using real data and also forecasts for the future.
- Assess solar resources across the KSA and generate reliable time series data to be used when evaluating solar power plants and their operation.
- Identify solar technologies with high potential value using technical and financial indices to compare these different systems. The aim is to provide an assessment of the effects of different solar technologies,

such as photovoltaic (PV), concentrated solar power (CSP) and hybrid systems and their future potential in the Saudi power sector.

- Investigate the impact of integrating solar power technologies on system cost and quantify the effects on oil use in the KSA.

1.3 Thesis Statement and Contribution to Knowledge

It is becoming a necessity for a country like KSA to efficiently utilise its abundant resources to secure its future electricity supply. This research will focus on the opportunities associated with integrating renewable generation in the Saudi context and thereby test the question: “Can solar power contribute substantially to the Saudi electricity system?”

The specific contribution of the thesis can be described as follows:

- It provides a concise description of the nature of the electrical load and grid infrastructure in KSA.
- No existing studies provide a test network or a system for the KSA; this work provides a representative system model for those who are interested in the Saudi electricity sector.
- The use of ground-based measurements with high resolution and quality allows the resource assessments in this work to provide a better understanding of the nature of solar power in the KSA.
- The data from these solar resources are used to evaluate different solar technologies using technical and financial indicators. The evaluation of solar Photovoltaic (PV), concentrating solar power (CSP) and hybrid combinations clearly identifies these technologies are well suited to the KSA.
- The overall work makes a contribution to the literature through its use of a whole system approach employing a combination of solar resource, technology and power systems modelling.

- Entities in the Kingdom such as the Saudi Electricity Company (SEC) and independent power producers (IPP) will find the analysis of the effects of solar power on generation patterns and oil and gas consumption of value.
- The approach and the wider system effects will be broadly applicable to other nations in the region especially countries with rich fossil-fuel resources.

1.4 Thesis Outline

Chapter 1 provides a background to the research and a summary of the objectives. It also presents the statement and knowledge contribution of this thesis.

Chapter 2 provides an introduction to energy in the KSA and a background to the Saudi context in relation to geography, climate and the social system. It then outlines some details about energy challenges in the KSA, the electricity sector in the Kingdom, renewables and solar technologies.

Chapter 3 provides a detailed investigation of power generation and demand in the KSA. It also engages in an analysis of power consumption key drivers and outlines a future energy demand forecast.

Chapter 4 presents an analysis of solar energy resources in the KSA to be used with different solar power technologies. Solar resources are investigated using different measurements including ground-based and satellite-based measurements. This takes into consideration the spatial and temporal variations.

Chapter 5 considers data from Chapter 4 analysis to be placed into an optimisation model to investigate and compare different solar power technologies. This shows different technical and financial indicators of each solar power technology and presents the most suitable technology for the KSA.

Chapter 6 presents the integration of different solar technologies using an economic dispatch model. It provides the economic dispatch for these technologies over a full year, showing seasonal variation and impacts on system costs.

Chapter 7 provides the thesis summary to conclude this work and then make suggestions for future work.

Chapter 2 **Background**

2.1 Introduction

Renewable energy is becoming an important global topic. Countries around the world are investing in clean technologies, highlighting that this will be a trend of the future. For example, in 2010 Germany spent 1.5% of its GDP on renewables and the world overall invested about 275 billion US dollars in renewables [4]. The Kingdom of Saudi Arabia (KSA) has abundant renewable resources, in particular solar energy, that could minimise the carbon dioxide output and add to the electricity generation mix. This chapter provides a review of KSA and its electricity system, as well as considering aspects that impact electricity, such as geography, climate and the social system. Renewable energy sources (RES) and the definition of distributed generation (DG) will be introduced, alongside some renewable generation types. A general review will be provided of key solar concepts and solar technologies; this study focuses on two types of solar technology: photovoltaic (PV) and concentrating solar power plants (CSP). The chapter concludes with some reviews of economic dispatch modelling and several studies that have been undertaken in the field.

2.2 The Kingdom of Saudi Arabia

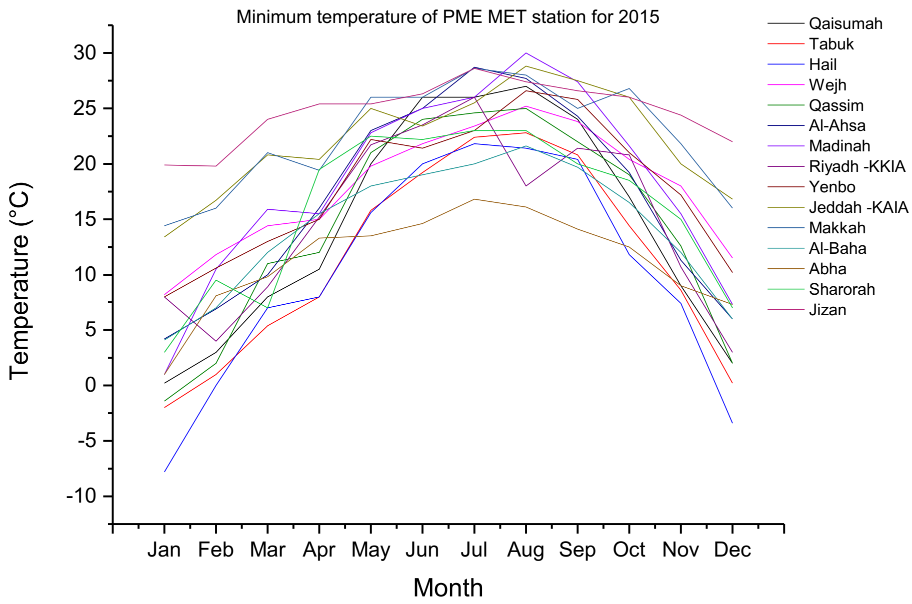
2.2.1 Geography

The KSA is located in the Middle East at the far southwest of Asia between latitudes 16°N and 33°N, and longitudes 34° and 56°E and occupies about 80% of the Arabian Peninsula. The country covers a vast empty land area and the whole country is nearly about 2,000,000 km^2 [5]. The terrain is mostly sand and soil desert, except the southern part of the country, which is mainly mountainous. Long coastal areas of about 1100 km^2 run along the Red Sea in the west of the country and about 610 km^2 along the Arabian Gulf in the east of the country. The country is the site of both Makkah and Madinah, the two holy places for Muslims, which attract more than two million people from all over the world just for the event of the Hajj. Saudi Arabia encompasses 13 administrative regions, each of which is governed by a member associated with the Ministry of Interior. The empty quarter is known as Rub Al-Khali and it is an uninhabited region at the south eastern part of the country that covers about 640,000 km^2 [6]. Figure 2.1 shows the map of the kingdom, highlighting the electrical grid and the different colours to show what has been commissioned (green), under construction (red) and planned (dark blue).

Figure 2.1 Map of the Kingdom of Saudi Arabia [7]

2.2.2 Climate

The climate in the KSA is different from one area to another due to the different topography of the country. The climate is arid, hot and dry during the summer in general, particularly in the middle region where the capital city Riyadh is located. The minimum temperature is above 30°C in the daytime and this is often accompanied by dust and sandstorms. In the winter, the temperature rarely goes below 2°C during the day. Rain is rare and mostly happens in the winter season from November to April. The east and north of the country are almost the same except that it gets colder in the north in the winter and more humid in the east during the summer. The temperature can reach 50°C during the summer in many places in the country, except the south and south-western parts. It rains a lot in the south-west during the summer, which makes the summer much colder and means this area makes less use of air conditioning in comparison to other regions. A detailed study of the seasonal rainfall and temperature of the Arabian Peninsula can be found in [8]. A number of studies have been undertaken to investigate climate change and its possible effects across the kingdom [9]–[11]. Although, climate change is another area of study, it is worth mentioning these studies since these papers discuss the weather in more detail. In Figure 2.2, different cities in the kingdom were chosen to show the minimum and maximum temperature in different regions of the kingdom over a year period. The data was obtained from the General Authority for Statics in the KSA. The impact of climate and seasons will be investigated further in the following chapter.



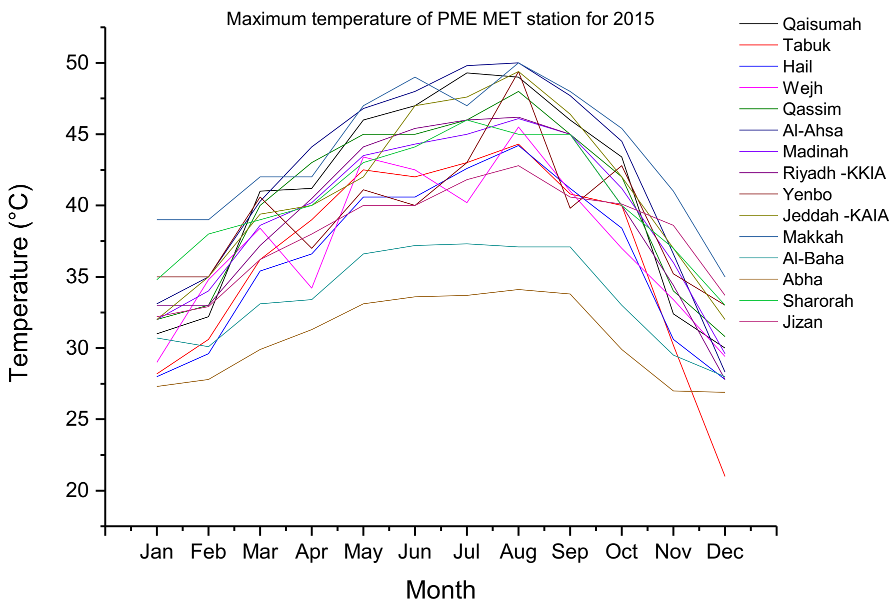


Figure 2.2 Minimum temperature and maximum in different regions of the KSA by month 2015

2.2.3 Social Context

The population of the KSA is approximately 31.7 million of that number, about 20 million are Saudis, with a growth rate of 6.86%, as noted by a survey of 2016 [12]. More than 93% of the population use gas for cooking and only about 5.95% use electricity for the same purpose. Since the KSA is an Islamic country, there are five prayers during the day and people adjust their day based on prayer times. The week begins on Sunday, not Monday as in many other countries around the world. The first prayer starts before sunrise and so always before 6am. Usually, people start their day by going to school or to their jobs when it is not the holidays. Students from primary to high school stay in school until 1:30pm at the latest. Public offices begin from 7:30am and run to 2:30pm with no lunch break. However, private companies and banks begin at 8:00am and run to 4:00pm. Most of the shops open at 9:00am and close around the Duhar prayer at about 12:00pm midday, opening again at 4:00pm and then closing around 12:00am midnight. Many restaurants and gas stations do not close.

The main public holidays are the Eid Al-Fitr and Eid Al-Adha festivals according to the Islamic calendar. Eid Al-Fitr comes after the month of Ramadan when people are not allowed to eat or drink during the day but only after sunset. During this month, most people stay up the whole night and sleep as much as they can during the day. Work hours in Ramadan in public offices and schools are reduced to no more than five hours, but they remain at about seven hours in the private sector. It is a holiday from the 25th day of Ramadan until the 5th day of the Shawwal month, which comes after Ramadan. Two months later, Eid Al-Adha takes place and 2–3 million Muslims from all over the world undertake a (Hajj) pilgrimage to Makkah and then to Madinah. The holiday for Al-Adha lasts for ten days. The school holiday begins around the end of May and lasts until the middle of September. During the vacation, many people switch their activities to the evening time because of the harsh weather.

People in the KSA are very social. Usually, there will be certain places where they gather at the weekends. Extended families come together and generally the generations will tend to gather together during the weekends at the grandparents' house. There are often evening banquets between families once a week or month and numbers can reach more than 20 people since the families are big. With regard to prayers, there are five prayers during the day and usually people practice these at Mosques (Masjid). Mosques are large buildings and the majority are bigger than 500 m^2. During the summer, it requires a lot of air conditioning to keep these spaces relatively cold. People prefer to shop at night time due to the hot weather; therefore, most big shopping malls stay open from morning until midnight. These malls consume a great deal of electricity for lighting and air conditioning.

It is necessary in this project to be aware of the social system of the KSA because understanding the life pattern of people within the country helps to predict the load fluctuations within the electricity system. Social and behavioural science is becoming an important part of research, particularly in demand-side management (DSM) and demand-side response (DSR) or demand response (DR). Many studies (e.g. [13], [14] and [15]) have discussed DSM and DR and their potential for achieving social objectives, smart grids, environmental and economic objectives. David et al. also investigated in [16] the effects of resident behaviour and some other factors on the load profile. In [17], Aldossary et al. studied the typical Saudi household and the patterns of energy consumption considering the harsh weather of the KSA.

2.2.4 Energy Challenges

Energy challenges are becoming a global issue, even for countries with rich resources. The KSA is among the world's most important producers of oil, but there is nonetheless recognition that their own energy supplies must be secured long term. Some observers, such as Chatham House, suggest that the country could be a net oil importer by 2038 since it is using more than one quarter of its total produced oil and this proportion is expected to grow [1]. Most of the electricity in the KSA is generated from fossil fuel resources, particularly domestically-produced oil and gas, as Figure 1 shows, which is affecting the economy of the country and environment and hindering the trend of the globe move towards renewable energy. Further, the need for electricity is growing rapidly in the country, making it challenging for the utility company to meet demand [18].

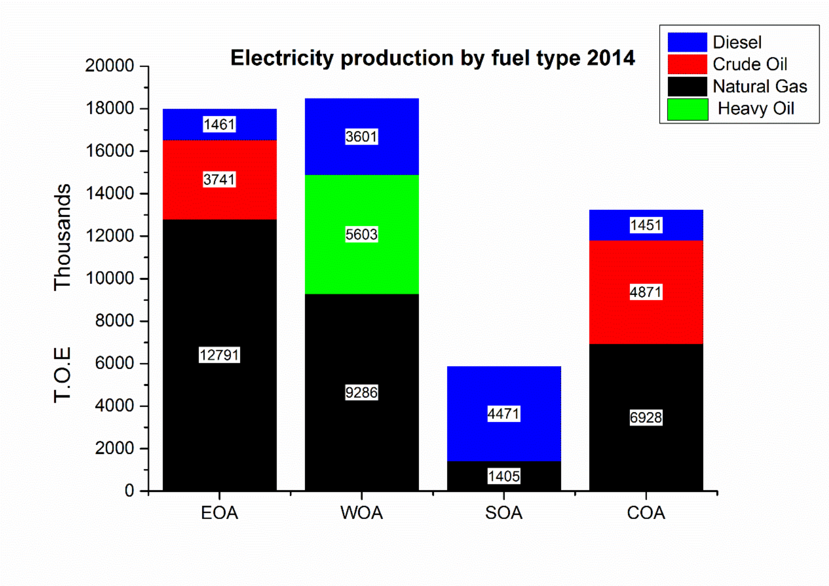


Figure 2.3 Electricity production in all operating areas in the kingdom (east, west, south and central) [19]

Climate change is also becoming a serious issue and most greenhouse gas (GHG) emissions result from energy usage. According to [20], in 2014 the KSA was the 11th largest CO_2 emitter, with 494.82 MTon. The government of Saudi Arabia subsidies electricity generation with more than forty billion dollars annually; however, more subsidies will be needed in the coming years [18]. This will tend to encourage a wasteful culture and, furthermore, the government will not be able to provide subsides in the long term. Added to this, the current alarming rate of GHG emissions should be moderated. In

2015, at the Paris Climate Conference, also known as the Conference of Parties 21 (COP), the KSA was one of more than 100 countries that agreed to contribute to stop the Earth's temperature from rising more than 2°C by the end of the century [21].

These challenges are urging the government to diversify the economy in order to be independent of hydrocarbons and also to diversify the energy mix. RES is considered to be one of the solutions that will mitigate the impact of global warming and at the same time it will enhance the capacity to serve energy demand.

2.2.5 Fossil Fuels

Reserves of the main resources, particularly oil and gas, are distributed across certain places around the world. KSA is one such place that has large reserves and it is indeed one of the top oil producing countries in the world. It has 266 billion barrels of proved oil reserves, about a quarter of the world's proven reserves according to BP [22]. It is ranked the fifth largest country with proven gas reserves. Most of the gas produced in the country is used domestically, mainly for generating electricity. However, the country's budget is heavily reliant on crude oil export earnings. Despite gas usage in electricity generation, oil is nonetheless continuing to be dominant in the power sector. Consuming about 1,59 billion barrels of oil equivalent (BOE) domestically in 2016 undermined the government plan to maximise hard currency from oil exporting [23], as shown in Table 2.1.

Fossil fuels and energy in general is subsidised in the kingdom, which is seen by many observers as a way of redistributing wealth. The price of gasoline, diesel and electricity is among the lowest in the world. According to the International Energy Institute (IEA), the rate of subsidisation is 72%, which reflects a major subsidy, rendering the country the second highest subsidiser in the world [24]. However, Lahn and Stevens argued in more than one report ([1] and [25]) that the policies of energy subsidisation, consumption and prices are risky. Reports have shown that the Ministry of Energy, Industry and Mineral Resources (MEIMR) estimates that about 10% of domestic oil gets smuggled to neighbouring countries. This also suggests that subsidy should be directed to the poor because the wealthy benefit more from the current policies.

Year	Consumption of LGP (Thousand Barrels)	Consumption of Natural Gas (Thousand Barrels)	Consumption of Crude Oil (Thousand Barrels)	Total (BOE)	Exported Crude Oil (Million Barrels)
2000	11,911	281,260	418,533	711,704	2,282.38
2001	12,203	305,080	420,356	737,639	2,203.10
2002	13,090	327,008	432,343	772,441	1,928.89
2003	13,328	339,796	454,668	807,792	2,380.85
2004	12,913	376,140	474,809	863,862	2,486.77
2005	13,235	416,897	493,796	923,928	2,631.24
2006	13,138	422,905	520,272	956,315	2,565.72
2007	14,905	439,960	563,819	1,018,684	2,541.16
2008	15,570	477,665	617,468	1,110,703	2,672.42
2009	15,847	466,242	669,156	1,151,245	2,287.66
2010	13,428	521,784	723,717	1,258,929	2,425.09
2011	18,292	550,702	752,417	1,321,411	2,634.59
2012	16,356	597,972	794,262	1,408,590	2,783.78
2013	15,259	597,235	811,302	1,423,796	2,763.32
2014	15,188	614,627	886,989	1,516,804	2,611.01
2015	16,127	627,676	942,695	1,586,498	2,614.51
2016	17,977	663,459	908,864	1,590,300	2,794.59

Table 2-1 Domestic consumption of fossil fuel and exported crude in the KSA [23]

2.3 Electricity Sector in the Kingdom of Saudi Arabia

2.3.1 Historical Development

The first introduction of electricity was in fact in 1939, just a few years after the kingdom was united, when a group of businessmen needed it for their business. In 1949, entrepreneurs in the city of Dammam in the eastern province of the KSA introduced the first private electricity company [26].

This company had the opportunity to serve residential in the area and then it began to serve the newly created Arabian American oil company (ARAMCO), known today as Saudi Aramco. Since then, the country has seen different companies and small-scale power plants emerge in different regions of the kingdom. All these companies were established to generate profit and not under the supervision of the government. Every company at that time set their tariffs independently from other regions.

In 1961, the Department of Electricity Affairs was established under the Ministry of Commerce with the purpose of organising and encouraging investment in the electricity market [27]. A new phase was established when King Faisal declared that "electricity should be for everyone". In 1972, following this declaration, the Department of Electricity Services started its task planning electricity for the whole country. Two years later, the tariff of electricity was fixed at a standard price applied to all companies. In 1975, a new ministry came into being called the Ministry of Industry and Electricity, which established the Electricity Affairs Agency. Six years later the government consolidated all the companies in all regions – central, east, west and south – into one company called Saudi Consolidated Electricity Companies (SCECOs) [28].

The council of ministers authorised the plan of privatisation in 1998, which led to another decision to merge all companies into one single state-owned utility called Saudi Electricity Company (SEC) in 2000 [29]. SEC came into operation in April of that year and it is still serving the electricity needs of the country. In 2001, the council of ministers agreed to establish the Electricity and Co-Generation Authority (ECRA) to regulate, supervise, study, ensure high quality and grant licenses in the electricity sector [30]. Today, the SEC is undergoing a plan of separating generation, transmission and distribution to independent companies in order to liberalise the electricity market in the KSA [19].

2.3.2 Organisations

The electricity sector in the KSA is affiliated with several organisations and entities. The electricity sector itself encompasses the following components:

- ECRA: this authority is an independent organisation chaired by the Minister of MEMIR and a deputy chair, who act as governors and are appointed by a Royal Order. The board has other senior members that represent other ministries. The main objectives of ECRA are to provide licences for service providers, monitor performance and tariff, regulate the market, implement laws and policies, make sure the prices are fair and reliable and to ensure sufficient production.
- MEIMR: the main task of MEIMR is to provide laws, policies and new programs and plans that advance the electricity industry and guarantee the best international practices.
- Electricity Industry: water desalination is a part of the electricity industry since most desalinated seawater comes from the Saline Water Conversion Corporation (SWCC), which uses co-generation to produce electricity and send it to the grid. Thus, this includes ECRA licenses for SWCC, SEC, independent power producers (IPPs), independent water and power producers (IWPPS) and any other entity practicing electricity generation, trading or distributing. For example, the industrial areas in Jubail and Yanbu cities get electricity and water through Power and Water Utility Company for Jubail and Yanbu known by MARAFIQ utility.
- King Abdulaziz City for Science and Technology (KACST): an independent organisation established in 1977 for technology transfer and research purposes. KACST has carried out a large number of projects with local and international universities and agencies. It has established several institutions to study energy, solar power and air conditioning in the KSA, alongside other initiatives.
- Saudi ARAMCO: a state-owned company that has the privilege to discover, drill and produce oil and gas in the KSA. Therefore, this

company plays a major role in SEC in terms of providing the fossil fuels needed, as well as furnishing its own electricity needs.

- King Abdullah City for Atomic and Renewable Energy (K.A.CARE): the responsible body of atomic and renewable energy activities in the KSA. It was established in 2010 by a Royal Decree to transfer and localise new technologies in the field. In 2012, K.A.CARE embarked on a very ambitious plan to provide one third renewable energy by 2032 [31]. However, it seems that K.A.CARE has made some changes to this plan. The role of the city has been limited up to this point and it is expected to cooperate with Saudi ARAMCO in upcoming projects.

2.3.3 Energy Efficiency

Electricity usage per capita in the KSA was almost three times higher than the world average at 9,444 kWh/person in 2014 [32]. This might reflect the wealth, development and modernisation of the country, as well as inefficient use of electricity. The Saudi Building Code (SBC 601) was established in 2000 by a Royal Decree to conserve energy in buildings [33] and, indeed, government buildings have been required to implement thermal insulation since 1995 [34]. The residential sector, however, represents 52% of electricity consumption in the KSA due to the high demand for air conditioning and the housing market boom, and there is some speculation that the SBC strategies are not being effectively implemented [35]. There are various other reasons for higher consumption as well, such as industrialisation, population growth, network losses, etc. The consumption of electric energy in 2014 is around 256 TWh per year [19].

There used to be no firm standards or efficiency targets in the consumer sector, which led to an inefficient and wasteful environment. Furthermore, there have always been challenges and barriers in this area, whether technical, cultural or institutional. The Ministry of Petroleum and Mineral Resources, which later became MEIMR, launched its first program in 2003: the National

Energy Efficiency Program (NEEP) [36]. The program was the product of a partnership between the United Nations Development Program and KACST; it broke ground in concepts related to efficiency and conservation and introduced polices aiming to tackle the lack of mechanisms and awareness. Some of the key objectives were the energy efficiency concept, labelling appliances, energy audits, construction standards, and energy management and training. NEEP has worked with several private and public entities and succeeded in promoting its measures and codes. NEEP was originally introduced as a temporary initiative for three years, but it was in place in its first manifestation until 2010 [37].

In 2010, the Council of Ministers decided to broaden the experience and transfer NEEP to a permanent program known as the Saudi Energy Efficiency Centre (SEEC) [36]. Since KACST had by this point begun the Institute of Energy Research, it was decided that SEEC would work under KACST supervision. It was then launched in 2012 to focus in the main sectors that consume the most electricity: buildings, industry and land transportation. The program has also considered promoting concepts such as DSM to be a part of their focus. According to SEEC, these sectors consume about 90% of the total energy used. The main task of this program [38] is to "Preserve the national wealth of energy resources, which consequently strengthens development and national economy, and achieves the lowest levels of possible consumption levels in comparison to the general national product and populations." Energy efficiency initiatives and schemes play a pivotal role in the country's economics. Applying measures, codes and best international practices will free up much of the oil burned for electricity generation. Since SEEC was implemented, a number of initiatives have followed and remarkable targets have been achieved, as revealed in [39]. The program is working under KACST since it is already involved in NEEP and energy research through the Institute of Energy Research. MEIMR and several governmental agencies are also involved in the administration of this centre.

2.3.4 Desalination

Water resources in the KSA are very limited since the country is located in one of most arid deserts in the world. Most of the drinking water in the KSA comes from seawater desalination and yet still there is a high demand and the whole country is not covered. The KSA is the largest producer of desalinated seawater in the world with more than 6 million m^3/day in 2014 [19]. Desalination is currently hydrocarbon dependent and consumes much of the oil and gas produced; however, the KSA uses multi-stage flash plants to produce electricity while desalinating and exporting to the grid through co-generation. SWCC is the state-owned authority in charge of desalinating water in the KSA and the National Water Company is responsible for distribution. There are a total of 26 plants in the county and SWCC has more than 16 of these, other plants are owned by private licensed companies and most of them co-generate electricity. SWCC has about a 60% share of the desalinated water produced and about 6% share of the electricity generated in the KSA. The water tariff is subsidised by the government and the end consumer pays about 10–15% of the actual cost; this might be a reason for the demand growth for water in households.

2.3.5 Power System

Traditionally, the power system was designed as centralised large units located away from residential areas and close to sources such as fuel and water in order to generate electricity and deliver through the power network. It was run as a vertically integrated public power company, aiming at higher reliability for consumers; however, the trend has recently changed to promote competition in the wholesale market between generators.

The power sector in the KSA has been undergoing reform for a long time, as mentioned above in the historical development section. This reform is still going on today with the aim of enhancing standards in the electricity sector and introducing an attractive economic environment for foreign investment.

Since SEC was established in 2000 as a joint stock company, it has become the dominant player and main provider of electricity throughout the whole country. Shares in the company are traded in the Saudi Capital Market and the government owns 74.31%, Saudi ARAMCO owns 6.93% and the rest is owned by other stakeholders [18]. SEC is responsible for generating, transmitting and distributing electricity all over the country. Other power producers such as IPPs and desalination sell their power to SEC by exporting to the grid. There are other producers who supply big consumers such as Power and Water Utility for Jubil and Yanbu industrial cities, known as MARAFIQ.

The kingdom is divided into four regions when it comes to the power network. These are called business operating areas and the operating areas are: central operating area (COA), eastern operating area (EOA), western operating area (WOA) and southern operating area (SOA), as shown in Figure 2.4. These operating areas cover the entire country and most of them interconnect. There are plans to directly connect the COA to WOA, but to date the two operating areas are not yet linked. SEC has the monopoly on the transmission and distribution network; however, the government and ECRA have pushed for privatisation as part of reforming and restructuring the electricity market in the KSA. In 2012, SEC transferred the transmission system to a separate limited liability company called National Electricity Transmission Company (NETC) owned entirely by SEC. Transmission is operated by a single system operator, which is SEC.

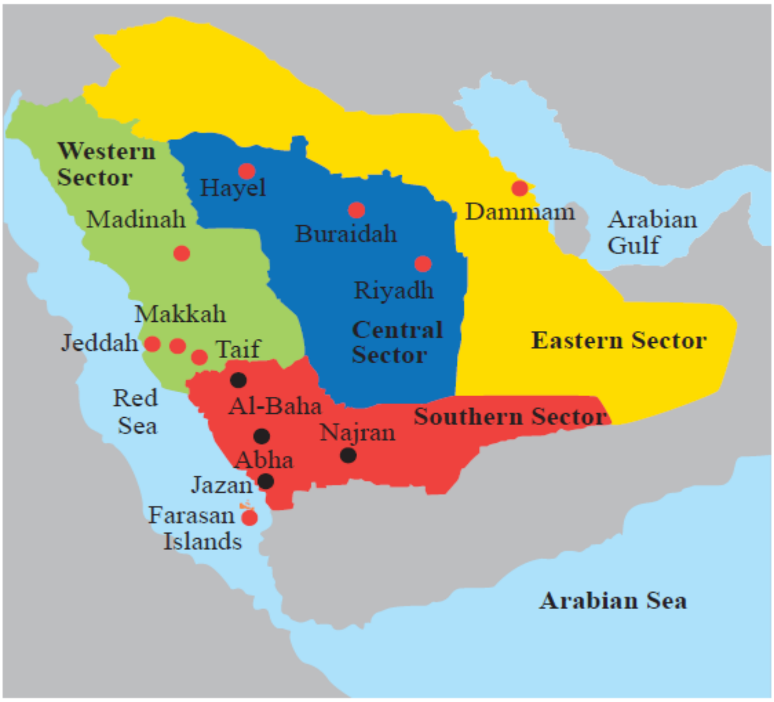


Figure 2.4 Power network division (business operating area) [19]

The plan is to later unbundle all the activities of the SEC. Each activity is intended to be an independent company; this will help it compete with the other companies expected to eventually enter the market. Figure 2.5 shows the way the electricity industry will be laid out after the full restructuring. A Principal Buyer will be created for the purpose of transparency of managing the electricity industry; it is responsible for the industry income since it will deal with all service providers by contract, which ECRA will review and approve. The intention is to create more than three distribution companies that will initially be owned by SEC. There are no arrangements yet for DG developers to connect to the network. However, the ECRA has begun to prepare the required policies and regulations as a step towards developing the electricity market in the KSA. Connecting DG to the network will be challenging, but this will not be discussed here since the main task of this work is to look at the power system as a whole, of which DGs are a part of the energy mix.

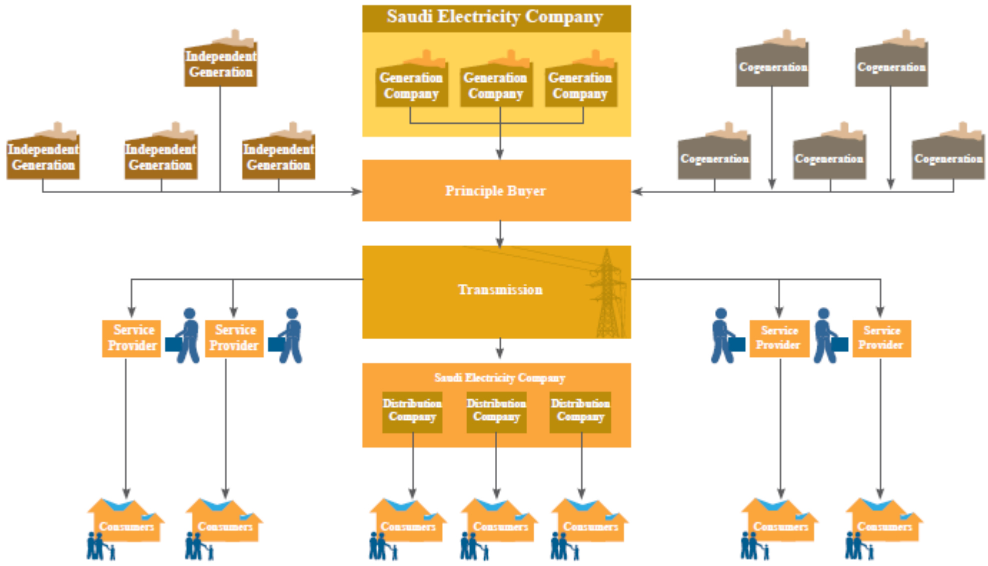


Figure 2.5 Saudi electricity industry after restructuring [18]

The actual generation capacity in SEC was 48,624 MW by the end of 2014. The total available capacity after all producers' contributions came to 65,506 MW. In the same year the total maximum load was 56,547 MW with an electric energy consumption of 245,502 GWh.

The KSA has been working with other Gulf Cooperation Council (GCC) countries to interconnect all six member states to the electrical power network. In 2011 the Gulf Cooperation Council Interconnection Authority (GCCIA), hosted in Riyadh, succeeded in linking all GCC states (KSA, United Arab of Emirates, Bahrain, Qatar, Oman and Kuwait) with a 400 kV supergrid. The 5 other member states have 50 Hz systems interconnected to the 60 Hz Saudi electricity system through alternating current (AC) with back-to-back high voltage direct current (HVDC). Figure 2.6 gives an overview of both the physical power grid and the geographical interconnection. This step will substantially change the model of electricity in the Gulf in the long run; it will help improving security, stability and reliability among the state members. More details and elaborations on the project, its benefit and possible future power market are talked about in [33–

35]. In future, this might lead to export of electricity to Africa through Egypt and later to further destinations including the Mediterranean area.

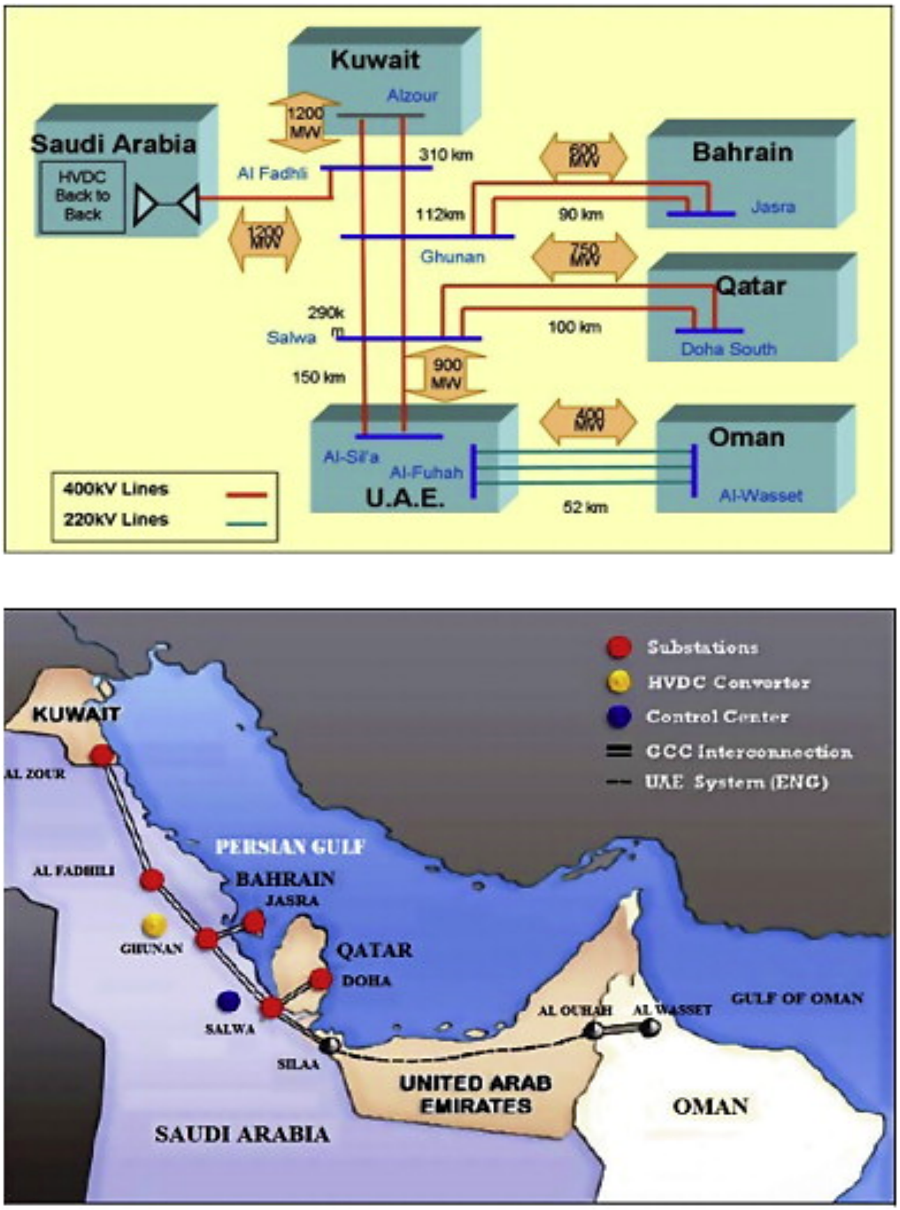


Figure 2.6 The top shows the power grid interconnection; bottom shows the geographical route [43]

2.4 Renewable Energy Resources

The world has been pushing towards clean energy in the electricity sector. There is a need to integrate more low carbon generation into the power system to counter climate change and lower carbon emissions. The most utilised renewable resources are hydroelectricity and wind because the technology for these has reached a more mature status. With regard to the GCC countries, in [44] discussed four economic benefits to investing in renewable technologies deployment: (1) achieve energy security by diversifying the energy mix; (2) increase revenue from exporting fossil fuels instead of consuming domestically; (3) supporting this sector will bring capital investment; and (4) this will result in high value jobs. Today, there is a significant amount of renewable generation integrated into the power system in many countries around the world. However, there are still some challenges posed by integrating these resources. The world leaders decided to take this issue seriously after the Kyoto Protocol initiative [45] and this was recently followed up with the Paris Agreement [46]. These initiatives were introduced by the United Nations Framework Convention on Climate Change (UNFCCC). Therefore, this section is devoted to presenting some details about the concept of DG, solar and wind. Other renewable sources such as hydroelectricity, wave and tidal and geothermal will not be discussed in this thesis since they are of less importance to the KSA at this point in time.

2.4.1 Distributed Generation

It was mentioned above that the power system is planned and operated in a manner whereby electricity is generated in bulk by centralised stations and then delivered instantly and in an unidirectional way through the power network [47]. However, this trend has been undergoing significant change since the beginning of the 21st century and is driven by governmental policy for the security of supply and technological advancement.

A new concept was introduced amid this transformation, which is known as distributed generation (DG). DG involves a new forms of energy with different characteristics for, planning and operation being connected to the network. This was one amongst various concepts introduced to smarten the grid or modernise the power system. These concepts were developed to counter the new challenges posed by the transformation of the power system.

DG is also known by other terms, such as “dispersed generation”, “decentralised generation”, “embedded generation” or “distributed energy resources (DER)” [48]. For the purpose of this thesis, the term DG will be used to refer to electricity generated by a renewable-based resource and connected to the network. In general, there is no specific definition of DG and its understanding varies from one country to another; there have been some definitions proposed by different organisations or researchers around the world. Some researchers define DG based upon its voltage level and whether it is connected to distribution or the transmission network. The IEEE defines it as “the electricity generation [in] which size is sufficiently smaller than central power plants as it could be connected at nearly any point in a power system” [49]. Others look at DG from the perspective of the proximity from the customer load and its size; based on this some would consider combined heat and power (CHP) as a DG. CHP is a conventional source, but it is also considered a low-carbon source when it is small scale [50]. In [51] Ackermann et al. allocate it to different categories based on capacity, where it ranges from micro-grid 5 kW to 300 MW as a large DG. Solar power and wind generally qualify as DG.

A recent proliferation of DG integration and penetration into the network has been taking place all over the world, especially in the developed countries. The European countries have already imposed regulation that a certain amount of electricity should be generated from renewable sources. The KSA is still lagging behind in its use of these sources, but several projects have been undertaken lately to regulate for renewable-based DGs. Renewable DGs are becoming part of the energy mix, thus creating significant changes in the traditional role of the distribution and transmission system. There are also technical and economic challenges posed by this incorporation [52], such as reliability, protection, reverse power flow, losses, voltage rise, power quality and many others. The system is moving from passive towards what is known as an active network. Researchers have conducted many studies, as in [47]–[49], into active network management (ANM), considering how to adjust the system and adopt variable and renewable resources. The term “smart grid” is related to ANM in that ANM is just one aspect of smartening the grid. ANM focuses on controlling network violations, while smart grid can be applied to many applications related to the development of the power system.

2.4.2 Solar

The sun is the source of most forms of renewable and non-renewable energy found in nature. The amount of sunlight striking the Earth is about 175,000 TWh/day, which is vast and theoretically converting even a small percentage of this would cover the entire world's energy demand [56]. Today, technologies that harvest solar energy are mature, well developed and cost competitive. Direct electrical and thermoelectric engines are the two main approaches for converting solar energy. In the first approach, PV panels are used to generate electricity from the movement of electrons when the sun's radiation hits the surface of the photoelectric cells. In the second approach, CSP, collectors focus the sun's direct irradiation on a point to create a high temperature able to raise steam and eventually drive a turbine. These two technologies and their applications will be discussed in detail in the coming sections.

Solar power in the KSA has a very high potential; however, due to the availability of oil and gas, solar resources are not being utilised very well. Even though fossil fuels have been the dominant resource, research programs related to solar power began very early in the kingdom. Saudi Arabia was amongst the first countries to begin investigating solar and its ability to power remote areas. The research progress and deployment of technologies in the KSA has stalled since then, however, because of poor policies and the absence of specialists. The KSA has no figure yet for how much solar energy is produced in the country compared to the United Kingdom (UK), which has less potential for solar power due its climatic conditions. About 7.6 TWh of solar energy in 2015 was produced in the UK [57], while the projects in the KSA were not intended to be part of the energy mix. By the end of 2016, the KSA had still not regulated the use of solar power, which might be a clear reason for not using it as a power source in the country. The UK, on the other hand, has introduced programs such as a feed in tariff (FIT) and renewable heat incentive whereby the government subsidises the installation of solar PV. This action by the government has encouraged many people in the UK to supply their power needs and sell excess production to power utilities.

2.4.3 Wind

Wind energy is one of the fastest growing and most promising renewables. In fact, people have been aware of the potential of wind energy for thousands of years and it has been used for various purposes, such as sailing and to power windmills to grind crops. In the contemporary era, wind has experienced its main development since the 1970s, and the biggest breakthroughs came after the 1980s [56]. Wind energy is usually distributed over certain geographical areas depending on the assessment of resource availability and this is why there are sometimes wind turbines in the middle of the ocean, referred to as offshore wind. Many countries have already tried to utilise wind power, whether onshore or offshore, and add it to the grid to replace conventional generation. This is certainly posing some challenges to system operation, however, and it has become a major focus of research around the world.

The European market has driven a lot of the change in the wind power industry. Countries in Europe, such as Germany, Spain, the UK and Denmark, are examples of countries who targeted defined percentages of wind power. In recent years, China has also added much capacity and is leading investments in this industry along other with countries in Europe and North America. In 2016, more than 90 countries had commercial activities in wind energy, which explains the addition of 55 GW of wind power worldwide, bringing the total capacity to 487 GW [58]. Onshore technology is more cost effective, but sometimes offshore is a more attractive location because wind speed is higher or because this approach doesn’t impact land availability.

In the KSA, several studies have been undertaken to analyse and assess the potential of wind power. These began in the mid-1980s when a joint program between the USA represented by the National Renewable Energy Laboratory

(NREL) and the KSA represented by KACST and the King Fahad University of Petroleum and Minerals (KFUPM); the program was called SOLERAS and was designed to assess solar energy [59]. However, part of the program also involved assessing wind speed, wind power, distribution of frequency and diurnal variation potential with data collected from 20 airport meteorological stations over the period of 1970–1982. In 1986 KACST published a wind atlas and many papers have since investigated data presented in the atlas, as in [53]–[58]. In [66] Alawaji debated the reliability of the data when it showed less than 4 m/s for many sites. Alawaji suggested that: first, the sites selected were near airports, where there is usually less wind, so the criteria for selecting a promising site was missing; and secondly, the sensors to measure wind speed were mounted at heights of 10 m or less. Alawaji studied five promising locations considering site selection, installing the right measuring equipment and trying different heights from 20 m to 30 m and 40 m. Alabbadi also investigated the atlas data and in [64] the assessment of wind energy resources for five new locations was published. The study covered the period of 1995–2002 and the data was recorded hourly, daily and monthly. The study suggested two locations; their annual average speed was found to be 5.4 m/s and 5.7 m/s and they were viable for remote wind energy applications. Another two locations were suggested to be grid connected to reduce the load.

Recently, K.A.CARE decided to install its monitoring system to map for wind resources, intending to develop more accurate and higher quality data. In 2013, K.A.CARE installed five stations in different locations across the KSA [7]. These locations showed a higher speed, whether for coastal areas or central areas as in the Riyadh region. Wind speed in these locations ranged from 5.5-10.5 m/s, presenting significant variability in different parts of the kingdom. Progress is ongoing in this project, aiming to expand the system all over the country. However, the overviews and impressions obtained from the few stations operating emphasise the high potential for wind energy in the KSA.

2.5 Key Solar Concepts

Since this thesis focuses more on solar energy than other renewables, there will be more detail provided on the relevant concepts related to this area. In the following sections, solar components will be explained and an overview will be provided of some terminology. Understanding the solar system and the nature of the Earth-sun relationship will be useful in the process of assessing and dealing with data. There is a large number of resources that explain this matter, or aspects of this matter, in depth; including [60]–[64].

2.5.1 Extra Terrestrial Solar Radiation

In this context, the sun as an important star has been studied and investigated by many researchers and scholars in order to understand its behaviour, characteristics and effects on the energy system as well as the environmental system. The sun is far away from Earth at a distance of about 1.496×10^{11} m, but its radiation reaches the surface of the Earth within 8 minutes and 20 seconds at the speed of light. The sun has a vast energy output, but the Earth receives only a small portion of this. This portion comes in the form of electromagnetic waves that have a certain spectrum wavelength between 0.15–3.0 µm.

The Earth is rotating around its axis and, meanwhile, orbiting the sun. A solar day is 24 hours, which is the time period it takes for the sun to cross a meridian once. This is not to be confused with the sidereal day, which is shorter than a solar day by 4 minutes; this is the rotation of the Earth around its axis with respect to non-moving stars. The Earth orbits in an elliptical orbit and its rotation happens around a tilted axis with an angle of 23.5°, which in turn produces day and night and seasonal changes.

The solar constant $I_{sun,c}$, for total solar irradiance, is defined as the rate of energy received from the sun of (W/m^2) at the average distance from the sun. This radiation received at the top of the atmosphere is called extra-terrestrial radiation and it is difficult to measure this from the Earth because of the atmosphere effects. Total solar irradiance is currently estimated to be 1366.1 W/m^2 as the latest accepted value [70].

2.5.2 Direct, Diffuse and Global Radiation

When radiation passes through the Earth's atmosphere, it undergoes a range of effects due to scatter, reflects and absorption as Figure 2.7 shows. The result in that radiation can be classified in three ways, and they are listed below:

- Direct normal irradiance (DNI): also known as direct beam irradiance, this is the "radiation received from a small solid angle centred on the sun's disk" [71]. DNI is of particular importance to concentrating technologies, whether CSP or concentrating photovoltaic (CPV). More detail about DNI is found in [72], which explains all related aspects.
- Diffuse horizontal irradiance (DHI): the solar radiation that is scattered by the Earth's atmosphere into the sky dome, excluding the DNI.
- Global horizontal irradiance (GHI): the total amount of hemispherical radiation on a surface plane [73]. GHI is of importance to PV and flat plate collectors in general. It is related to the other solar components by:

$$\mathrm{GHI} = \mathrm{DNI}\cos(\theta) + \mathrm{DHI} \tag{2.1}$$

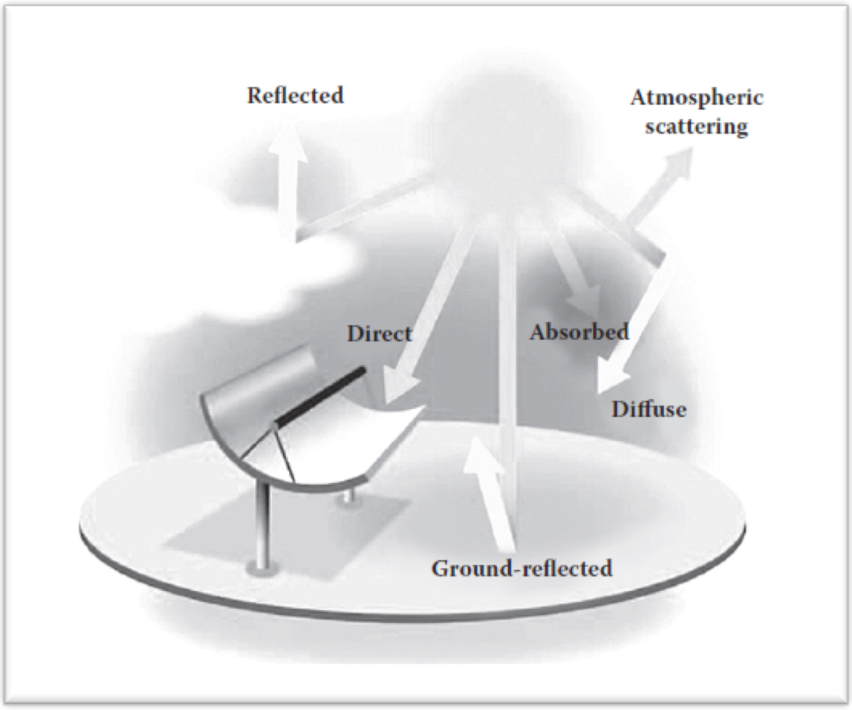


Figure 2.7 The components of solar radiation. Image by Al Hicks, NREL [67]

2.5.3 Measuring Solar Radiation

Designing or analysing solar energy systems need estimates of radiation level. Certain equipment and instruments are already in use for getting the required parameters mentioned in the previous section: DNI, GHI and DHI. A long history of research and development in these technologies is reviewed by Coulson in [74]. These instruments are common for ground solar radiation measurements, while satellite-based data is also widely in use, whether for comparison or for when there are no ground measurements available.

There are two main types of equipment for measuring solar radiation. The first type is a pyrheliometer and this is an instrument that measures the DNI component. It is a long tube that has a detector to collect the direct beam and blocks out other diffused photons with a 5° angle field of view; it is usually mounted on a tracker to keep following the direct beam irradiation during the day. The second type is a pyranometer, also known as a solarimeter, and this is an instrument for measuring the total or the so-called GHI and diffuse beam. It should be noted that GHI is measured with an unshaded pyranometer since the pyranometer alternates between shaded and unshaded mode allowing it to measure diffuse also. Both types are used in the KSA to measure solar radiation and this will be discussed further in Chapter 4. Figure 2.8 shows the basic two instruments commonly used in the process of measuring solar radiation.

Figure 2.8 (Left) First class of pyrheliometer (right) First class of pyranometer [75]

2.6 Solar Photovoltaic (PV)

2.6.1 History

The photoelectric effect was discovered in the 19^{th} century by the French physicist Edmond Becquerel [76]. However, the real development came after using it in the space program in the 1960s. It then gained more usage as an alternative power source in the 1980s following the oil crisis of the 1970s. This was almost 30 years after Bell Laboratories found out about semiconductor material use in solar cells. In the 1990s, individuals were able to use it after being mostly used in communication and space applications. In 2011, it was reported that PV was growing at a 30–40% rate, which reflected the demand for PV applications [76]. In 2016, PV set a worldwide record for the first time, with the greatest added capacity and net of commissioning more than any other power generating technology [58]. Among other renewables, PV accounted for 47% of the installed capacity in 2016. However, despite the boom in the PV industry and market, the efficiency of PV cells is still a major challenge.

PV cells directly convert solar energy into electricity. PV is becoming a cost effective source in certain conditions and it is an attractive option, both for individuals and governments. In 2016, the world total capacity of solar PV was around 303 GW, which reflects the new policies governments' have put in place to encourage installation. This rapid growth is lowering the cost of solar cells. According to [77], world energy demand is expected to increase 30% by 2040 and PV is predicted to play a significant role in covering part of the demand as it is expected to be the cheapest renewable source by that time. Many countries around the world have achieved more than a 5% share of PV in their energy mix. By the end of 2016, countries such as China, Japan, USA, India and several others were installing large scale PV capacities. For example, in one year China added more than 34 GW of solar PV and the European countries had already achieved their 100 GW target in 2016, which reflects the incentive programs and new laws governments have applied [58]. Non-residential large-scale projects have been the main driver of solar PV in countries like the USA and Japan. Although residential distributed PV has helped in these countries, some of this is declining because many governments have been unable or not chose to keep their incentive programs.

In the Middle East and North Africa (MENA) region, the KSA is one of the countries that has a long history with solar energy. The application of solar energy began in the 1960s through universities due to the high potential for solar energy resources and the vast land area of the country where many remote areas cannot be connected to the electrical grid [65]. In 1977, KACST began research and development in the field of solar energy resources and its technologies. The energy research institute in KACST at the time had some international joint programs; include SOLERAS with NREL, and another with Germany was known as HYSOLAR because it aimed for the utilisation of hydrogen and solar. Most of the projects developed through these partnerships were solar PV applications. The Solar Village project is one example that was developed during these joint programs in the 1970s to serve villages that had no grid connection [78]. This operated from 1981–1987 with a capacity of 350 kW and a lead-acid battery storage of 1100 kWh. Recently, 2 MW of solar PV was constructed on the roof of King Abdullah University for Science and Technology (KAUST). 10 MW of PV was also built to cover over 4,000 car parking lots in the Saudi ARAMCO company [79].

PV has meanwhile been playing a pivotal role in electricity generation in many countries and it is posing significant challenges to the grid [80]. These technical challenges have forced some countries to slow down projects that were intended to be connected to the grid [58]. More about these technical challenges will be discussed in Section 2.8. Numerous other issues have hampered progress, such as, for example, legislation and lack of clear policies, incentive schemes, and land availability in some countries. In KSA and Gulf countries, dust is one of the greatest challenges facing all types of solar technologies.

2.6.2 Semiconductor Materials

Solar cells are made of semiconductor materials that have some insulator properties and some metal properties. The most common element on Earth after oxygen is silicon (Si), which is the most commonly used in PV cell manufacturing. The Fraunhofer Institute for Solar Energy Systems in Germany estimated that 94% of total PV production in 2016 was based on silicon wafers [81]. Multi-crystalline Si also has a 70% share with of the total production, while thin film technologies comprise only 6%. The cell usually has several layers with different types of materials; the semiconductor is the most important as this is where the PV effect happens. The electric field is set from joining two different layers of semiconductor, usually negative (n)-type and positive (p)-type. These two different types are obtained by applying some dopants such as phosphorous for n-type or boron for the p-type. More on semiconductors, the physics of electrons and holes, p-n junction and the PV effect, can be found in [74–76].

A cell is a single PV device with a typical size of 150x150 mm that is able to convert sunlight directly into electricity; this device is usually able to produce 2–4 watts. However, this device is always connected to other devices to produce more power and in this form these devices are known as solar panels. A panel will now come with a maximum power of 250–300 W and hold 36–60 cells connected to each other electrically using a series and parallel arrangement. When several modules are connected together they will form arrays where are wired together to produce more power based on the demand to be covered; and this can range from watts to several megawatts. Arrays produce direct current (DC) and this is converted to AC through inverters. The voltage and current of these systems are decided based upon the connection arrangements of these arrays.

2.6.3 Types of Photovoltaic Technologies

PV technologies are divided into different types that generally fall into one of three basic types [83]:

- First generation, where most PV technologies belong, is based on silicon wafers.

- The second generation is thin film, which is less popular but has a lot of potential and is a promising technology.

- There is also a new emerging area of research that could be called the third generation; this is still undergoing much investigation and research but includes, for example, organic PV, nanotechnology and dye-sensitised cells [84]. These types are summarised in Figure 2.9. Below is a brief introduction to each technology, while figure 2.10

presents the best research cell efficiencies according to NREL and other independent organisations.

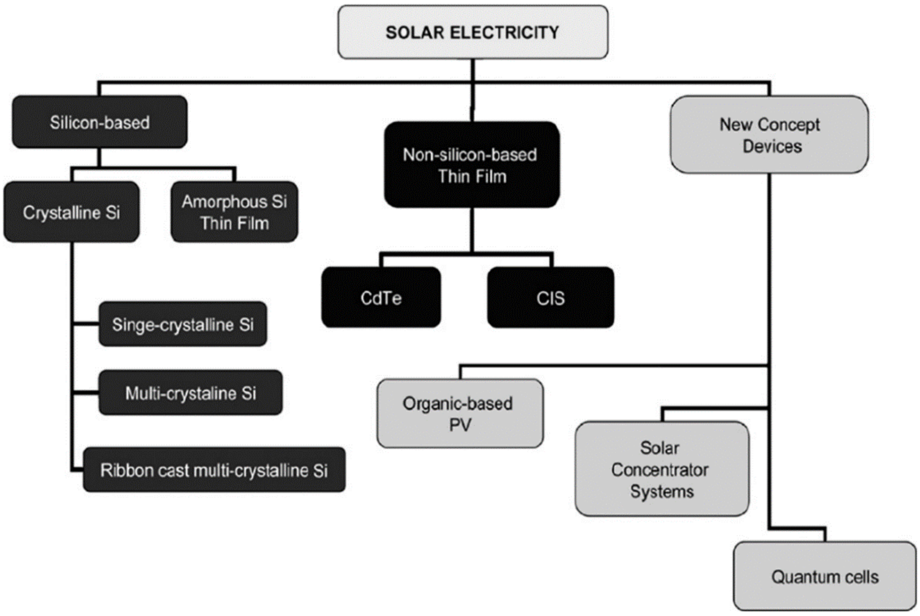


Figure 2.9 Types of PV Technologies [85]

2.6.3.1 Crystalline

Monocrystalline silicon (c-Si) is the highest in efficiency; it is also the most expensive because it has fewer impurities and defects. The process of making this type of cell is called Czochralski; it is slow and requires complex manufacturing that increases the cost. Polycrystalline silicon (pc-Si) was developed as a cheaper material that has many small grains of monocrystalline but is less efficient. Multi-crystalline or polycrystalline involves simpler manufacturing and it can be made using different approaches; one method involves casting molten polycrystalline into ingots and then cutting it into wafers [86].

2.6.3.2 Thin Film

This type is based on materials such as cadmium telluride (CdT), amorphous silicon alloys (a-Si) or copper indium gallium diselenide (CGIS) [87]. It is one of the most promising systems because of its low cost for mass production manufacturing. One advantage of this type of technology is that it absorbs light more efficiently than the crystalline types. It can also be deposited on different types of substrate. However, it has some disadvantages, such as low efficiency and degradation after a period of installation, while the polycrystalline types maintain their efficiency for at least 25 years.

2.6.3.3 Multi-junction

This consists of multiple layers of different semiconductor materials where each material is stacked on top of the other. Each layer will be stacked in a certain way to make it absorb the energy coming from the spectrum of light. This approach increases the conversion efficiency but has a very high cost because of the complexity of the manufacturing process, which makes it a more applicable choice for space applications. Material such as a-Si and III-V semiconductors are used in this type of technology where different band gaps occur in this type of technology. A detailed review about this technology was given by Norttam et al. [88].

2.6.3.4 Concentrated PV

The reason for different types of technologies is the search for more efficient technologies that can convert more energy. Concentrated PV (CPV) uses the same concept as CSP technologies in the following section, where solar radiation is concentrated in cells through mirrors. This gives the advantage that much solar power is harnessed and less area of cells is needed. CPV is expensive since it uses multi-junction PV cells and therefore it has higher efficiency. This technology is still not popular and it has a lower share of the PV market, but when new techniques are there to lower the cost and improve efficiency, it will probably have a bigger share [89].

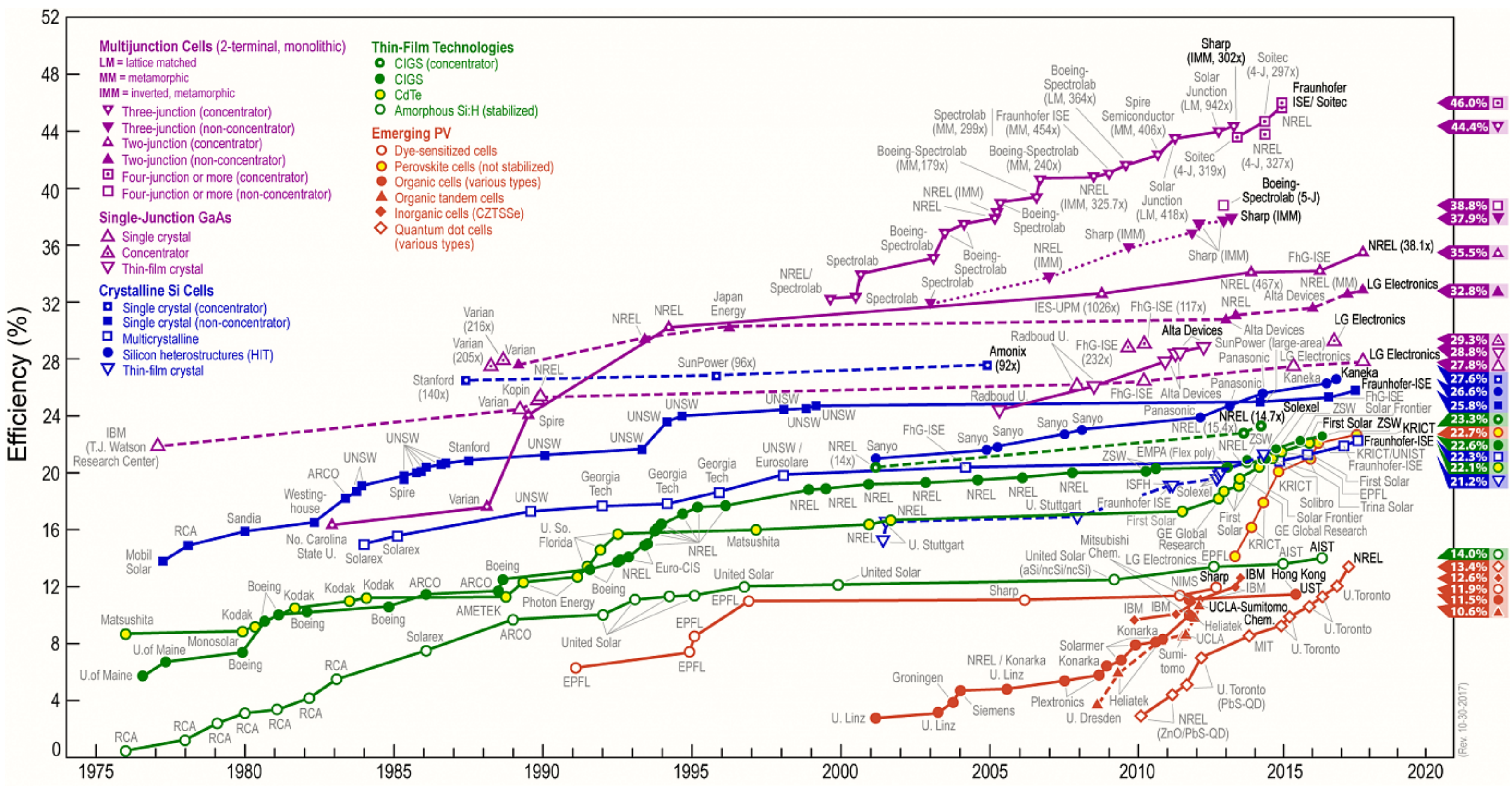


Figure 2.10 Best research: cell efficiencies courtesy of NREL, Golden, CO [90]

2.6.4 Applications

The increasingly wide use of PVs has led to a variety of applications being developed with the intention of utilising electricity from PV systems. According to [91], PV applications can be classified as: grid-connected systems which interact with the grid, hybrid systems and stand-alone systems. Each application can be subcategorised into several other systems.

Grid-connected applications are becoming common in domestic households where electricity generated during the day is either consumed or, when nobody is in the house, the electricity is sold to the electric utility often through a net meter. In the evening time when there is no electricity generated, electricity is bought from the electric provider. In this case, the grid acts as an energy storage where the excess is absorbed instantly by the power grid. In hybrid systems, one or more other types of electricity generator, such as wind or diesel, accompanies the solar generator. In this case, the other generator will either increase the output or provide power in the absence of the other generator. Another application is a stand-alone system, which, as the name suggests, is an independent system that is away from the grid or in a remote area where the power directly supplies the load. This system is commonly used to power off-grid or to provide loads that cannot be supplied through the electric grid. Usually, the excess power is stored in batteries, from which power can be consumed at night or, when necessary, during the day.

In the case of stand-alone systems, the system will usually consist of more equipment, which will be briefly outlined here. In addition to the PV modules, battery banks are used most of the time to store the excess electricity after the demand is covered. Batteries are usually accompanied by charge controller devices to prevent overcharging batteries. Therefore, the main task of this is to regulate power from the modules to the bank of batteries. Since the batteries generate DC, an inverter is needed to convert DC into AC and to convert it at the highest efficiency.

Due to the increase of PV applications use, it has become potentially valuable to have a reliable technology to store energy. The energy storage, and in this case batteries for PV, will mitigate the effects of PV's sudden absence, for example, when weather circumstances block the sunlight. Batteries in such cases could play a pivotal role in covering demand, especially in recent years the grid is penetrated with large scale quantity of variable sources. However, most energy storage is not commercially feasible and much research and development is required to develop these technologies.

Energy storage is commonly grouped into three different categories [92]: electrical, mechanical and electrochemical systems. Electrical energy storage is still under development where energy can be stored in supercapacitors or superconducting magnets. Mechanical storage includes types such as pumped hydro, flywheel and compressed air energy storage. The most commonly used storage type in PV systems is rechargeable electrochemical storage. This includes, for example, lead acid, nickel-iron, lithium, and nickel cadmium. Lithium ion now is becoming the standard. Lead acid is the most developed and commonly used technology with the PV system; it has the highest market share, although much research is ongoing with a view to improving it [93].

It is mentioned above that these applications can be split or subcategorised into many other applications. Desalination plants powered by PV is one such application that is becoming a viable option in many water-scarce places. This has been studied as an option for desalinating drinking water for small communities in remote areas, as in [94]. Such applications could be implemented in many places in the KSA since potable water is scarce, the cost of PV is declining and there is abundant sunlight. In [95], Ali et al. provide a detailed review of the economic and technical feasibility of PV desalination systems. Other applications, such as building integrated PV systems, solar home systems and space application, are discussed in this paper: [85].

2.7 Concentrating Solar Power (CSP)

2.7.1 History

CSPs are thermal power systems that have been known about for a long time. Since the 18th century people have used this in different applications, for example, solar concentrators built by the French chemist Bouffon, or a printing press that was powered by steam and exhibited in Paris by Mouchot [56]. A few decades ago the technology found its way back and several large-scale applications began operating. The 1980s in California was the site of the first industrial for CSPs [96]. The technology saw a decline in the 1990s, but it picked up momentum again at the beginning of the 21st century with new economic and technical scenarios. Thus, in comparison with wind or PV, CSP has little installed capacity. PV commercialisation began a decade or so earlier, while CSP commercialisation and development began again around 2005. CSP is still more expensive than PV to generate electricity, but adding storage to CSP could provide more value. In the literature, all solar thermal applications in general are classified as CSP, which covers many types, as will be discussed.

CSP technology exploits direct sunlight and uses mirrors to focus it or concentrate it, as the name suggests, to harness heat, which raises steam to drive a turbine and generate electricity. This is a two-step process where first sunlight energy gets collected and secondly heat gets mechanically converted into electricity by heat engines. The capacity of CSP can vary between two megawatts to hundreds of megawatts and the higher it is, the better [56]. This could be one of the reasons for the delay in CSP development, as larger capacity necessitates more capital and investments for even bigger steam turbines; however, the trend has changed now and there appears to be much more investment into all kinds of renewables.

Countries with hot weather have higher potential for CSP, and those located near the equator in particular. These desert areas have an annual solar radiation from 2,000–2,500 kWh/m^2/y when there is a clear sky [84].

California and the south of the USA are examples of areas where very high radiation can be obtained. Spain also has several CSP projects now in operation. The KSA has an average irradiation of 2,200 kWh/m^2 annually and much uninhabited land that may make it worthwhile attempting to operate CSP in the country [97]. The trend in recent years has changed whereby more capacity for CSP has been installed in different countries such as China, Morocco, South Africa and India. However, Spain is still the global leader with an installed capacity of 2.3 GW and the USA is second with 1.7 GW. By the end of 2016, the total global installed capacity reached 4.8 GW, but more is under construction [58].

There are various different types of CSP technology; they all have the same basic principle but they differ in their structure and temperature range. These different types can be used in different applications, as illustrated in Figure 2.11. Two types of CSP technology depend on a line focusing system – parabolic trough and linear Fresnel – while the other two types – power tower and dish sterling – depend on focal focusing. Parabolic trough and power towers are the dominant technologies. More explanation about these technologies will be provided in the next section.

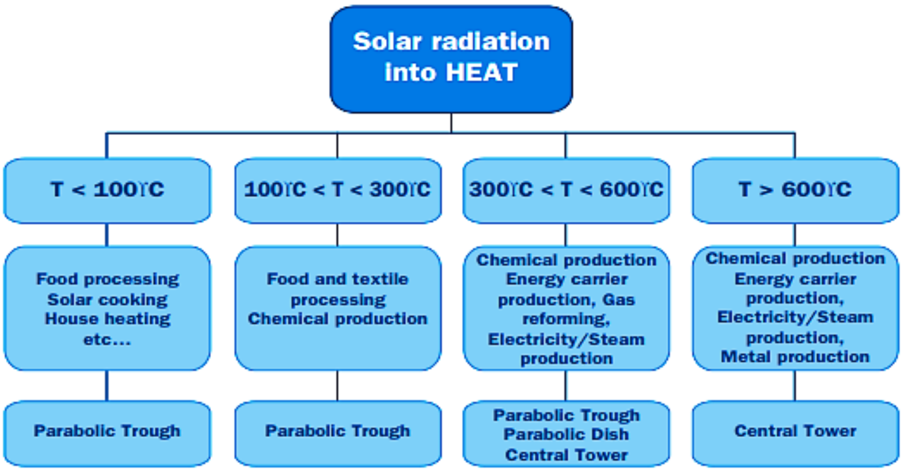


Figure 2.11 Different types of CSP for different applications [98]

2.7.2 Types of Concentrating Solar Power

2.7.2.1 Parabolic Trough

This is the most mature design and the most used system to produce power from CSP [99]. This system uses large curved or trough-shaped mirrors that track the sun to reflect linear focus onto a tube containing a heat transferring liquid located at the focal axis. The parabolic trough can be made of polished metals or glass silver mirrors. The tube absorbs heat and usually has a synthetic oil as a heat transfer fluid (HTF) that can be heated to above 300°, which then produces high temperature steam via the Rankine cycle. Recently, a more direct steam generation system has been used. The collectors track the sun with photo sensors or with a very accurate astronomical mathematical algorithm. Figure 2.12 shows the schematic for the concept of the parabolic trough collector, while figure 2.13 provides a closer look at the technology constructed.

Parabolic trough collectors are considered to be the most mature technology amongst types of CSP. This was the first type to be commercially developed and built and this was undertaken by a company called Luz International in the USA. From 1984–1991 Luz built nine plants in the Mojave Desert in California to generate electricity with capacities ranging from 13 to 80 MW (a total of 354 MW) [84]. The project is known as the Solar Electricity Generating System (SEGS) and it came online in different stages with each stage boasting further enhancement and development. For example, in the second stage, SEGS II, the configuration included a natural gas boiler where this hybrid system could help the turbine to be driven by either the solar steam or natural gas boiler. Other elements were developed during this experience, such as raising temperature, better steam turbine and higher efficiency in performance. At the beginning of the 1990s Luz stopped constructing plants due to the availability of cheap gas; however, it has been reported that after 10 years of operation these plants still function reliably and cheaply [69].

Morocco has its Noor II 200 MW parabolic trough and China has its first 10 MW plant and it is willing to install 1.4 GW [58]. Spain constructed Andasol 1 with 50 MW, while PS10 and PS20 were already generating enough electricity for 200,000 houses. In the USA, Nevada's project Solar I (Figure 2.13) is operating with a capacity of 64 MW, and there is another one in Arizona. These are just some examples of the expansion of CSP projects and many of them are in developing countries.

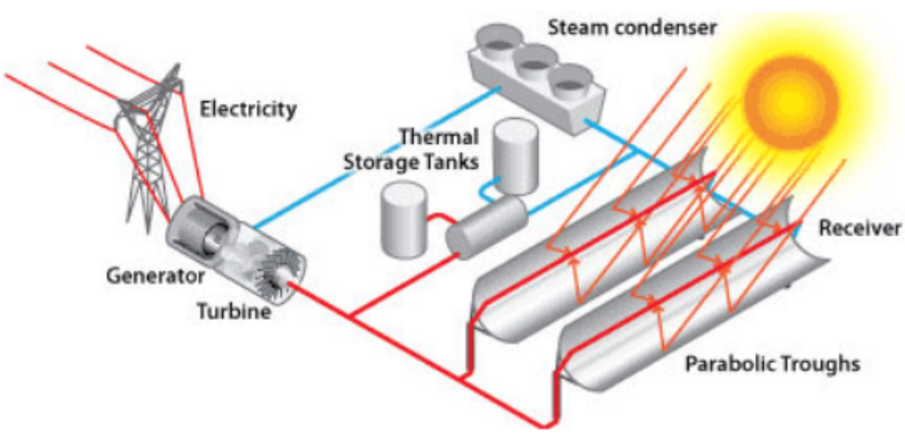


Figure 2.12 Schematic for the concept of parabolic trough collector [100]

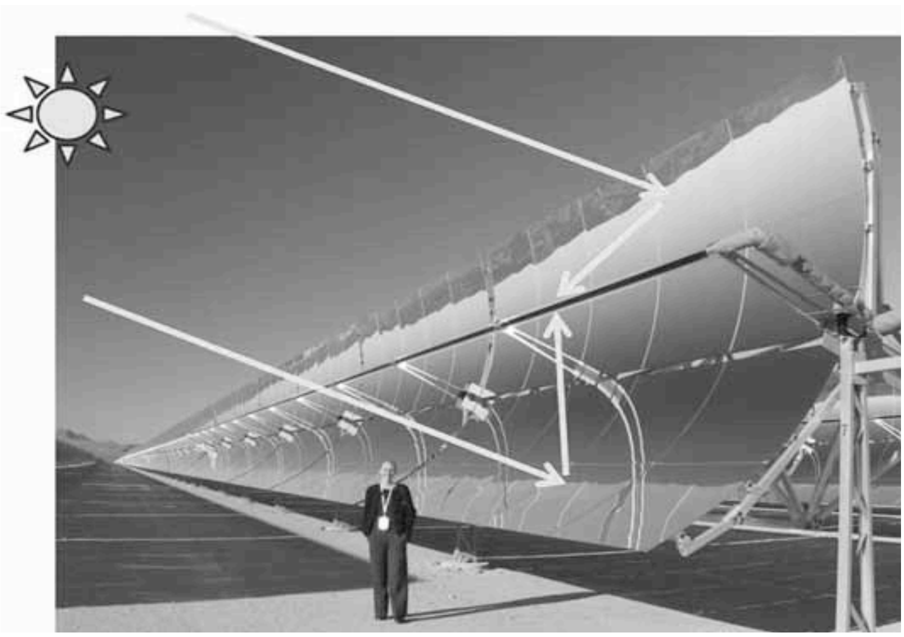


Figure 2.13 Nevada solar one parabolic trough collector [101]

2.7.2.2 Linear Fresnel

This technology uses a line-focusing system the same way a parabolic trough does. Flat mirrors or Fresnel reflectors are mounted on the ground with a single-axis to track sunlight and direct it to a very long tube “receiver” located above the mirrors. These tubes are very long and coated with heat absorber to generate more steam and drive the conventional turbine. There are far fewer Linear Fresnel projects than parabolic trough collectors and most of them are in Spain, China and India [102]. These are usually installed with small-scale capacities of less than 50 MW. The capacity of the system to reach higher temperatures has stopped the technology from being an attractive option. Figure 2.14 and 2.15 show the schematic and the technology constructed, respectively.

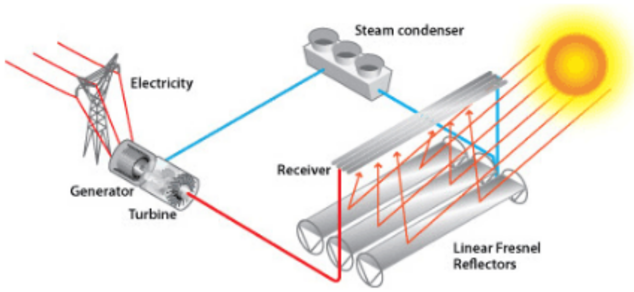


Figure 2.14 Schematic for linear Fresnel technology [100]

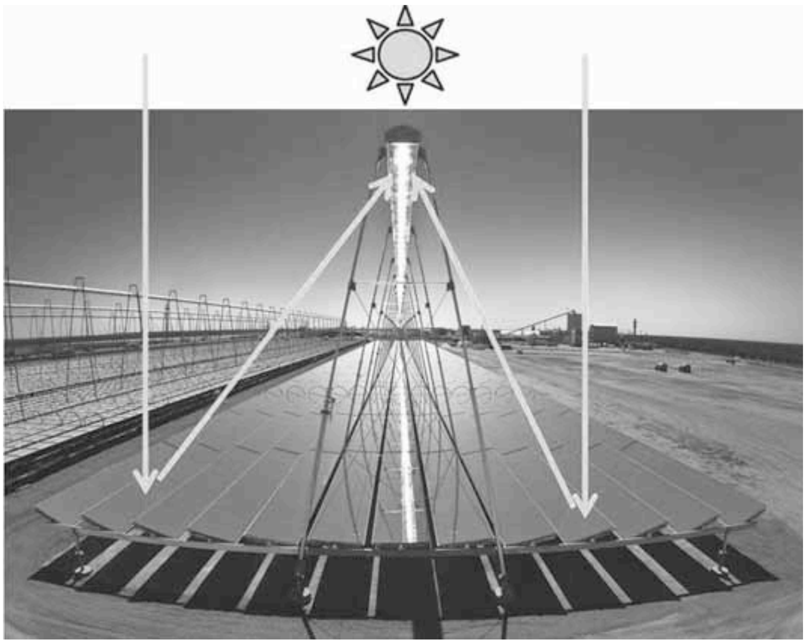


Figure 2.15 Linear Fresnel technology in the field [101]

There is a different structure of linear Fresnel, which is known as a compact linear Fresnel. In this type of structure, more receivers are used and a different set of mirrors is inclined differently to focus on the appropriate receiver. Concentrated photovoltaic is an evolution of this type of structuring whereby these lenses are packed into a heliostat in a very high density and with higher efficiency [103].

2.7.2.3 Central Receiver Tower

A central receiver tower or solar power tower system uses heliostat mirrors in large circular arrays to reflect and focus solar radiation on the receiver, a point positioned at the top of a tower, as depicted in Figure 2.16. These heliostat mirrors usually use two axis tracking systems to track the sun and focus its rays on the focal point, as shown in Figure 2.17. The concentrated radiation on the receiver, which usually contains a synthetic oil or molten salt, is heated to high temperature above (600 °C) and steam then raised to drive the turbine at the conversion system at the ground level. Sometimes steam is produced directly without the need for any type of HTF [67].

Solar towers are more efficient than the linear Fresnel reflector systems, which made them disseminate faster and meant they were installed with larger capacities. These capacities could reach 400 MW, as in Ivanpah solar power plant where three separate units joined together to comprise the largest in the world with a total of 392 MW [101]. The first of this kind was Solar 1, 10 MW erected in California, USA, at the beginning of the 1980s as a prototype that used water as a HTF. In 1995, Solar 2 was built and operated until 1999; this addressed the problems occurring in the previous project, for example, the water-steam was replaced with molten salt because water showed difficulties with storage [84]. In this project, molten salt successfully demonstrated the ability to store energy and use it at a later time. More of this technology was either constructed or is now under construction in various countries such as China, Spain, India, the USA and Morocco.

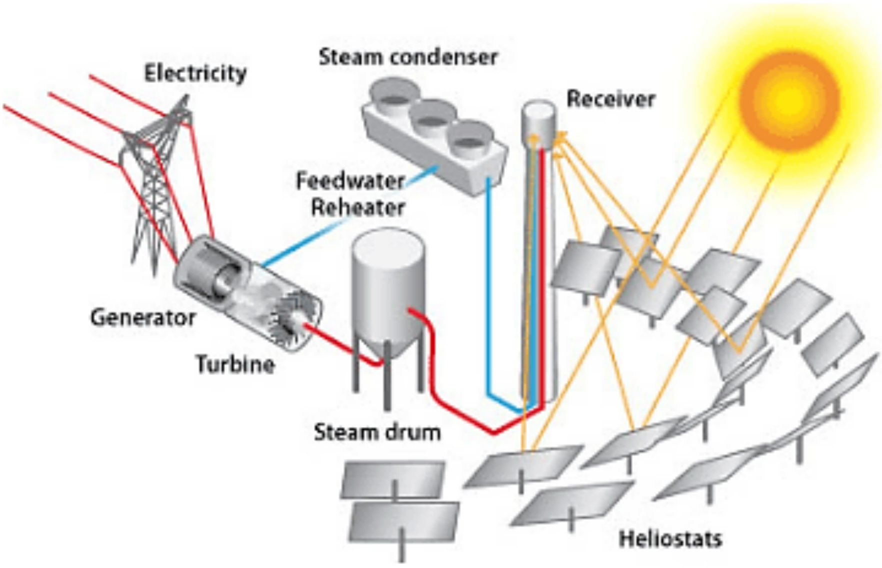


Figure 2.16 Schematic of central tower receiver [100]

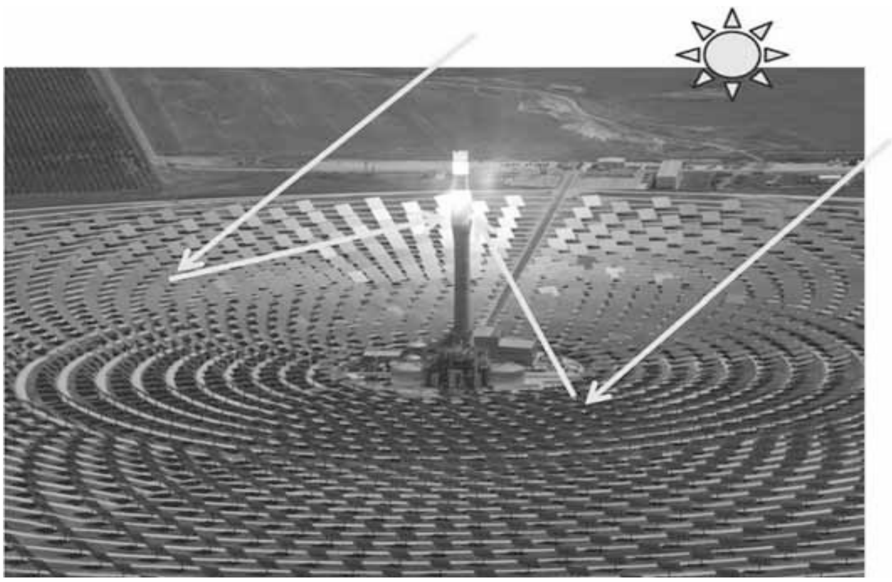


Figure 2.17 Central tower receiver and heliostat around [101]

2.7.2.4 Parabolic Dish System

This is another focal-focusing system where the approach is to have the heat engine right at the focus of the mirrors. Figure 2.18 and 2.19 show the schematic and actual technology in the field, respectively. Mirrors have a parabolic shape situated in a dish where many dishes can be constructed around each other with capacities ranging from 3–25 kW. A direct beam radiates an engine which either a steam engine or what has been recently seen to be more efficient: the Stirling engine. The latter can operate at higher temperature close to 1,000°C, similar to the central receiver. The Stirling engine usually uses the heated fluid to produce mechanical work through piston movement.

The dish system uses dual-axis tracking systems with the diameter of parabolic dish ranging from 5–15m. This makes it the highest and most efficient system in terms of converting energy. However, this technology is the least used and developed among the CSP technologies. The first project of this type was a pilot of 60 dishes constructed in Arizona in 2010. Recently, two projects were constructed in the USA; one of them is in Utah and the aperture diameter of the dish is 35 m^2, each dish with 3.5 kW. The total number of dishes is 429. The other is in Arizona using a Stirling engine and this has a total capacity of 1.5 MW [102].

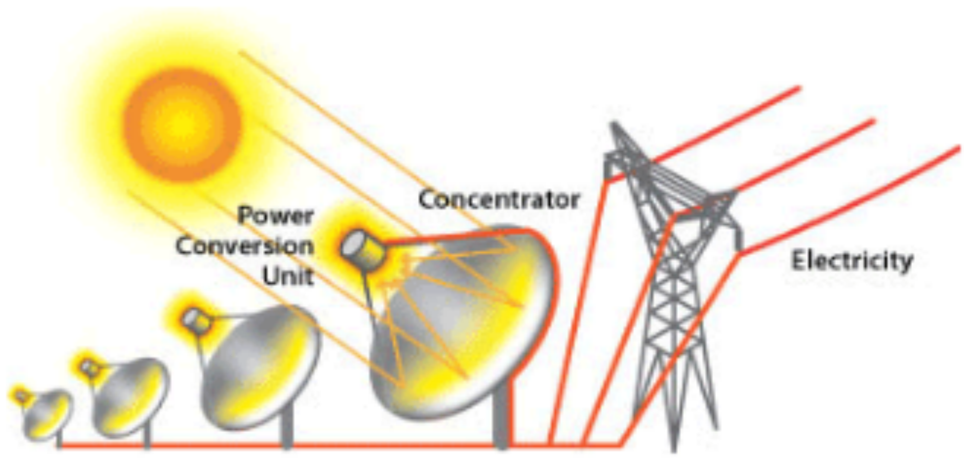


Figure 2.18 Schematic for parabolic dish system [100]

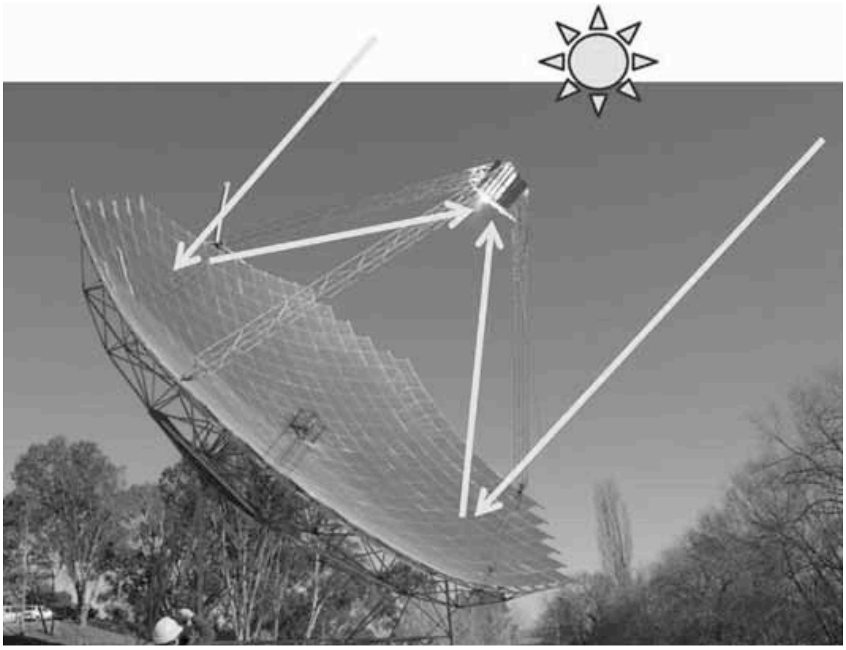


Figure 2.19 Actual parabolic dish system implemented [101]

In 1982, the KSA, represented through KACST, began a joint program with the German Federal Ministry of Research to work on a Stirling dish system [78]. The project consisted of two large dishes with a diameter each of around 7 m. Both dishes concentrated on the Stirling engines to produce the required mechanical work to drive the generator. The project was intended for demonstration to illustrate the potential for future use in remote areas. However, the results showed the impracticality of the large diameter and it was not cost effective in terms of operation and maintenance. It is worth noting this was the only CSP project developed in the KSA until 2012 when a solar thermal plant for water heating was constructed in Princes Nora University in Riyadh [79].

2.7.3 Storage

Increasing attention has been paid to CSP because energy from CSP can be stored to use the energy later when it is needed, especially at night time. Lately, most commissioned projects have come online with thermal energy storage (TES) since it is becoming an advantage to give more flexibility for dispatch [58]. Thermal energy storage types are suitable technologies for CSP and they have been in use commercially. Synthetic oil has been used as heat storage and sometimes molten salt is used as a cheaper alternative. Storage usually increases the cost of the CSP plant once included into the design; however, it decreases the levelled cost of energy since the plant will work for longer hours and can be dispatchable to attract higher prices.

2.8 Grid Integration

The term "grid integration" is widely used in the literature, especially in relation to the growing connection of renewables to the grid. Connection can be made to different levels of the grid, either to distribution level or directly to the transmission system. For example, in the UK PV arrays of several kilowatts are connected to the low voltage level of the distribution network, usually 230–400V, while larger systems in terms of 1 MW and above are connected at a higher level 11–33 kV [84]. This method of connecting is a global trend, with higher capacities getting connected to higher levels and lower outputs connected to distribution level.

Many countries around the world have already outlined a plan to integrate a certain amount of renewables into the grid. For instance, Germany is planning to integrate what covers 50% of its consumption from renewables by 2030 and to increase that share to 80% by 2050. In the KSA, very little has been integrated into the grid; however, as a part of the new vision for the country, known as "vision 2030", a target has been set to integrate 9.5 GW of renewables into the grid before 2030.

Integration of renewables into the grid is changing the traditional way the power system functions. This process is posing economical and technical challenges, however, and thus a large number of publications address these aspects. This seems to be the future trend for the electricity system in order to create a sustainable energy system. In relation to this, network infrastructure, such as distribution and transmission, is seen by some experts to be aging and it needs to be upgraded; in this regard, the integration of DG could play a pivotal role [104]. Hence, in the following subsections, the positive and negative consequences of DG grid integration are outlined alongside the impact on economic dispatch.

2.8.1 Benefits of DG Integration

The main reason for the growing amount of DG integration is the promise that DG can add to the power system. Obviously, one of the important benefits of this is that DG will help meet the demand for energy in the future. Joos et al. [105] outline some of these benefits, for example, companies can save money because DG is connected in proximity to load, which will defer investing in reinforcement or expansion in the network; IPPs will be encouraged to install their own generation to profit from selling; and flexibility to consumers to install their generation to either consume or sell the excess to the grid, especially with the decrease of DG cost installation. There is also scope to provide ancillary services to the transmission system, such as reserves, enhanced frequency response, reactive power supply and capacity.

Installing these DGs properly will help reduce losses in transmission and distribution systems; however, larger penetrations could reduce the reliability of the system [106]. Pathomthat et al. divided these benefits into two major groups – economical and technical – as summarised in Table 2.2 [107]. Even when DGs are connected to the distribution network, there is a strong influence at the transmission level. However, reduced power flows in the transmission network when DG is connected to distribution will tend to reduce the risk of instability of the system.

Technical Benefits	**Economic Benefits**
Improve voltage profile	*Deferral of reinforcement investment*
Increase efficiency	*Better productivity*
Enhance power quality	*Reduce O&M*
Reduce emissions	*Improve health due to better environment*
Relieve congestion	*Reduce operating cost*
Reduce losses	*Higher security for critical loads*
Increase security and reliability	*Less reserve costs and requirements*

Table 2-2 Technical and economic benefits of DG integration [107]

2.8.2 Impacts of DG on the Network

It was mentioned above that integrating DGs into the network will result in some unfavourable technical difficulties. Many of these DGs are connected to the distribution network, which has been a passive system and is designed to have electricity flow unidirectionally from transmission to distribution and eventually to customer. This has changed now and customers can supply their excess power to the network in a bi-directional process, which causes some constraints to the network. Therefore, many studies into planning and operation have considered these constraints in order to attempt modernising and converting the grid from passive to active operation through new techniques and technology , for example, smart meters and control over the distribution network using digital communication [108]. These studies mostly focus on the voltage rise effect, reliability of the system and protection, as in [106], reverse power flow and losses, as in [109], and exceeding thermal ratings and power quality, as in [52].

The voltage rise effect is a significant issue when connecting DG to the distribution network that could limit connecting capacity. This usually depends on where the DG is connected, as well as the type and capacity of the DG. The voltage profile should not be adversely affected with the addition of more DGs and it should be maintained within its nominal ratings. Similarly, when more DGs are connected, reverse power flow can take place [110]. After supplying the demand at the distribution level, power from the DG will be transferred to the transmission. This will also lead to another effect where the conductors heat up and may exceed their thermal ratings, which will degrade or damage the conductor. As a consequence of these factors, losses may increase to an unacceptable level. The impact on power quality because of DG integration is widely discussed in the literature because it adds several challenges (e.g. harmonics, voltage imbalance and flicker) [111].

Most of the work reviewed in the literature revolves around the distribution network. There is more attention given to distribution since many developers and owners integrate their DGs into distribution. Thus, direct challenges and impacts become obvious and require more immediate solutions. At the same time, connecting large capacities to the transmission system will result in several issues affecting the operation and stability of the system. In their book [112], Bollen and Hassan present a very detailed chapter on these effects, for instance, power flow variation caused by solar power because of the time (daily, weekly, seasonal) variation. Further, since renewables are variable, it requires the transmission operators to predict production and the resulting power flow, especially when it is cloudy.

2.8.3 Economic Dispatch

As has been seen in the previous sections, integrating DG into the power grid will in most cases create some technical difficulties in different areas of the power system. However, there is a wider issue regarding the extent to which DG can contribute to large scale supply at national scale. Duong et al. undertook some simulations using the IEEE 9-Bus test system with four scenarios of wind and solar PV penetration to examine fault level, frequency and voltage and they found that the system performs better when the penetration is less than 30% [113]. Malagueta et al. analysed and simulated CSP plants based on optimisation models to investigate the integration of large solar quantities on the Brazilian electricity system. The study suggests that solar is not the proper choice and not economically feasible in Brazil although there are some areas in Brazil where DNI reaches 6 kWh/m^2 /day [114]. Schroeder et al. presented an assessment with different scenarios for integrating renewable energies into the German transmission grid and the study quantified and showed the need for reinforcement of transmission [115]. These are just a few examples to show the large amount of research that has been done into integration and planning. In [116], Singh et al. review about 200 of the research papers executed in this area.

One important area in this regard is the economic dispatch (ED) when integrating large capacities of solar or wind power. ED was introduced into the power system at the very early stage to minimise the cost of production [47]. Since the power system has multiple and different sizes of generation with different fuel costs, it needs to be scheduled and balanced to meet the demand with the cheapest generators first. With renewables penetrating into the system, many studies have been undertaken to reassess the ED and different aspects related to different constraints. The addition of power flow constraints to the economic dispatch is commonly called an optimal power flow (OPF) study, and the addition of ramp rates and unit characteristics (with or without power flow constraints) is generally referred to as a unit commitment study. These studies are used to explore the issues raised by the penetration of DGs; for example, loss minimisation, voltage effects and thermal ratings. DC OPF is run to solve ED related to operation at the transmission level and this comprises the focus of the current thesis. AC OPF can be also be used to study many conditions of the dynamic state of the system. These studies include active and reactive power flow, contingency, DG allocation and maximisation of capacity, whereas most studies have focused on the distribution system. In this regard several techniques were used, either the conventional analytical approaches or the advanced methods such as genetic algorithm, particle swarm optimisation and simulated annealing. The authors in [117] reviewed in detail most of the techniques that have been used in the planning and operation of the system.

Operational planning for the power system with different capacities of renewable resources is a focus of many studies, such as Singh and Banerjee in [118], Hetzer et al. in [119] and Hanhuawei et al. in [120]. These are examples of the work that has been done on ED focusing on incorporating variable resources. The authors in [118] used dynamic programming and linear programming to assess the impact of large PV integration on the system of Mumbai, alongside existing hydroelectricity generation in the system. The results showed a high annual saving in the generation cost in the Mumbai electricity system. In [119], the authors incorporated two wind generators alongside two conventional generators to analyse the speed variation and its effects on the cost of optimal solution. In [120], Hahuawei et al. simulated and analysed the scheduling of solar power considering two approaches, one to solve the ED and unit commitment problem (UC) on a daily basis, the second to schedule all thermal units and solar power based on real-time prediction. There are a few studies that focus on the scheduling of generation with large capacities, specifically with solar power. Despite these studies, there is no research addressing integrating solar power into the national grid in KSA. Doing so necessitates studying the demand of KSA in order to understand how the whole system operates as well as the characteristics of solar. Therefore, in Chapter 3, a detailed study of the current and future demands of the Kingdom is presented. In terms of the KSA power system, there is a gap in the literature in relation to studies that understand the operations of the system when increasing the capacity of solar power, which is addressed by this thesis.

2.9 Summary

In this chapter, an overview was provided of the KSA to create an overall picture when studying the power system of this country. Related details were discussed, such as the geographical, climate and social context, with a view to understanding the factors that might affect the use of electricity. Then, a snapshot of the electricity sector in the kingdom was presented, with some details about desalination, the power system and how it is structured. Renewable resources that have higher potential in the KSA, such as solar and wind, were reviewed alongside the Saudi experiments that have been undertaken in this field. This led to defining DG and providing more detail about solar technologies and the key concepts of solar power. PV and CSP are the main technologies that can be used in different applications in the KSA. Therefore, the PV technologies were explored so as to understand the efficiency of cells, the maturity of technology and its share in the market. The same review of CSP was undertaken considering storage since most of the recent commissioned projects focus on storage. Since these technologies are connected or integrated into the grid, the grid integration was also explained, alongside benefits and impacts on the grid. This review of the grid integration included the aspect of the economic dispatch and the related studies in this area were briefly reviewed.

Chapter 3 **Saudi Arabian Energy Demand**

3.1 Introduction

In the previous chapter, an overview of Saudi Arabia and its electricity sector was presented and details about renewable technologies and the main concepts of solar radiation were reviewed. The chapter concluded by considering grid integration and its benefits and impacts on the grid, and it finally discussed the economic dispatch aspect in this regard. In this current chapter, power generation and demand in Saudi Arabia will be investigated in detail. This is an important aspect, not only for the analysis of the power system, but also for energy policy makers. Based on data, the future demands of the country will be predicted in order to be able to undertake analysis of the power system in Saudi Arabia [1] [121]. Most of the data sets in this thesis were obtained from related entities in the KSA: ECRA, K.A.CARE and SEC.

3.2 Power Generation and Energy Consumption

KSA has a very high rate of reliability, and the electrification reaches a rate of 99% [19]. Shortages are only expected at certain times of the year, usually in the summer time when peak demand occurs. The country is also experiencing a rapid growth in its energy demand due to a surge in the population and national economy and the industry boom in the country [122]. During the period of this study, it was found that the published reports were insufficient and they didn't contain the necessary data to study the energy system in Saudi Arabia. A field trip was undertaken to the KSA and some historical data was obtained from SEC after spending a couple of months at the company. After extensive review, it was decided that the aspects of power generation and consumption in the KSA should be analysed.

3.2.1 Power Generation

SEC supplies all its generation through thermal power plants, which accounted for 68.0% of the total power sent to the network in 2014. To cover demand for the whole country, SEC buys the rest of the power generation from other producers, from IPPs and desalination plants. IPPs have a capacity of around 27.4% and desalination plants share about 4.5%. The power produced by IPPs or desalination is usually sold to SEC to cover the demand all over the country. There is no coal or nuclear power used to generate electricity in the KSA, and there are a few small solar projects, but these are negligible compared to the total generation capacity. Hence, virtually all power generated in the KSA comes from thermal sources, even if we consider other producers besides SEC. The generation fleet in the KSA is unusual since OCGT is more than half of the units in the system. Most of these are old and inefficient and will need to be replaced. Given the make-up of the KSA system and fuel that is very cheap, efficiency has not been a strong factor in decision making.

According to the data received from SEC, in 2014, the power generated by SEC was 214,589 GWh out of 311,807 GWh, the total available energy. Therefore, SEC purchased 97,218 GWh, which was sent to the network by Saudi ARAMCO and other producers. The energy produced at SEC grew at a rate of 5.3% annually from 2000–2014. Table 3.1 illustrates the total energy generated from SEC's power plants in the last decade.

Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Generation	148	154	163	176	184	186	190	207	198	214

Table 3-1 Development of energy generated by SEC (TWh/year)

The available capacity at SEC has increased by 5.8% per annum in the last decade. In 2014, the total actual generation capacity was 48.6 GW. From a technology point of view, electricity at SEC is generated from different types of technology, including steam turbines (ST), open cycle gas turbines (OCGT or GT), combined cycle gas turbines (CCGT or CC) and diesel engines (DE). In the course of approximately the last decade, the capacity of these technologies – ST, GT, CC and DE – has increased by 8.1%, 4.5%, 7.9 and decreased -4.3%, respectively, as shown in Figure 3.1.

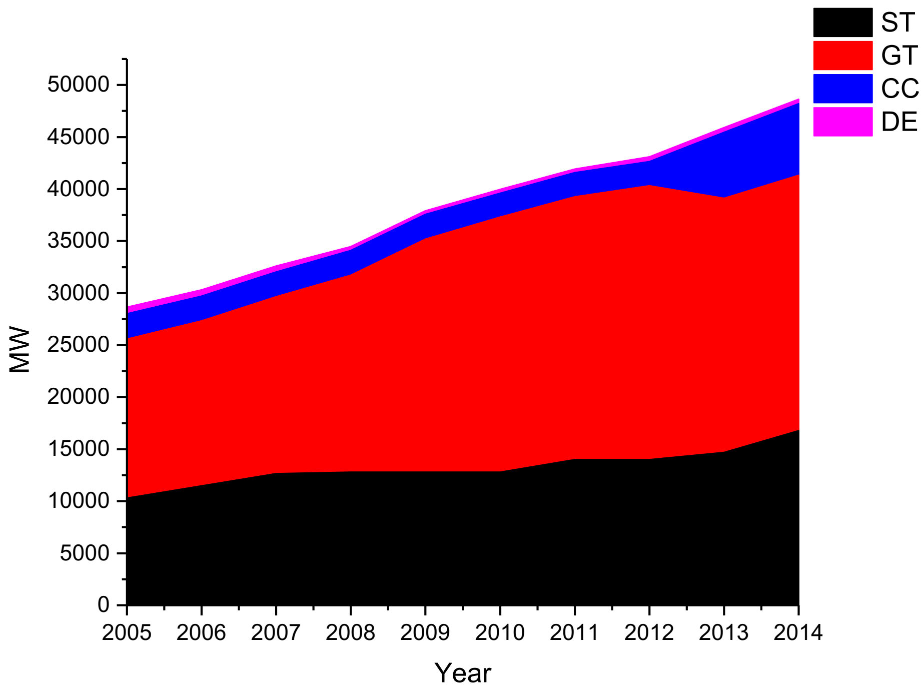


Figure 3.1 Development of generation capacity at SEC [19]

The energy produced at SEC has been increasing annually at a rate that is higher year on year in KSA. The most energy is produced from GT, followed by ST and then CC. However, the greatest growth in energy production from a technology perspective is seen in CC. While ST increased by 6.6% and GT by 3.4%, CC increased by 9.0%. Clearly, SEC has added more CC capacity in the last couple of years. Figure 3.2 shows the produced energy for each technology. Notably, the capacity of diesel engines has decreased in the last decade at SEC; however, rented diesel engines has increased at a rate of 17.9%, which are owned by IPPs and produces around 1,495 GWh.

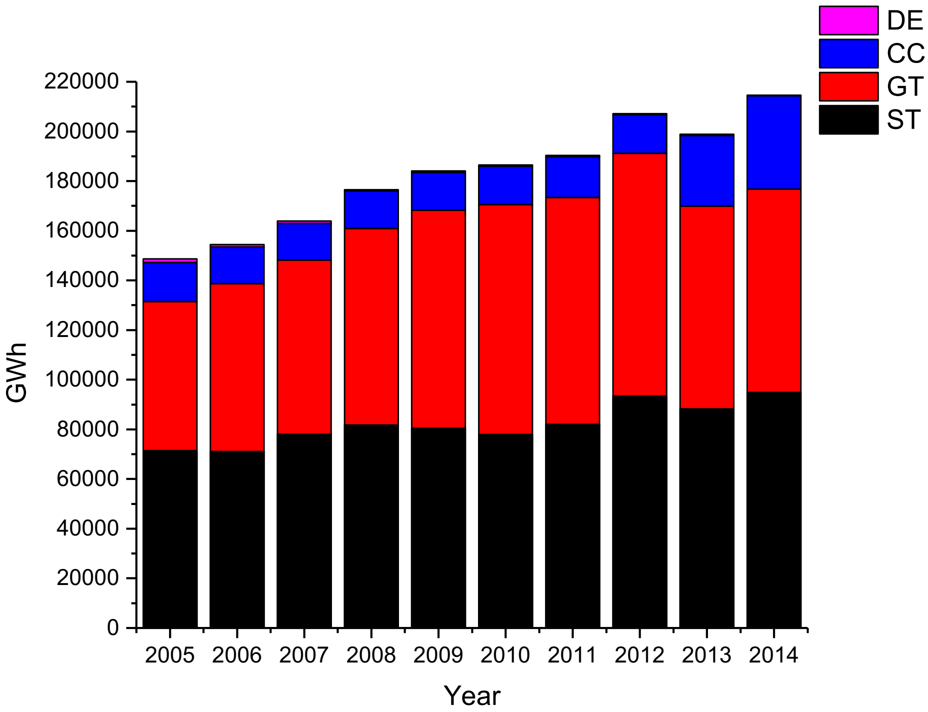


Figure 3.2 Energy produced by each technology at SEC [19]

The remainder of the electricity generation comes from other producers, as shown in Table 3.2, along with their contribution.

Year	Desalination Plants	Water & Electricity Companies	Big Producers	Rented Diesel Engines
2005	2,539		711	411
2006	2,905		1,429	358
2007	2,395		1,597	354
2008	2,444		1,840	488
2009	1,954	945	2,906	767
2010	2,059	1,739	4,643	724
2011	1,811	1,753	4,602	1,057
2012	1,570	1,755	5,892	1,289
2013	1,717	1,771	7,560	1,506
2014	2,676	1,750	10,961	1,495

Table 3-2 Contribution SEC receives from other producers in MW

With this addition of other producers, the total available capacity amounts to 65.5 GW. This has increased at an average of 6.8% per annum, about 102% over the last decade, which reflects the proportional need for more capacity installation to cover the future high demand. According to [123], losses at the transmission and distribution level reached 8.3% in 2009; however, in 2014, this increased to 10.0%, double that of best practice countries [19]. These losses came to 29.7 GWh in 2014, which includes power generated from rented units whose power is eventually purchased by SEC. This also includes technical and non-technical losses such as electricity theft or faulty equipment [124].

SEC consumed the equivalent of about 408 million barrels of oil (MOE) in 2014, with an annual increase at a rate of 4.7%. Fuel types included gas (44%), crude oil (32%), heavy fuel oil (HFO) (11%) and diesel (13%), as shown in Figure 3.3. Crude oil consumption has almost doubled since 2008 and increased at an annual rate of 7.8%. Even though the country has large gas reserves, the plan is to keep these for domestic use. The KSA has been planning to use more gas in electricity generation; however, gas is also replaced with crude in some power plants when they are short of gas. More investments are required to raise the available gas capacity in order to reduce the consumption of crude oil.

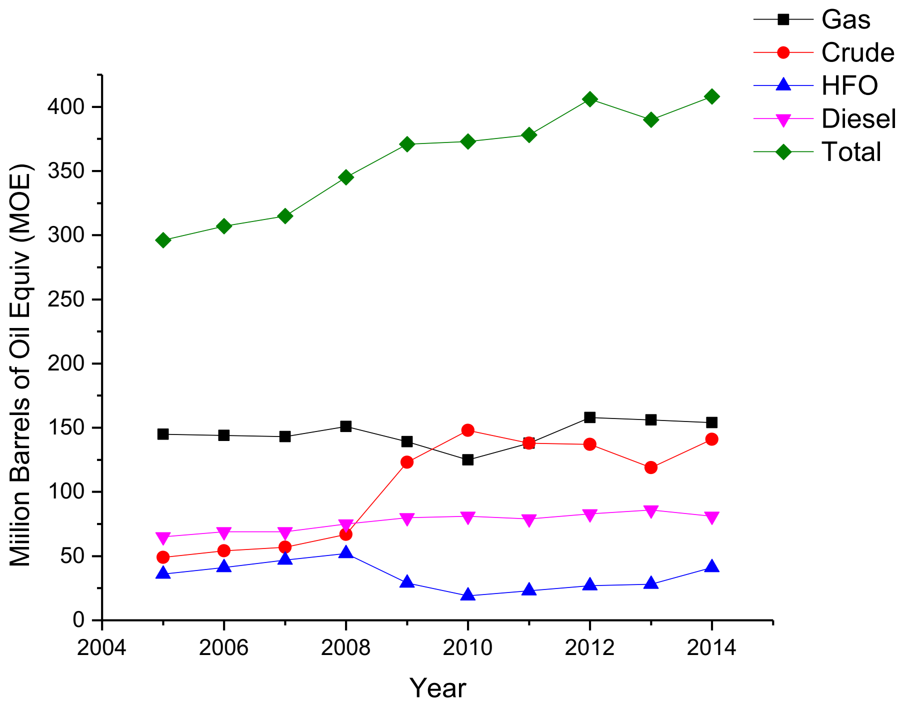


Figure 3.3 Types of fuel consumed in SEC [125]

3.2.2 Power Demand

It is crucial to study the characteristics of the energy demand in the KSA to understand how the power system is operated. It is important to note here that demand, consumption and load terminologies are used interchangeably in the literature. In this context, however, demand is used when denoting load over a certain period of time, while load is used to describe how much power (MW, kW) is required by the system at a given moment, for instance, peak load.

Several researchers [126]–[129] have studied the drivers of energy consumption. For instance, in [129], Yaya suggests there is a proportional relationship between income and energy consumption whereby countries with a higher income per capita have a higher energy consumption per capita. In the KSA, energy consumption increases at a rate of 6.5% annually, as shown in Figure 3.4, while this figure is about 3% in developed countries, with an energy peak demand increase at a rate of 0.9% per year [129]. In the KSA, the peak maximum load and the number of customers have been increasing annually at a rate of 7.09% and 5.4%, respectively.

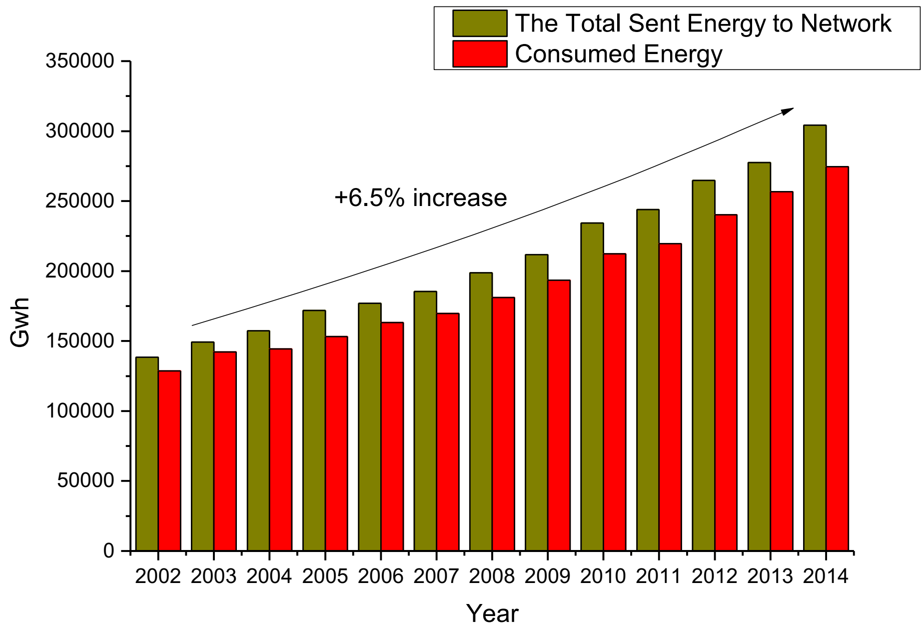


Figure 3.4 Produced and consumed power

SEC has been increasing its installed capacity, mostly with a view to covering the peak demand that usually occurs during the summer time for a few hours during the day. Table 3.3 shows the peak load for the system, as well as the number of customers, which increased from 4.72 million in 2005 to 7.60 million in 2014. This illustrates that peak load has almost doubled during the last decade and, in turn, it is expected to increase a great deal more in the future since the economy and population are still growing. The following section will present more detail about the components of load, where it is classified into six sectors, to understand where most demand comes from.

Year	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Peak Demand (GW)	29.91	31.24	34.9	38.0	41.2	45.6	48.3	51.9	53.8	56.5

Table 3-3 Peak demand in KSA

3.3 Load Classification

Load in the KSA is composed of six main components or sectors: residential (domestic), industrial, governmental, commercial, agricultural and others. This section will present an overview of these components in terms of the number of customers and the energy consumed by each sector. Then, further details will be given about each operating area. Table 3.4 illustrates the growth of the energy consumed by each sector, with commercial experiencing the highest growth, at an average rate of 11.0% per year, whilst the residential sector remains steady, consuming almost half of the produced energy in 2014. The total energy consumption grows at an average of 6.5% annually

Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Residential	78	86	89	96	100	108	109	120	125	135
Industrial	33	32	30	32	34	38	42	41	51	51
Government	16	18	19	20	22	24	23	26	27	30
Commerce	15	17	19	21	23	29	33	39	39	42
Agriculture	3.1	3.3	3.1	3.4	5.0	3.6	3.7	4.2	4.3	4.6
Others	5.7	6.1	6.8	6.7	7.0	7.6	7.6	8.2	8.8	9.7
Total	153	163	169	181	193	212	219	240	256	274

Table 3-4 Energy consumption (TWh) in KSA by sector

Table 3.5 lists the number of customers subscribed to each sector, reflecting the annual consumption of each customer in each sector. By considering these tables, it becomes clear that the residential customers in the KSA consume higher amounts than the average consumer around the world [130]. Figure 3.5 presents the average unit consumption by a residential customer. This shows that the average annual energy consumed by a residential customer was about 23.4 MWh in 2014.

Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Residential (Million)	3.9	4.1	4.3	4.5	4.7	4.9	5	5.3	5.6	5.9
Industrial (Thousand)	615	627	669	696	728	748	764	816	847	921
Government (Thousand)	95	100	103	110	118	118	117	123	131	141
Commercial (Thousand)	609	641	679	709	756	830	1,035	1,097	1,154	1,329
Agricultural (Thousand)	51	54	56	57	59	61	63	67	72	75
Others (Thousand)	5.7	6.1	6.8	6.7	7.1	7.6	7.5	8.2	8.7	9.6
Total (Million)	4.7	4.9	5.2	5.4	5.7	5.9	6.3	6.7	7.1	7.6

Table 3-5 Number of customers by sector

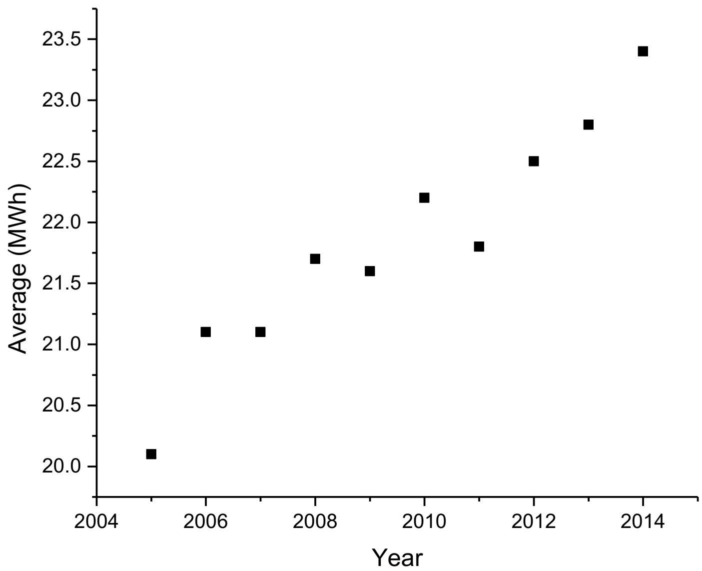


Figure 3.5 Residential customer average annual consumption

A small number of studies have been undertaken to analyse the situation of high energy consumption in the residential sector in the KSA. In [17] Aldossary et al. investigated this in relation to the building sector, considering different types of houses and flats. Three different houses and three different flats in Jeddah city were used as a case study to be simulated and analysed. Jeddah is in the WOA and its weather is mostly similar to that of the COA and EOA, especially during the summer time, which makes the study applicable to these two operating areas as well. The properties were simulated using IES-VE software and then analysed by considering the annual average consumption and architectural design. The findings showed that more than three quarters of the energy consumption comes from cooling systems in both types of housing. The study also reflected poor architectural design and bad habits by the occupants having an impact on this consumption level. It is worth noting that the greatest electricity consumption in the residential sector comes from single-family houses.

Almutairi et al. [131] undertook a life cycle assessment evaluating the environmental performance of air conditioning in the residential sector in KSA. The study revealed that the use phase has the largest share of the impact, and fuel type is the next most important factor to impact the magnitude in each region. In comparison to other countries, policies have been put in place in countries such as the USA and in the EU to abate the increase of energy consumption. For example, in the EU the residential sector is expected to contribute to saving half of the intended goal of 20% by 2020, as noted in [132], even though the residential sector only accounts for 24% of the total demand in OECD Europe [133]. Alaa and Moncef [134] investigated improving energy performance in the residential sector in KSA through building envelope systems; the analysis used optimisation and sensitivity analysis considering different energy efficiency measures to be applied in five different cities in KSA. The study showed that around 36% of government subsidies could be saved over the life of a residential building with no change to prices.

The KSA industrial sector is mostly concentrated in the eastern region for chemical, plastic and oil products and companies and it has the highest energy consumption after the residential sector. However, even though the commercial sector is slightly lower, it is growing at a higher rate than the industrial sector: 11% annually. Fasiuddin and Budaiwi [135] studied the commercial sector, suggesting that buildings in this sector consume more energy per unit area than buildings in any other sector. The study investigated different heating, ventilating and air conditioning system (HVAC) designs and strategies for better utilisation since it is the largest end-user. Using a multi-step approach, the study showed that up to 30% of energy can be conserved. For a more detailed investigation, the following sections are devoted to exploring each region in relation to sector consumption and number of customers. Analysing each region will help to understand accurately which region has the greatest electricity usage and allow for the prediction of future demand, customer numbers and other important factors.

3.4 Regional Demand

Following an extensive review of the historical data provided by SEC, numbers were derived from electricity sales for each region and sector. In the following sections, analysis will be carried out for each region using decade-long data in order to provide insights into demand in the KSA; for example, distribution of demand across the Kingdom, customers and growth rate etc. Data was gathered during a visit to KSA in the form of row data in spreadsheets and company's internal reports.

3.4.1 Central Operating Area Demand

COA has a high population density and it is located in the middle of the desert. Figure 3.6 outlines the growth of energy sold in the COA for each sector over a period of a decade. It is clear that the residential sector dominates the energy being sold in this area and it increases at an average rate of 6.5% every year. However, the commercial sector is making strides in energy consumption at a rate of 11.5% annually. More than half of the energy consumed in COA is in the residential sector and the rest is divided between the other sectors. Specifying the end-use equipment consuming the energy is beyond the scope of this study, but based on the studies discussed above, cooling dominates end-use, with a share of above 70%.

The number of customers in the residential sector is two-thirds of the total number of customers in all other sectors. There were over 1.8 million customers in 2014, most of them in Riyadh. According to [5], there are more than 7 million people in Riyadh; therefore, this confirms that large single-family houses are common and these dominate the residential sector. Energy consumption increases in all other sectors at a rate of no less than 5.0% annually, except for the agricultural sector, which increases at a rate of 4.0%. The increasing number of customers in each sector each year is shown in Figure 3.7.

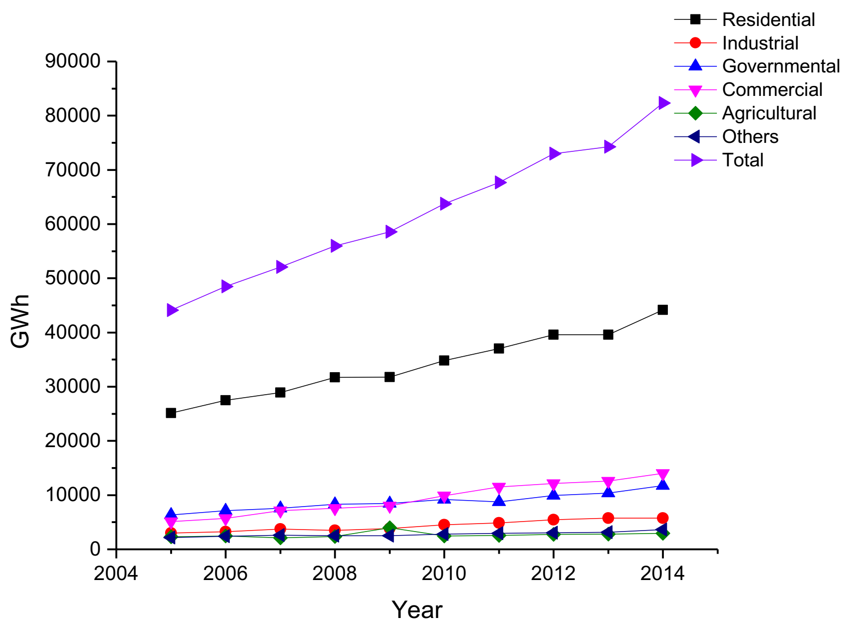


Figure 3.6 Energy consumed in COA by sector

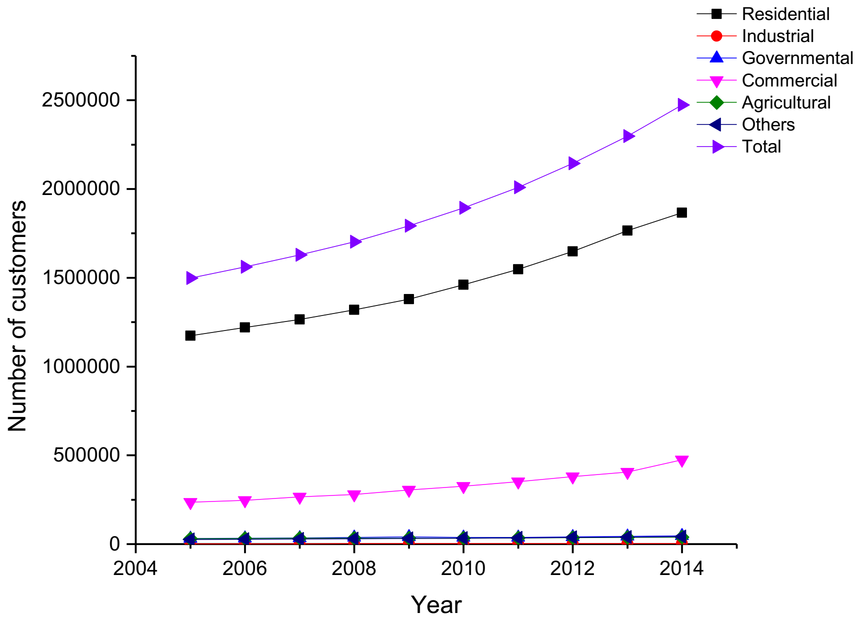


Figure 3.7 Number of customers in COA by sector

3.4.2 Western Operating Area Demand

When the numbers were analysed, the western area was found to have almost the same share energy consumption as COA. WOA is slightly higher in overall energy consumed, with the residential sector still the highest, as shown in Figure 3.8. Similarly, the commercial sector energy consumption is also growing at the very high rate of about 11.4%. The industrial and governmental sector rates of energy consumption are also higher than in COA and the annual rate is about 7.1% and 7.8%, respectively. The weather is similar in WOA and COA, as is the population; as Figure 3.9 shows, these are almost the same and consequently both areas have a very similar overall energy consumption.

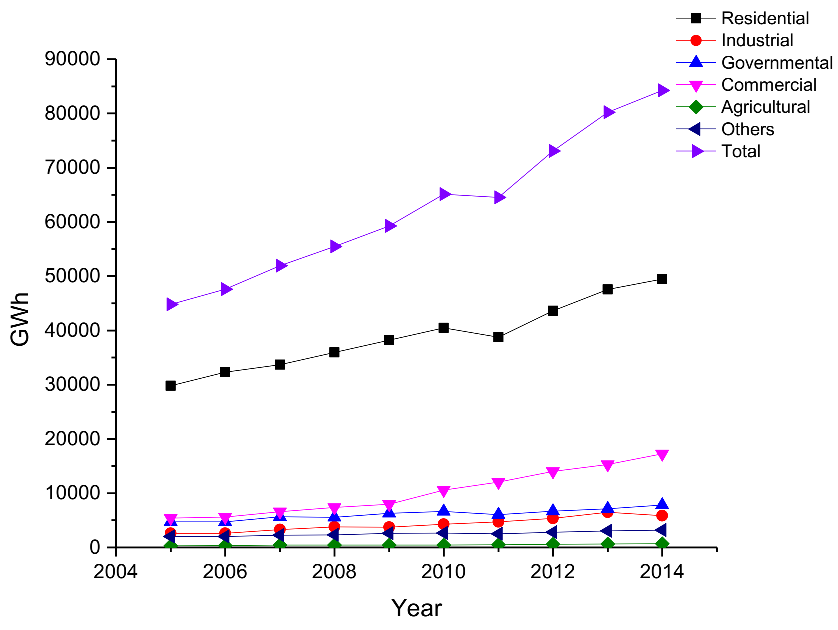


Figure 3.8 Energy consumed in WOA by sector

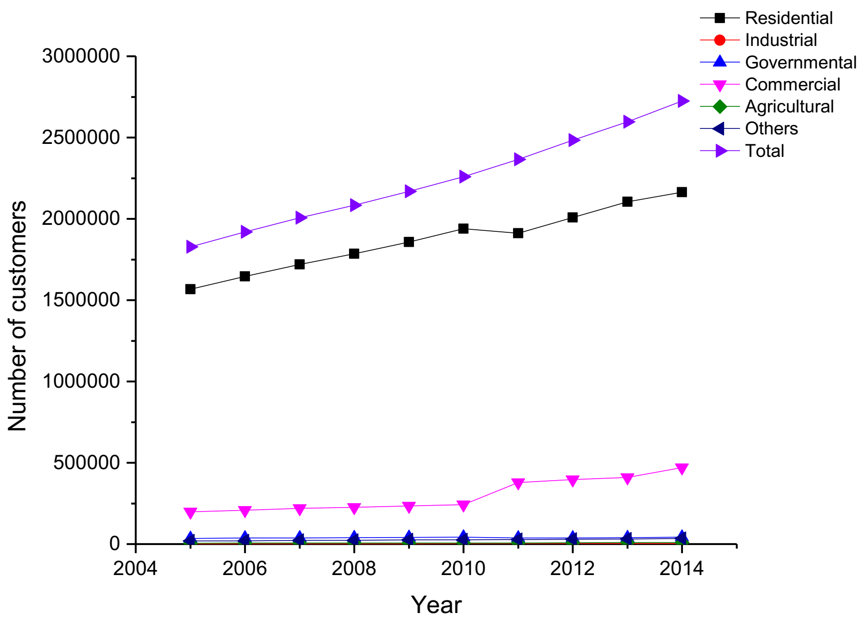


Figure 3.9 Number of customers in WOA by sector

3.4.3 Eastern Operating Area Demand

EOA has similar overall energy consumption levels to COA and WOA, however, in this area the industrial sector dominates the electricity usage, as shown in Figure 3.10. Products such as plastic, steel, cement, many other petrochemical products and giant factories are being built in the eastern region near to the fuel sources. The number of customers in all sectors are increasing greatly at a rate of 5.7%, as shown in Figure 3.11.

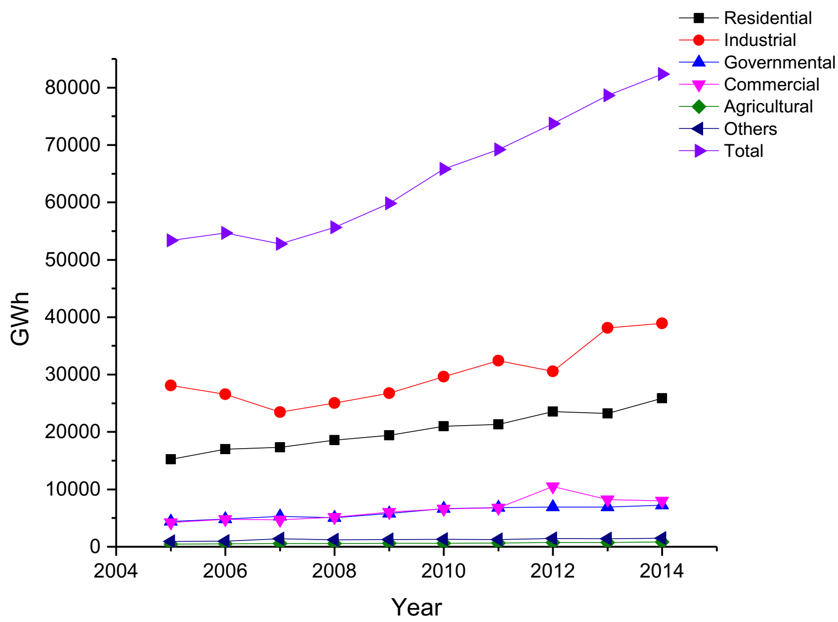


Figure 3.10 Energy consumed in EOA by sector

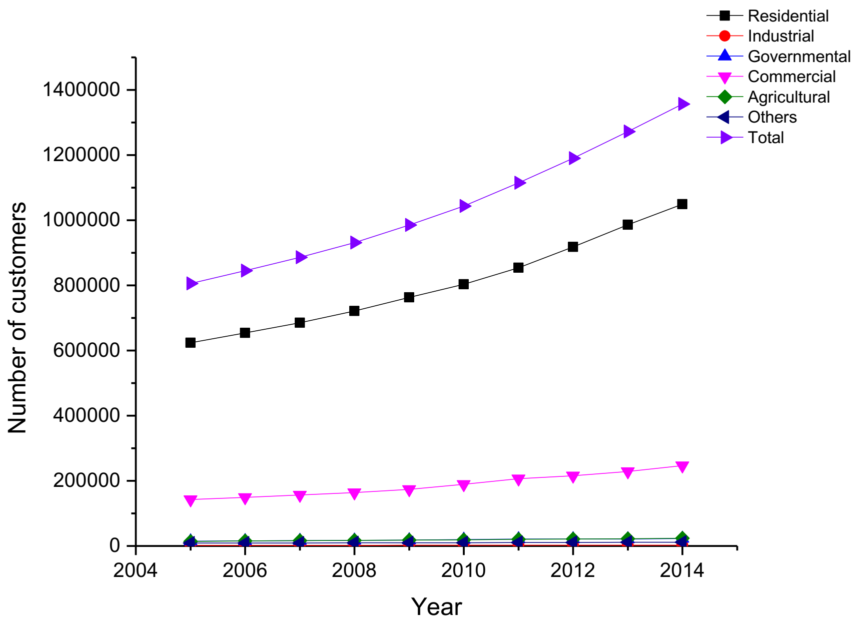


Figure 3.11 Number of customers in EOA by sector

3.4.4 South Operating Area Demand

This area has the lowest share of the country's overall energy consumption. However, SOA is experiencing a substantial growth in all sectors, higher than all other operating areas. In the course of the last decade, the energy consumption in the industrial, commercial, governmental and residential areas has increased by 17.8%, 14.0%, 10.4% and 8.1%, respectively, as shown in Figure 3.12. SOA is also experiencing an overall growth in the number of customers that is higher than the other areas, as shown in Figure 3.13.

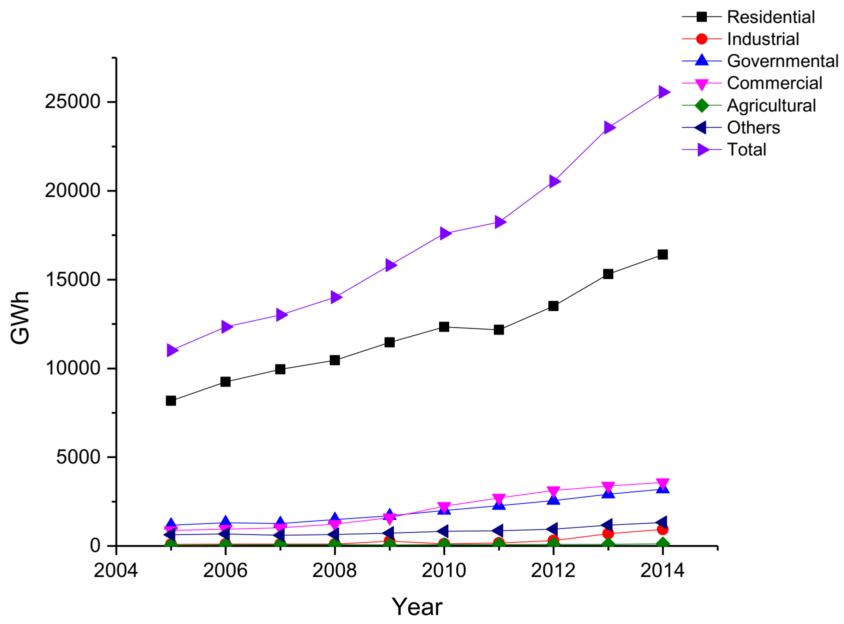


Figure 3.12 Energy consumed in SOA by sector

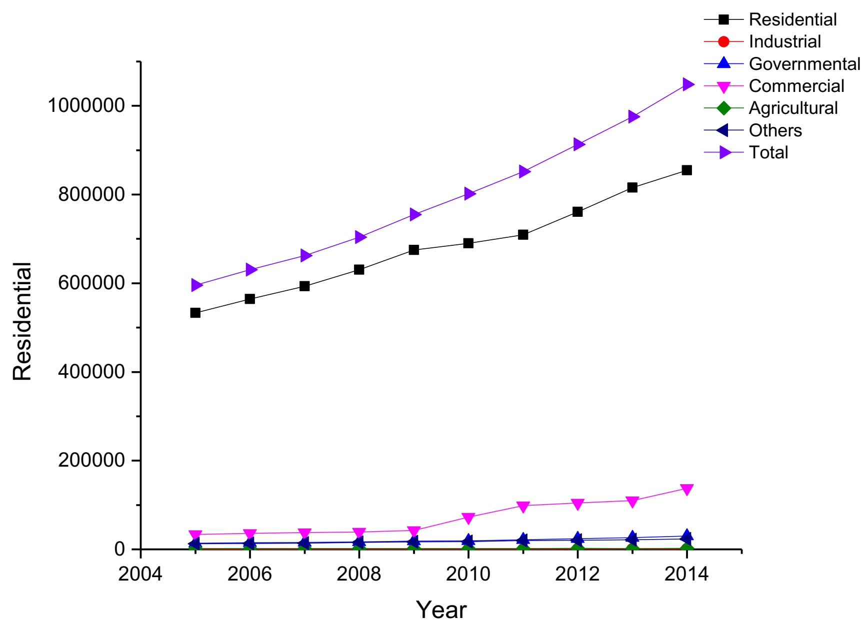


Figure 3.13 Number of customers in SOA by sector

3.5 Tariff Experience/Structure

The tariff system is a very important component by which to manipulate the electricity system, curb the rise of energy consumption, defer grid expansion and introduce system decarbonisation. Tariff can be dynamic and many countries have undergone reforms to find the optimal structure for pricing. For this reason, the electricity market is liberalised in some countries, mostly in developed ones, but this is yet to be put in place in a number of other countries. Several researches have therefore looked at the structure of the tariff system in different countries for different purposes.

In [136] Ryan et al. used a case study to review the residential tariff structure of Ireland, Italy and California since all three have different tariff system structures. The study investigated the impact of policy design on areas such as integration of renewables, demand response, energy efficiency and cost recovery. Considering these four areas, they looked at the pricing system with regard to flat rates and time-of-use tariffs (TOU). The flat rate, or block tariffs, are types used for pricing, where customers are given rates for different blocks or are charged with the same rate regardless of the time flat rate. For example, in block tariffs customers who consume less than 2000 kWh/month will be allocated to the first block with a cheaper rate; those who exceed this quantity will be charged a higher rate and so on. This will require heavy users of electricity to curtail their consumption. TOU, on the other hand, is a form of DSM that was discussed in the previous chapter and it essentially involves charging a higher rate during peak times when the cost of energy generation is higher. This technique is intended to push consumers to shift their load from peak time to off-peak; they are charged higher rates for use during these peak times, either daily or seasonally. Ryan et al.'s study showed that block tariffs are sometimes implemented even though the electricity market in all the three chosen places is deregulated, as in California and Italy. It concludes with the assumption that TOU tariffs are better able to achieve the targeted goals in the three considered areas. Matar [137] looked at households' reactions in KSA if TOU was applied to the residential sector, concentrating on air conditioning and appliances. Four scenarios were used in the analysis and the findings showed that load in all scenarios was reduced, while households would pay up to 57% more in the summer than in other months.

Another study considered two different tariffs – progressive tariff and electricity saving feed-in tariffs – to examine electricity savings and energy efficiency in the residential sector. In this study [138], Prasanna et al. used price elasticity and incentive elasticity to test the effectiveness of this approach in six different countries. This approach addressed the behavioural and psychological measures that were discussed in the previous chapter as important measures in DSM studies. Progressive tariffs are essentially block tariffs that rise progressively every time the user consumes a higher quantity. This is a disincentive or punishment strategy for large quantities of consumers, while electricity access is granted to low-income users. In contrast, electricity saving feed-in tariffs provide incentives to consumers to save targeted quantities of electricity over a certain period of time. The findings of this study show that progressive tariffs work better and more effectively when measured across the population. One important finding is that increasing electricity prices is not always the solution because the saving could be limited when the local context is considered. At the end, the study proposed a logical approach: offering incentives when users achieve the targeted goals and disincentives when they fail to do so. There is a similar study comparing the Brazilian and German system implementing a technique called white tariff to achieve an optimal tariff system [139]; this study also focused on changing the habits of consumers to shift load to off-peak times.

In KSA, the tariff system has undergone several changes since the early years of electricity use in the kingdom. Private companies led by entrepreneurs, as mentioned in the previous chapter on the historical development of electricity in Saudi Arabia, sold electricity with different tariffs based on generation and operation costs. According to [18], the government intervened in 1954 to set the prices based on consumer financial capability. For instance, the cost was reduced in Jeddah from 55.0 Halalah/kWh to 32.5 Halalah/kWh and a similar set-up was put in place in other cities, while making sure these companies achieved a reasonable profit. Then, it was changed again in 1960 with a new tariff decided by the council of ministers. Block tariffs and TOU were used, with the first block set at up to 100 kWh based on whether the electricity was being used in the first four hours after sunset or the second four hours after sunset, as shown in Table 3.6. In 1963, the council ministers lowered the tariff and made it standard across the country. The government then agreed to subsidise private power companies that were not making sufficient profit.

City	Regular customers (Halala/kWh)				Mosques (Halala/kWh)
	First 100kWh	Above 100kWh	First 4 hours after sunset	Second 4 hours after sunset	
Jeddah	24	21	24	18	18
Makkah	30	25	30	17	15
Madinah	30	25	30	18	15
Khobar	30	25	26	17	15
Dammam	30	25	26	17	15
* 100 Halalah = 1 Saudi Riyal (SR) – 1SR ≈ 0.27 USD					

Table 3-6 Prices of electricity in KSA main cities by 1960 [18]

The tariffs changed again in 1972, with basic fees being applied to the monthly bill between 5–20 SR depending on whether it related to industry or non-industry usage. Later, in 1973, new changes to tariffs were made, involving a 50–60% cut in prices, making it 20 Halalah/kWh and the profit was guaranteed by the government as a subsidy to encourage investments. Nationwide electricity tariffs again became standard in 1974 and changed to be very cheap – 7 Halalah/kWh for the residential sector and 5 Halalah/kWh for the industrial sector – and then, after 10 years, in 1984 for the first time changes introduced clear block tariffs, as shown in Table 3.7.

Monthly consumption (kWh)	Residential (Halalah/kWh)	Industrial (Halalah/kWh)
1-1,000	7	5
1,001-2,000	10	
More than 2,000	15	

Table 3-7 Tariffs in KSA starting in November 1984 [123]

Further changes in the tariffs followed after 1995, mostly focusing on expanding blocks and adding more beneficiaries. The tariffs in Table 3.8 were used from 2000 until 2017 with no changes in residential sector tariffs except in 2015, the price was higher for consumption higher than 4 MWh. Prices are fixed and cost approximately 1.33 US cents per kWh for the first block up to 2 MWh. However, some changes have taken place for the commercial and governmental sector and there has been a large change to the industrial sector to increase efficiency and decrease peak demand using TOU.

<table>
<tr><th>Monthly Consumption (kWh)</th><th>Residential Commercial Governmental (Halalah/kWh)</th><th>Agricultural Mosques (Halalah/kWh)</th><th>Industrial (Halalah/kWh)</th></tr>
<tr><td>1-2,000</td><td>5</td><td>5</td><td rowspan="9">12</td></tr>
<tr><td>2,001-4,000</td><td>10</td><td rowspan="2">10</td></tr>
<tr><td>4,001-5,000</td><td rowspan="2">12</td></tr>
<tr><td>5,001-6,000</td><td rowspan="6">12</td></tr>
<tr><td>6,001-7,000</td><td>15</td></tr>
<tr><td>7,001-8,000</td><td>20</td></tr>
<tr><td>8,001-9,000</td><td>22</td></tr>
<tr><td>9,001-10,000</td><td>24</td></tr>
<tr><td>More than 10,000</td><td>26</td></tr>
</table>

Table 3-8 Tariffs used in KSA from 2000-2011 [18]

Table 3.9 shows the details of the mandatory industrial system tariff introduced in 2011. This considers seasonal variations, which clearly peak in summer during May-September and from 12:00-17:00. This tariff is not applicable unless a digital meter is implemented. This program is voluntary for large commercial customers with digital meters. The winter in KSA is from November-April when the load drops significantly. Users are also divided into small and large users. Large users are those with contractual loads over 1,000 kVA, while small users are anything less than that. The objective of this tariff is to shift the peak load to off-peak times.

Seasonal Tariff (October-April)		
Type of consumer	Halalah/kWh	
<1000 kVA	12	
>=1000 kVA	14	
Seasonal tariff (May-September) users with digital meters		
Days	**Time of use**	**Tariff (Halalah/kWh)**
Saturday - Thursday	00:00-08:00	10
	08:00-12:00	15
	12:00-17:00	26
	17:00-24:00	15
Friday	00:00-09:00	10
	09:00-24:00	15
Seasonal tariff (May-September) users with electromechanical meters		
15 Halalah/kWh		

Table 3-9 Industrial tariff using TOU applied 2011 [18]

In December 2017 a new tariff was announced by a council of ministers decree, to be in place from the beginning of 2018. According to the vision outlined, the plan is to increase the tariff gradually until 2030 [140]. The current tariff that began in January 2018 is shown in Table 3.10. There is a monthly fee added to the bill depending on the breaker capacity. This cost covers maintenance, reading meters and bill preparation. There is a fee of 10 SR for breakers less than 100 Amps, 15 SR for less than 200 Amps, 21 SR for less than 300 Amps, 25 SR for less than 400 Amps and 30 SR for more than that [141].

Consumption (Halala/kWh) / Type	1 – 6,000	More than 6,000
Residential (Halalah/kWh)	18	30
Commercial (Halalah/kWh)	20	30
Agricultural, Charities (Halalah/kWh)	16	20
Industrial (Halalah/kWh)	32	
Governmental (Halalah/kWh)	18	
Private Hospitals, Edu. (Halalah/kWh	18	

Table 3-10 Current tariff used in KSA 2018 [141]

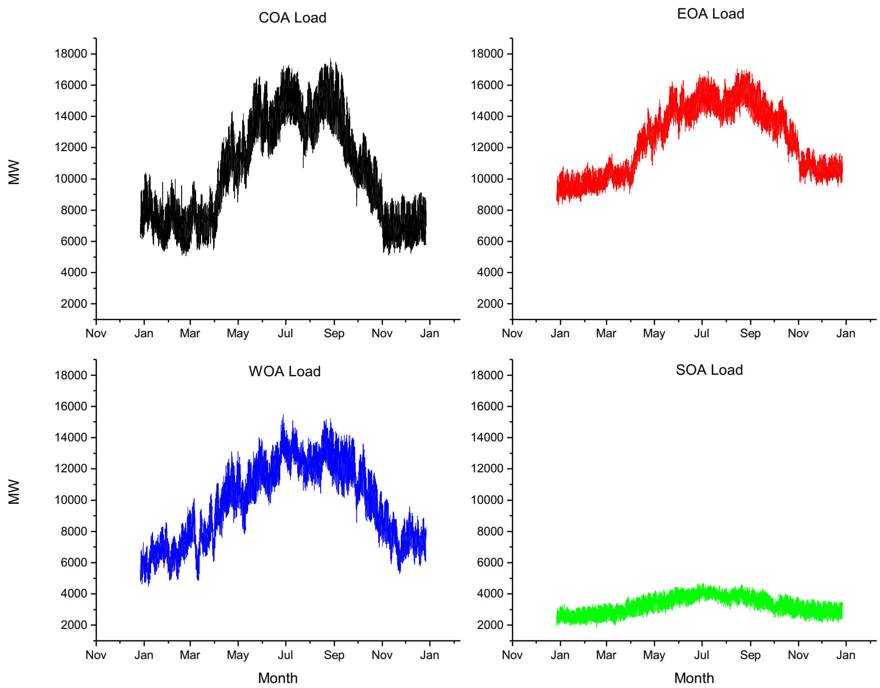
These prices are still low compared to international electricity markets, as was discussed in Chapter 2. The tariff system of KSA is also not widely discussed in the research with regard to optimal design; instead, discussions of it relate to the implications of low tariffs and energy subsidies. The cost of producing and pricing electricity was thoroughly investigated in [142], where the authors estimated the cost of producing a unit at 37.2 Halalah/kWh based on the international market. A report published by ECRA showed that SEC is selling at less than the production cost at an average of 12.3 Halalah/kWh and a production cost of around 13.8 Halalah/kWh [123]. However, this calculation was proven wrong by Alyousef et al. [142] and certain numbers were found to be correct.

3.6 Demand Analysis

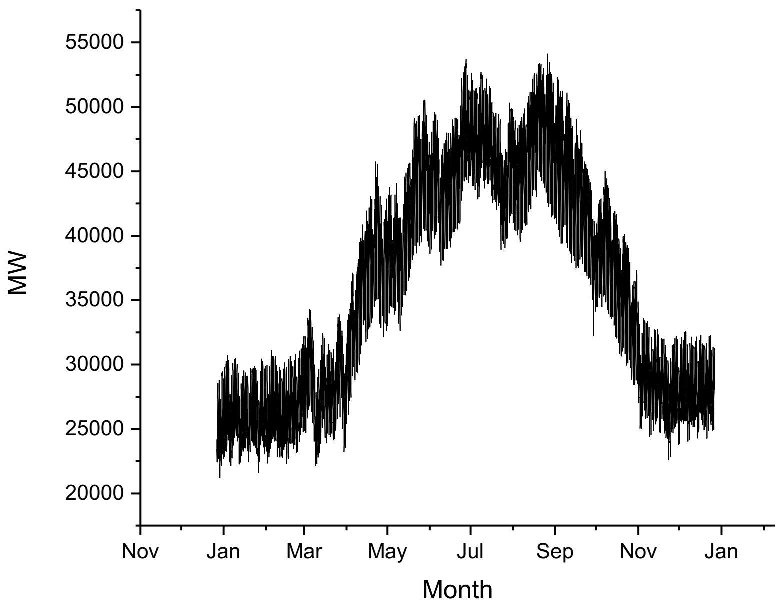
System demand needs to be tracked second by second to keep the system well balanced and to avoid any blackouts or faults within the system. When the generation is higher than the load, constraints occur in the system and the operator has to deal with this; otherwise the frequency will rise. Similarly, the same thing would happen if load is higher and the system gets affected in both cases. These constraints are common, especially with the entrance of renewable DGs into the system. For instance, when connected, wind sometimes blows much higher than is expected, or, similarly, wind farms may be shut down because of strong winds. Therefore, there always needs to be a team ready to study the system demand, not only for the above-mentioned cases, but also for many other reasons, such as reserves, prices, planning and expansion, etc.

In order to understand the system demand in KSA, during the visit, the author accessed the hourly system demand from SEC for 2014. Based on this data, time series for the KSA system demand was analysed. Different load curves for operating areas, seasonal variations and different days of the week were extracted. SEC does not present this data to the public, neither data related to the grid supply point nor sector demand. The data was received in the form of spreadsheets and intensive scrutiny was applied to identify and amend errors or missing data. Errors and missing data were not serious; therefore, a process to fill in the gaps was applied by averaging the predecessor and successor of a certain missing hour. Hourly time series for the system load in KSA and each operating area are shown in Figure 3.14. This peaks the most during the summer in the central region and it is lowest in the southern part of the country. A daily load profile for each operating area was generated considering seasonal and diurnal variation. Figure 3.15 shows only one case during the winter weekdays. The remaining generated figures for other conditions and operating areas can be found in appendix A.

In recent years, studies related to predicting the demand or supply for power systems have gained increasing importance. Load forecasting is the process of predicting future electric load for a power system, which can be challenging since this depends on different sets of parameters and characteristics. These studies sometimes consider different periods of time depending on the purpose of the study. This can involve short range forecasting from one day, to a week, using an hour-by-hour method to predict, for instance, the daily peak when planning for the day ahead. Or, it can be medium range, from one week to several months' prediction, or long range, from several months to several years when forecasting peak demand affected by monthly or seasonal variation.



(a)



(b)

Figure 3.14 a) Load curve in each operating area for 2014; b) Time series system load for KSA 2014

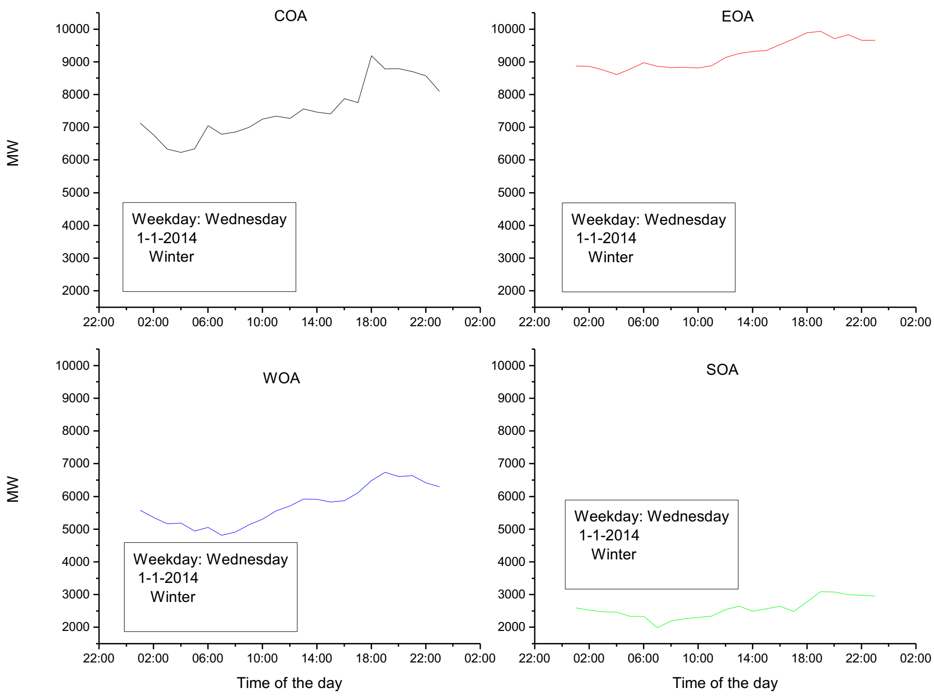


Figure 3.15 Weekday load profile during winter 2014 for each region

These forecasting studies help operators and planners to take the actions necessary for the system. For example, short and medium forecasting will allow operation planners to secure the required supply for the expected demand in the optimal way. The same is true of long range forecasting when it comes to expansion planning, investment allocation and efficient technical and financial operation. Forecasting outcomes also help policy and decision makers to develop the best measures and practices for future situations. Forecasting studies are stochastic and usually associated with uncertainties, driven by a variety of parameters [143], including: 1) time: hour of the day, day of the week, time of the year; 2) load classification: residential, industrial, commercial, or other, since each exhibits different norms and characteristics; 3) economic indicators; 4) population increase rate; 5) tariffs; and 6) weather. This list of parameters can be extended to include more parameters that might affect the forecasting.

In the literature, a large number of papers have discussed energy demand forecasting issues and different techniques and models have been applied based on the orientation of these studies. Common models discussed are, for example, curve fitting, Box-Jenkins, autoregressive and econometric. Some of these models are deterministic, as with trend analysis, and others are probabilistic, while some need historical data and others do not need measured data. Numerical techniques, such as particle swarm optimisation, genetic algorithm and artificial neural network, are also applied in DSM studies. Suganthi and Samuel [144] presented a review of load forecasting models in a detailed article. More than 13 models were analysed in detail, along with their references and purpose of use. This showed that statistical models can produce good results with limited data and few parameters. Yuan et al. [145] forecasted the energy demand for China until 2030 using the Bayesian approach focusing on uncertainties associated with the model. The study argued that analysis at the regional level is more useful, although regional and national levels were also investigated in the work. The driving parameters, such as econometric, technological progress and demographics were also investigated. The study covered more than 30 provinces and several scenarios were developed. The results of this study showed that probabilistic forecasts are rich in information and can provide policy makers with better insight. The Bayesian approach also gives better functionality in curve fitting models than fixed methods. It was concluded that the authors were able to predict which provinces would have more energy demand consumption based on the driving factors considered in the model. The energy demand up to 2030 for China was also forecasted by Zhang et al. [146] to calculate the external costs of generating electricity using a long range energy alternatives planning system (LEAP). Ozer et al. [147].also used this LEAP tool to predict the Turkish energy demand until 2030 with a view to addressing the carbon emissions issue. With regards to specific sector forecasting, the residential sector has received the most attention and it has been evaluated using different models and techniques (e.g.[148]–[151]).

3.7 Demand Forecasting for KSA

In the case of KSA, SEC note in their 2008 annual report that they expect the energy demand to be 75 GW and 120 GW by 2020 and 2032 respectively under current circumstances [152]. A few studies related to KSA have studied energy demand independently, but they have usually used these two numbers given by SEC to evaluate certain cases. These two sets of numbers are insufficient to understand the projection of future energy demand in KSA, however. Therefore, after obtaining historical data from SEC, several methods were attempted to estimate the rest of the years up to 2032 with numbers that meet or are close enough to the two sets of numbers SEC has published. Three different models are used in this current study to forecast peak demand up to 2032 for the KSA. One method is the compound growth model, which provides close enough numbers involved for calculating the average annual growth rate using equation (3.1) and applying this to equation (3.2) to obtain the future value.

$$r = \left(\frac{V_2}{V_1}\right)^{\frac{1}{n}} - 1 \qquad 3.1$$

$$V_2 = V_1(1 + r)^n \qquad 3.2$$

where r = growth rate, V_1 = value at first known year, V_2 = value at last known year and n = number of years between these two values. In order to obtain a future value, the rate at which the energy consumption increases or decreases over a certain period of time should be defined. In this case, the rate of change is calculated for the past 10 years. Using these equations with an average annual growth rate of 4.75% annually gave numbers that were very close to the future values for energy demand published by SEC. This helped to generate a projection for future energy demand up to 2032 using historical data for annual demand from 2005 to 2014, as shown in Figure 3.16. In comparison, 74,702 MW and 130,371 MW were the numbers obtained from this calculation for 2020 and 2032 respectively.

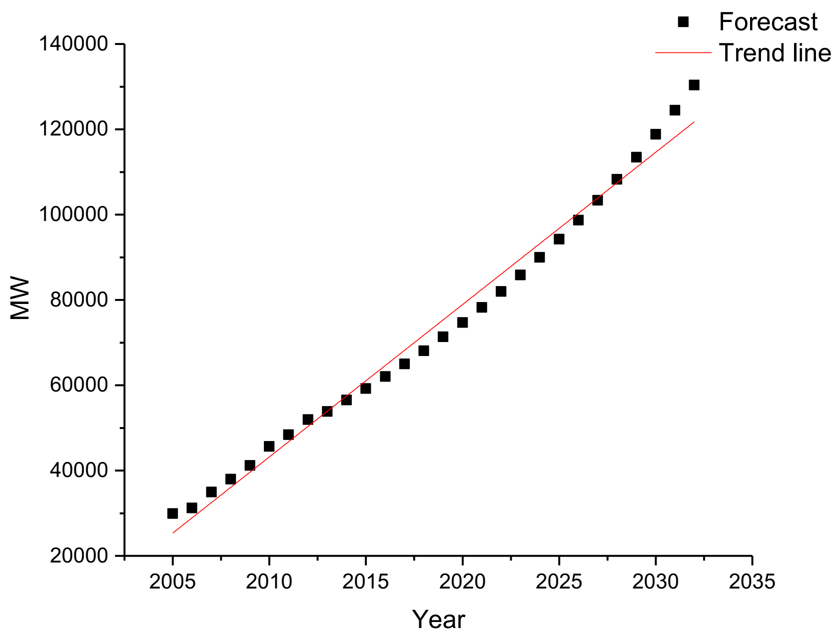


Figure 3.16 Peak demand forecast for KSA using average annual growth rate energy demand

The second model is a simple linear regression where an extrapolation for the available historical data from 2005 to 2014 was carried out to compare it with the estimated numbers obtained using a compound growth model. Excel software was used for this computation using trend analysis function to estimate the energy demand up to 2032. The number at 2020 is a little higher but it is much lower in 2032 compared with SEC's prediction for the chosen years of 2020 and 2032: 76,168 MW and 113,881 respectively. This might not be a reliable analysis because linear regression assumes a linear relationship between dependent and independent variables as well as no autocorrelation.

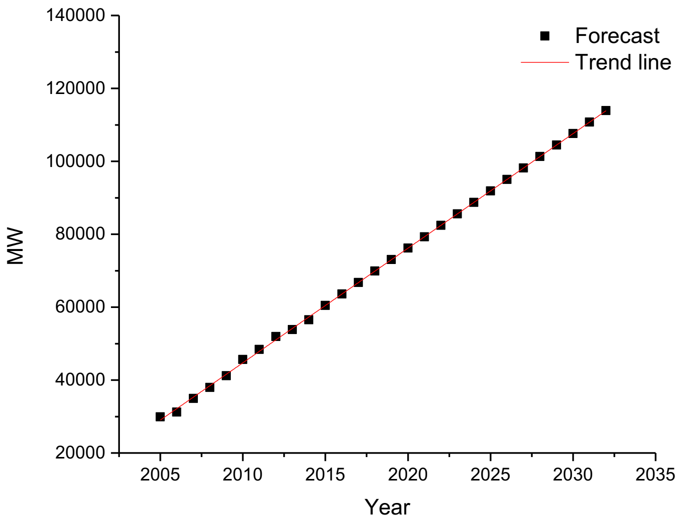


Figure 3.17 Trend analysis method to forecast KSA load

A third model is deterministic straight-line demand forecasting adopted from [153] was used to forecast electric load by fitting the model to the historical data. The fundamental idea of this model is to optimise for a curve-fitting model by minimising the peak demand, and then solve for the parameters to predict the future demand. This model was chosen because the available historical data showed more of a straight line trend, which this model provides appropriate computation of. The model optimises the peak demand using equations (3.3), (3.4) and (3.5).

$$J = \Sigma_{K=1}^{n}(e(k))^2 = \Sigma_{K=n}^{n+1}(d_P(k) - a - bk)^2 \qquad 3.3$$

where J refers to the sum of the square of $e(k)$, and a and b are stochastic variables.

$$\mathrm{E(k)} = \int_{\mathrm{t_k}}^{\mathrm{t_{k+1}}} \mathrm{d(t)dt} \qquad \mathrm{d(t), t_k \leq t < t_{k+1}} \qquad 3.4$$

where $e(k)$ measures the distance of data from the model at year *(k)*. Future time intervals are described as (t_k and t_{k+1}).

$$d_P(\mathrm{k}) = a + bk \qquad 3.5$$

where $d_p(k)$ gives the peak demand at a given year in MW. This model was computed using Matlab software curve fitting, which found parameters a and b, and then putting them into equation (3.5) to give the peak demand in a given year. This model revealed even more conservative numbers for energy demand peak by 2032 as it is less than the other two models, as shown in Figure 3.18. Peak demand was found to be 79,310 MW in 2020 and 110,739 in 2032, which is significantly less than the numbers obtained from the trend analysis.

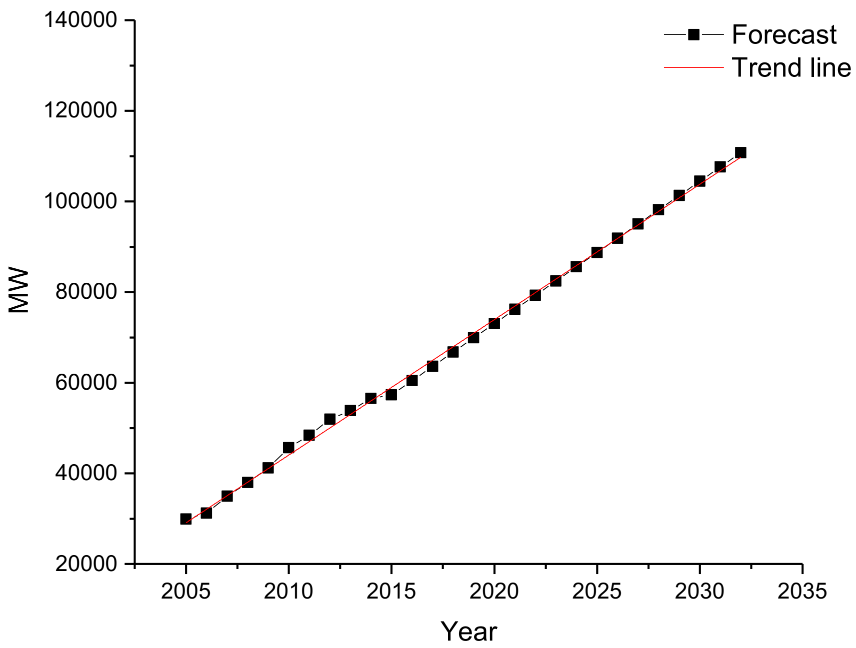


Figure 3.18 Demand forecast using deterministic model

The three models are compared with each other in Figure 3.19, which shows the three different scenarios. Electricity forecasting has always associated entailed uncertainty because it is sensitive to a large number of parameters such as weather, econometrics, population, etc. In the demand forecast the external trends follow the same assumptions as the SEC made in their report [152]. The forecast models were trained on historical data and the future demand estimated based on the projection of these external factors.

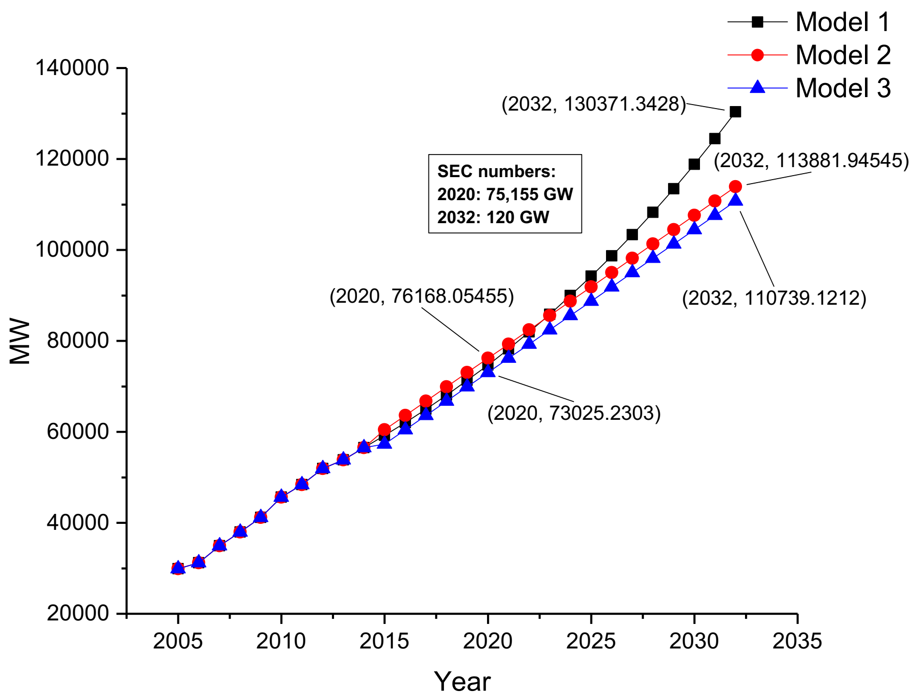


Figure 3.19 Comparison of different demand forecast models

3.8 Summary

In this chapter, power generation and consumption in KSA were studied independently. In relation to generation, available capacity, fuel, type of technology and producer and how much energy is being produced were discussed. In relation to consumption, the historical data provided by SEC was used to undertake an analysis. Analysing the historical data provided an opportunity to decide several factors, ranging from investigating indicators of supply and demand for the Saudi power system, to measuring average annual growth rate for multiple things, such as consumption, fuel and generation etc. The characteristics of each load sector and operating area were examined. The overall energy consumption by sector was compared with customers subscribed to that sector. The tariff experience in the KSA was discussed, reviewing the timeline and the structure of the tariff system since it is still administrated by the government and heavily subsidised. The system demand over a one-year period was also modelled using hourly time series; this included the entire system and each operating area. Insights into the daily load curve shape in each operating area were provided considering seasonal variation. Finally, three different models were used to generate an electric load forecast for KSA up to 2032 under constant parameters based on numbers published by SEC. Different tools were used to compute these models, which showed some differences; the projection provided by SEC predicted the greatest demand. Further analysis could be carried out on the data, but this is an area for further work.

Chapter 4 **Solar Energy Resources**

4.1 Introduction

The previous chapter was devoted to studying and analysing energy demand in the KSA, which helped to understand the pattern and areas that have the greatest energy consumption. The analysis included power generation and the tariff experience in the KSA that affects energy consumption in one way or another. The demand of the KSA was then modelled and future demand was predicted. This study will be extended in this chapter to include an analysis of solar energy resources in the KSA. It is imperative to add renewable generation to the energy mix in the KSA in the coming years in order to utilise these free resources and mitigate fossil-fuel consumption.

4.2 Solar Resources

There is no doubt that the importance of solar resources in the KSA will increase in the 21st century due to dwindling fossil fuel resources and the world transition to renewables. It is very important to have the most accurate data on solar resources to study and analyse when proposing the deployment of large-scale facilities. This is required to minimise the financial and technical risk and better optimise planning and location of solar power plants. However, in the KSA there has been no long-term study of these resources, although attempts have been made on a few occasions. It is believed that earlier measurements of solar radiation in the KSA were limited by less understanding of temporal and spatial characteristics, as will be discussed later in this chapter.

In order to assess the solar resources in the KSA, a large amount of data has been collected, both new and old. These data will be investigated separately, including satellite-based and ground-based measurements. In terms of satellite-based data there are very different sources of long-term data, but this research prefers to use the locally available data that has provided a reference for a number of studies in the KSA due to their quality. This is generally not a problem in the KSA as solar irradiance levels do not vary significantly over an average hour.

4.3 Solar Resource Estimates

For several decades, Surface Solar Irradiance (SSI) has been of significant interest to scientists in the solar energy field. Its importance emerges from the fact that it provides the measurement of solar radiation hitting the surface of the Earth at a certain time and a certain location at ground level [154]. Vernay et al. define three different approaches that scientists have been using to address SSI: the first is ground measurements using physical equipment such as the pyrheliometer and pyranometer; the second is re-analysis weather and climate models; and the third approach is satellite-based images generated by geostationary satellites [155]. Cros et al. discuss in detail these means of obtaining solar irradiation data and assessed related issues to offer better accessibility and quality for users [156]. On the other hand, solar irradiation estimates can be acquired using different approaches and techniques, which has been discussed widely in the literature [157]–[159].

There have been local efforts by some countries to build their own networks for meteorological ground stations, as well as efforts by the scientific or international community through programmes such as the Baseline Surface Radiation Network (BSRN) [160] and Global Atmosphere Watch, which are both archived in the World Radiation Data Centre (WRDC) controlled by the World Meteorological Organisation (WMO). BSRN is one of the World Climate Research Programme (WCRP) projects targeting solar radiation in order to understand its effects on climate change. This recorded data can be used to assess different locations, providing more accuracy or even validating the satellite-based measurements. Re-analysis models are another method by which to study solar resources through blending observation and weather forecast model output to come up with a reliable numerical measurements for the climate system [161]. This has been discussed more widely with the comparison of different models in [158] and [159]. Examples of common re-analysis data sets are ERA-interim from the European Centre for Medium-range Weather Forecasts (ECMWF) and the Modern-Era Retrospective Analysis for Research and Application (MERRA) by NASA. Satellite-based models are a common methodology and this is the third means by which to obtain different components for solar resources. Zarzalejo et al. used satellite images to derive global horizontal radiation with a new statistical approach [163]. In [164], Perez et al. used this to derive several indicators, including DNI and GHI for certain locations. This satellite-based approach uses a geostationary satellite that is able to get images about the state of the climate and atmosphere on a continuous basis. This subject has been reviewed and discussed in several studies, for example [162] and [163].

Each of the above approaches has its advantages and disadvantages, such as higher temporal resolution in ground measurements, while this is sometimes lower in satellite-based models and the reverse when talking about spatial resolution. However, sometimes there is no choice but to use what is available amongst these approaches. In this study, different approaches were reviewed in the KSA to be used when deriving data for solar resources. All the available models were investigated with a view to engaging the most reliable, recent and accurate data. Four different approaches were used in the KSA to monitor solar resources throughout the kingdom, two of these are ground-based networks and two are satellite-based models; all four are discussed in detail in the next sections.

4.3.1 KACST Network

The first serious engagement in solar measurement studies in the KSA was in 1987 through cooperation between KACST and the US Department of Energy (DOE) represented by NREL. The study was carried out from 1993 to 2000 to assess solar radiation resources in the KSA through ground-based measurements. Previous to this, measurements were taken by several entities in the kingdom, including the Saudi Meteorological and Environmental Protection Agency (MEPA), universities, and the Saudi Ministry of Agriculture and Water, recording most historical data using bimetallic actinography, which did not provide accurate data whenever it was partially cloudy. The bimetallic actinography is an old instrument used to record and observe daily variations in radiation [167].

KACST and NREL created a network that has 12 monitoring stations distributed all over the kingdom to measure solar radiation components (GHI, DNI and DHI) as well as relative humidity and ambient temperature [168]. KACST worked with Eppley Laboratory to design some parts of the model and they later introduced their Hickey-Frieden absolute cavity radiometer as the calibration reference. Sites for monitoring stations were selected based on some criteria, such as personnel availability, power and telephone reliability, no obstruction of the horizon and representative climate [168]. The selected sites are shown in Table 4.1 and more details about the network, data collection and quality, design and operation, calibration and instrument characterisations can be found in [169].

It appears that only about four stations were available for comparison during the two stages of this contract, providing the monthly mean daily total. This model is considered to be limited and outdated and it does not provide the breadth and depth needed to explore solar resources in Saudi Arabia due to the small number of monitoring stations and parameters being compared for the area of the KSA and the maintenance and aging of equipment [170]. At the same time, it does provide preliminary impressions about solar energy in the KSA and confirms the high insolation level in Saudi Arabia. Several small-scale projects have since been undertaken based on this data and they have used it against satellite-based models to improve estimations. This model will not be used in this current study; however, it is part of the K.A.CARE model, providing early insights into challenges and solar variability in the kingdom. In the long-term, some of these stations could be used with the K.A.CARE model to study inter-annual effects in the KSA.

Station	Latitude (°N)	Longitude (°E)	Elevation (Meters)	Started Operating
Abha	18.23	42.66	2039	06/1995
Al-Ahsa	25.30	49.48	178	01/1995
Gizan	16.9	42.58	7	06/1995
Qassim	26.3	43.77	647	11/1994
Jeddah	21.66	39.15	4	05/1996
Madinah	24.55	39.70	626	09/1995
Qaisumah	28.32	46.13	358	08/1995
Sharurah	17.47	47.11	725	06/1995
Jouf	29.79	40.10	669	08/1995
Solar Village	24.91	46.41	650	11/1994
Tabouk	28.38	36.61	768	08/1995
Wadi Aldawaser	20.44	44.68	701	04/1995

Table 4-1 Monitoring stations distribution across the KSA [168], [169]

4.3.2 Geo-model

The importance of considering solar resources has been increasing in the last few decades as it is crucial to evaluate sites for an energy system during the planning stage and before deployment. This may save a lot of money that can instead be invested in a better location and technology. Ground-based measurements have long been scarce and sometimes expensive when they are available, which makes satellite-based models an attractive option. However, this does not mean that ground-based measurements are always better by default; satellite-based data can offer better quality and accuracy, especially when measuring with faulty or unmaintained equipment [171].

A number of satellites have been developed and designed by different countries to continuously monitor the Earth for observation purposes. Weather-related satellites are classified as orbiting satellites and Geostationary Operational Environmental Satellites (GOES). These satellites cover the entire globe, providing intensive data and images related to weather, including solar irradiation. Thus, an estimate of solar irradiation is available at any specific time and location, which is impossible in ground measurements given the current number of distributed ground stations all over the world. The satellite models also offer the advantage of high spatial resolution since they cover a wide geographical area. In [155], the authors reviewed most of the available satellite-based models, outlining the advantages and disadvantages of satellite-based models and ground-based measurements.

In the current research, K.A.CARE provides data for the satellite-based model, Geo-model, that has been used in the KSA to offer estimates of solar radiation for the period of 1994–2012. This model is based on METEOSAT observations of the geostationary satellite from the ECMWF Monitoring Atmospheric Composition and Climate (MACC) model. The METEOSAT model has relatively high temporal resolution, whereby images of the same place are taken every 15 minutes and then sent back to be processed and analysed. This includes monthly-averaged aerosol optical depth, which essentially provides measurements of particles, such as dust or smoke, that are blocking solar irradiation by absorbing or scattering the sunlight. It has been reported that the data uncertainty of this model ranges between ±8% and ±15% for the DNI and ±4% and ±8% for the GHI, while the spatial resolution is 1 km × 1 km [171].

4.3.2.1 Geo-model Global Horizontal Irradiation

Using the geo-model estimates, monthly-averaged daily total series of maps were produced for this study using the Renewable Resource Monitoring and Mapping (RRMM) tool developed by K.A.CARE [172]. This investigation aims to identify the spatial variability within the KSA, including both irradiation DNI and GHI. The common characteristics found in these maps will also be compared to other maps in the following section using a different satellite model. Finally, observations and analysis of these maps will help to decide on the best location for several solar power plants through this research. Figure 4.1 shows a map of the historical annual average GHI in $Wh/m^2/day$ over the period of 1994–2012; the stars represent the major cities in the kingdom. Solar irradiation is concentrated more towards the north-western side of the country.

More maps were produced to look closely at GHI monthly variation, as shown in Figure 4.2. From left to right this begins with January in the top left corner and ends with December in the bottom right corner. Overall, the Geo-model showed a high solar irradiation across the KSA, ranging between 5.5 $kWh/m^2/day$ as the lowest monthly averaged daily total GHI in Al Khafji, located in the eastern part of the country, and 6.5 $kWh/m^2/day$ as the highest in Najran in the southern part of the country. There were about 43 different sites, each in a different city, and sometimes with more than one in a region to facilitate this analysis.

It is clear that there is a high spatial variability from October–March during the winter season, which means that the southern region has a superior GHI. On the other hand, the solar irradiation of GHI reaches the highest monthly-averaged daily total during the summer season, as the maps in Figure 4.2 (from April–September) show. The city of Tabuk receives the highest GHI during the summer and it gets around 8.4 $kWh/m^2/day$ in June and July. The eastern and central areas get the lowest GHI compared to the northern area, western coast and southern area. Al-Ahsa, Al Dhahran, Al Khafji and Dammam are different locations in the eastern part of the country and they have amongst the lowest GHI in the KSA according to the Geo-model estimates, ranging from 3.1 $kWh/m^2/day$ in December to 7.6 $kWh/m^2/day$ in June. Hafar Al Batin is located in the east, but it shows a better overall GHI, especially during the hottest summer months from May–September, averaged to 7.2 $kWh/m^2/day$. The eastern coast shows less solar irradiation than inland; for example, when comparing Al Jubail on the coast and Hafar Al Batin, which is inland, Hafar Al Batin has around 5.7 $kWh/m^2/day$, higher than Al Jubail, which has about 5.5 $kWh/m^2/day$, even higher than other coastal locations.

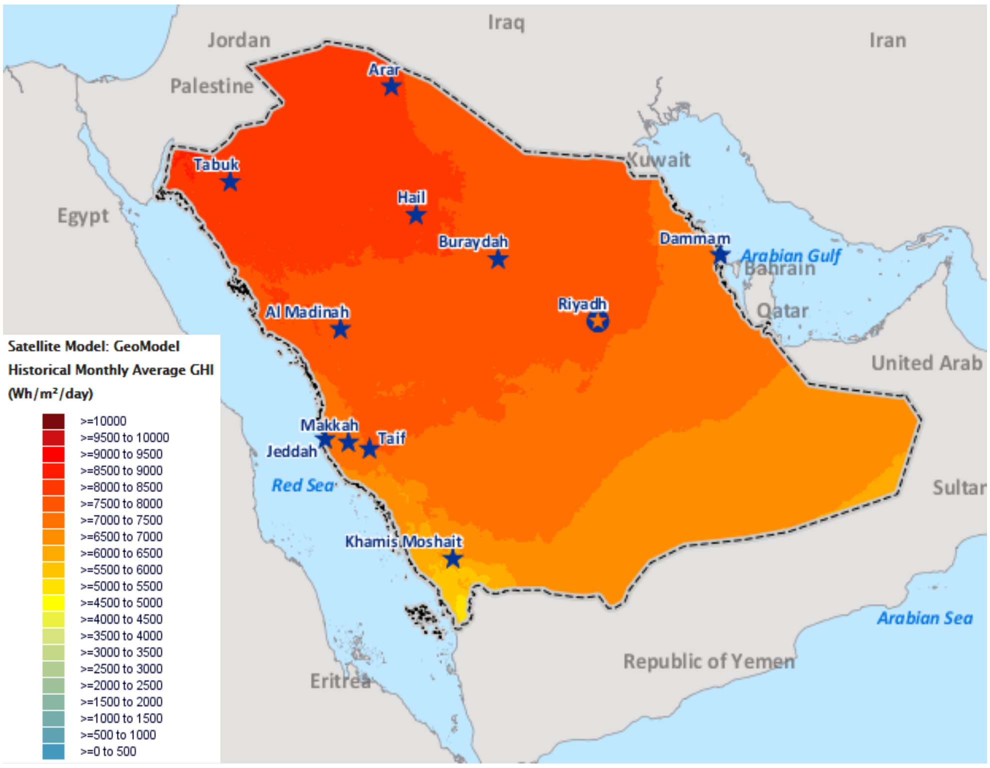


Figure 4.1 Historical annual average GHI map for the geo-model

In the central area, different locations were analysed (e.g. Al Dawadmi, Al Kharj, Aluyaynah, Afif, Qassim, Majmaah and Riyadh) and data showed less GHI in areas around Riyadh, where it gets low in the winter, ranging from 3.9 kWh/m^2/day in December in the Riyadh area; the highest is in Afif at 7.8 kWh/m^2/day in the month of June. All months have been averaged for locations in the central area and this shows that Afif has the highest GHI with 6.2 kWh/m^2/day. Al Dawadmi comes next with a range of 6.1 kWh/m^2/day, whilst other locations in the central area have a monthly-averaged daily total less than 6.0 kWh/m^2/day.

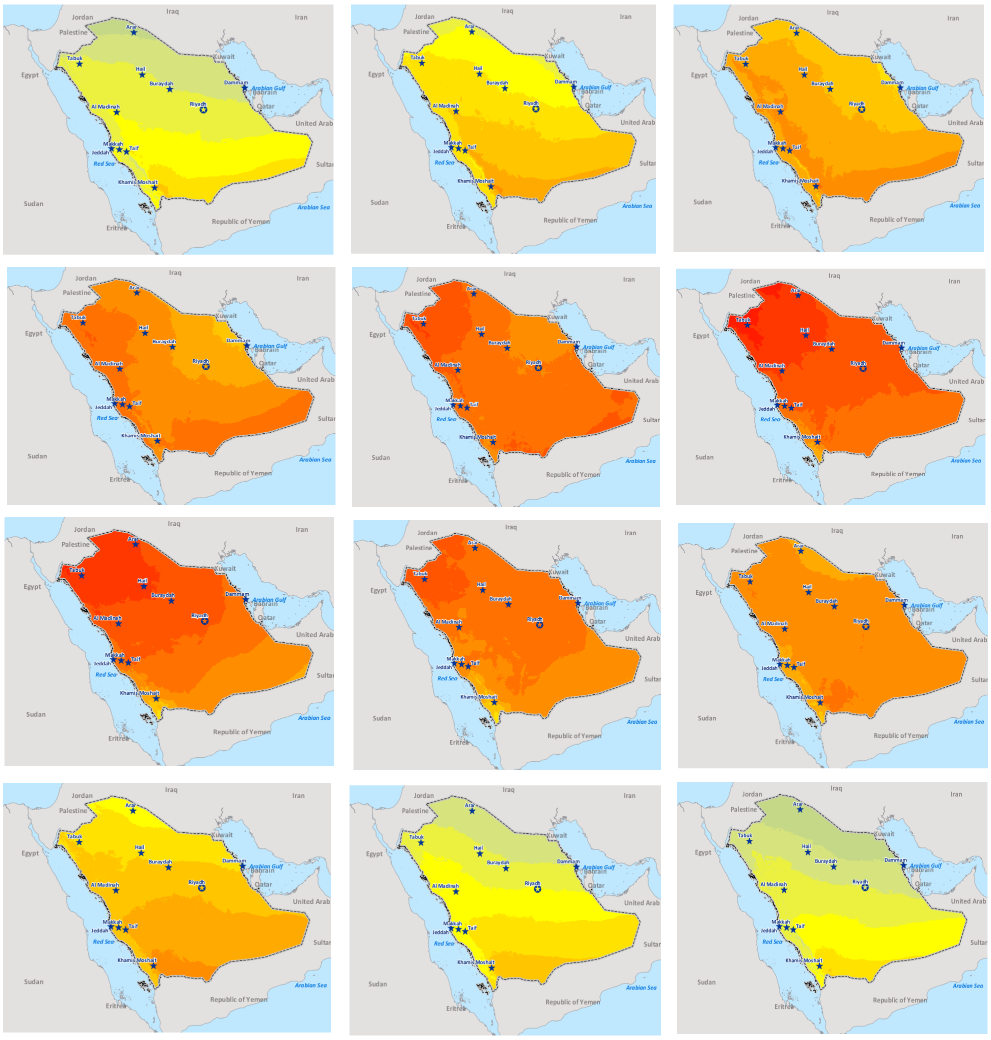


Figure 4.2 GHI monthly-averaged maps of Geo-model from Jan (top left) to Dec (bottom right)

A similar pattern as the east coastal and inland areas is exhibited in the western area where inland shows much higher irradiation than coastal areas. For example, GHI does not exceed 6.1 kWh/m^2/day in western coastal areas such as Ynbu, whilst inland western areas receive above 6.3 kWh/m^2/day, as in Taif. For clarification, the maps here are divided the same way the electricity operating areas were divided in the second chapter. Hence, the western area includes cities in the northwest, such as Tabuk and Timaa, and the eastern area includes up to Arar. Therefore, in this entire analysis the north area is divided between west and east, which makes this consistent with the analysis in previous chapters.

4.3.2.2 Geo-model Direct Normal Irradiation

DNI solar maps of the monthly-averaged daily total have also been generated based on Geo-model solar estimates. Figure 4.3 shows a map of the historical annual average DNI in $Wh/m^2/day$ for the period of 1994–2012. The map presents the intensity of the solar irradiation gradient as it moves outwards from the centre towards the north and is highest in the north-western area. At the same time, the southern area shows overall poorer irradiation and this should be looked at closely by investigating different locations within the southern area in different months. DNI is of particular interest to concentrating solar power plant applications and it therefore becomes an important factor when selecting concentrating solar sites to perform operational analysis for power plants in this study.

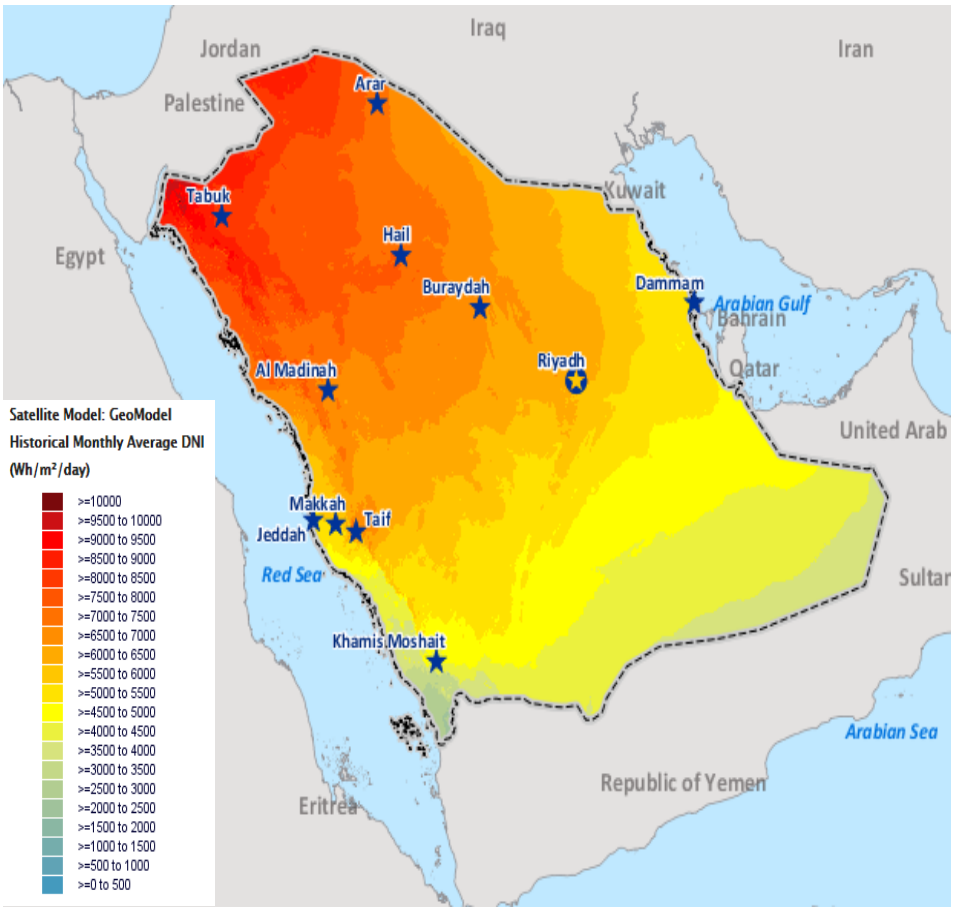


Figure 4.3 Historical annual average DNI map for the geo-model

Maps are generated for each month from January–December to closely follow the monthly DNI variation based on Geo-model solar estimates, as shown in Figure 4.4. Overall DNI in the KSA is promising and suggests significant potential when looking at the average amount of irradiation the country receives per year. After calculating the monthly-averaged values for more than 43 cities all over the KSA, Jazan in the south-western area near the coast showed the lowest annual DNI with an average of 4.2 kWh/m^2/day. Most cities located in the eastern area and more specifically those located on the coast come after Jazan since it shows low DNI ranging from 4.4-4.8 kWh/m^2/day. The central area obtains moderate irradiation, with the highest in Afif with 5.9 kWh/m^2/day, and the lowest in Al Uyaynah with 5.3 kWh/m^2/day. Taif in the western inland area is one of the places with highest

DNI. The north-western area records the highest irradiation, with Tabuk the highest at 7.0 kWh/m^2/day. The north-western coastal area comes after Tabuk in terms of the highest DNI (e.g. Hagl, Timaa and Duba).

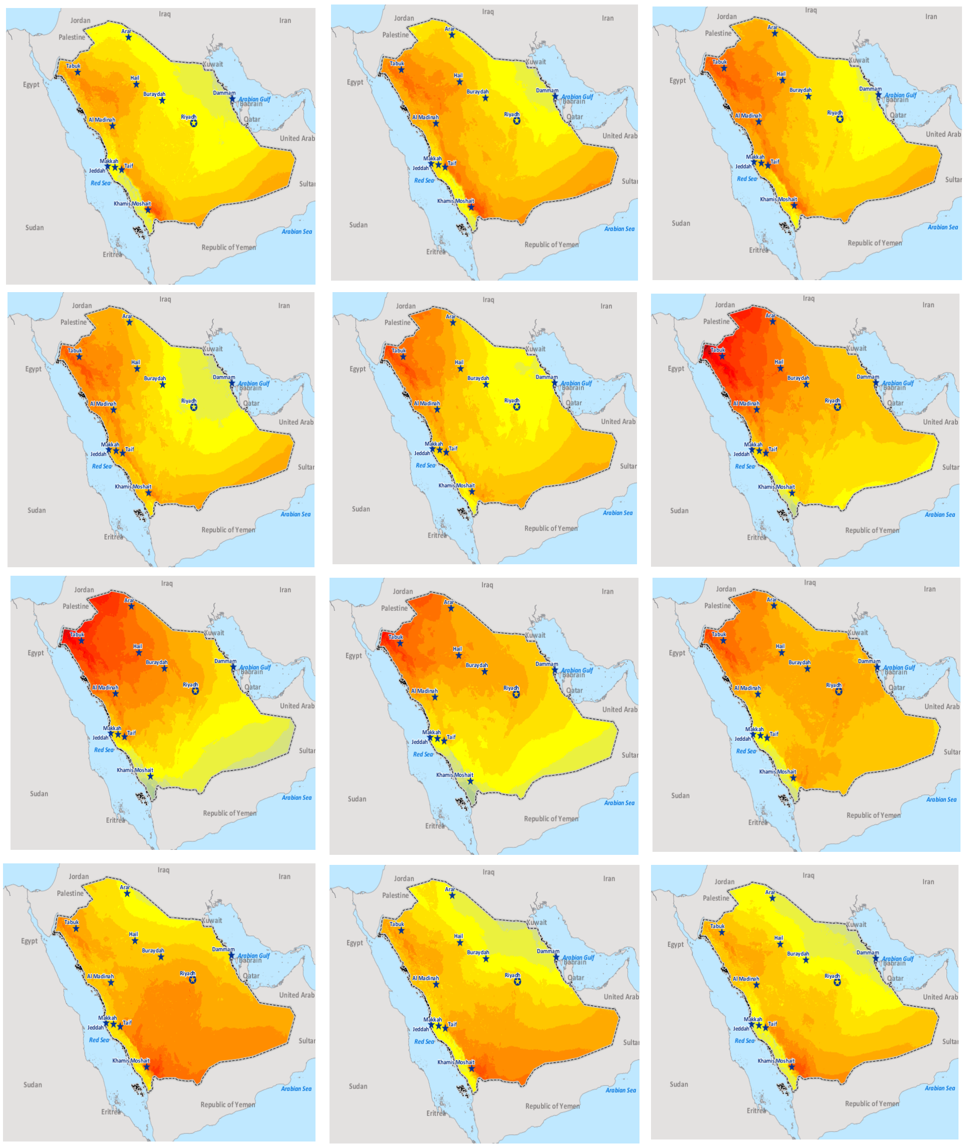


Figure 4.4 DNI monthly-averaged maps of geo-model from Jan (top left) to Dec (bottom right)

4.3.2.3 Geo-model Solar Components

In order to develop a clearer picture of the variability related to space and time, numbers are listed in Table 4.2 to show the solar components in all four different regions.

Region	Location	Avg. daily total GHI (Wh/m²)	Avg. daily total DNI (Wh/m²)
Central	Afif	6,228	5,942
	Al Dawadmi	6,132	5,733
	Al Uyaynah	6,069	5,304
	Al Kharj	5,959	5,245
	KACARE City	6,125	5,611
	KACARE HQ	5,842	5,712
	Majmaah	5,969	5,473
	Layla	6,197	5,438
	Shaqra	6,031	5,520
	Qassim	5,953	5,485
Eastern	Al Ahsa	5,770	4,811
	Al Dhahran	5,718	4,840
	Al Khfji	5,504	4,539
	Al Jubail	5,542	4,457
	Arar	5,662	4,681
	Dammam	6,058	6,086
	Hafar Al Batin	5,705	4,998
Southern	Abha	6,243	6,217
	Al Baha	6,281	6,223
	Al Farshah	6,222	5,844
	Najran	6,524	6,025
	Jazan	5,768	4,193
	Sharurah	6,497	5,900
	Rania	6,334	5,943
	Wadi Addawasir	6,319	5,509
North & Western	Al Hanakiyah	6,208	6,180
	Al Jouf	5,980	6,102
	Al Qunfudah	5,933	4,630
	Al Wajh	6,155	6,199
	Duba	6,171	6,446
	Osfan	6,095	5,306
	Hada Al Sham	6,119	5,353
	Hail	5,791	5,646
	Hagl	6,071	6,699
	Jeddah	6,066	5,161
	Madinah	6,154	6,083
	Makkah	6,108	5,281
	Tabuk	6,254	6,980
	Taif	6,399	6,485
	Thuwal	6,080	5,305
	Timaa	6,232	6,570
	Umluj	6,177	6,067
	Yanbu	6,193	5,919

Table 4-2 Annual averaged daily total of geo-model solar components

Data was collected for locations that will match ground-based measurements from the RRMM network, which will be discussed later in this chapter. Data from 43 sites were investigated and their annual averaged daily total of GHI and DNI was then analysed to show the amount of solar irradiation received across the entire country.

The number of sites chosen per region differs from one to another, with the western area containing the largest number. The western region clearly has a greater potential for solar irradiation; however, there were enough sites distributed over all areas to understand the patterns and variabilities. Using statistical analysis to calculate inter-annual variability across the 43 selected sites, the coefficient of variation (COV) was considered. COV is defined as [173] standard deviation percentage of annual mean of GHI or DNI relative to (1994–2012) average of the annual mean, as in equation (4.1). This was used to quantify inter-annual variability of annual mean daily total irradiation for all 43 sites.

$$\%\ \mathrm{COV} = \frac{\sigma_t}{E_T} \times 100 \qquad (4.1)$$

Where σ_t is the standard deviation for each solar component (GHI & DNI) in (kWh/m^2) and E_T is mean values of each solar component (GHI and DNI) in (kWh/m^2). Figure 4.5 shows the computation results presenting the extent that both GHI and DNI could vary across the country. In comparison to DNI, GHI showed a significantly larger variation, which consequently may affect the power output from the PV solar power plant. In most parts of the country GHI was higher than DNI, except the southern area, which showed a similar or lower variation that could be related to mountains and type of topography in the area. The eastern part of the country exhibits the highest variability in comparison to other parts of the country. On the other hand, there is less variation in DNI except in some places, which could be the effect of aerosol or clouds.

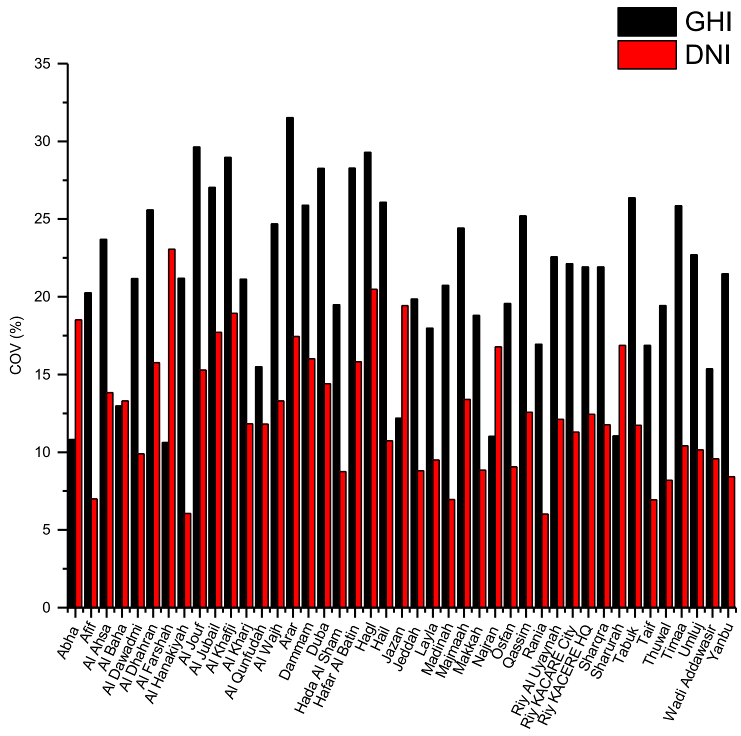


Figure 4.5 Percentage COV of annual mean daily total irradiation from 1994–2012

4.3.3 SUNY Model

In addition to the models discussed above, State University of New York (SUNY) at Albany developed another type of satellite-based model that has been used in the KSA and provides data from the period of 1999–2013. This model was developed by Perez et al. and provides estimates of GHI and DNI based on METEOSAT observations of clouds and climatological averages of atmospheric constituents, such as perceptible water vapour, stratospheric ozone, and aerosol optical depth, using satellite imagery [164]. It has a temporal resolution of monthly mean daily total radiation derived from hourly data. The spatial resolution of the SUNY model is 10 km × 10 km or 5 km at sub-satellite point since geostationary satellites are classified based on the longitude of the sub-satellite point on the equator [67], [174]. Uncertainty for the SUNY model was reported to range between ±8% for GHI and ±15% for DNI in the optimal condition [175].

4.3.3.1 SUNY Global Horizontal Irradiation

Solar component data generated from the SUNY model will provide more insight into solar resources in the KSA. This model will also be useful in the current research to compare it with the Geo-model analysed in the previous section. An investigation of the SUNY model has been carried out with a similar process of analysis done for the Geo-model for 43 different sites, each in a different city. A monthly-averaged daily total series of maps was produced using the RRMM tool to visualise the spatial variation within space and time across the KSA. A map of the historical annual average GHI in (Wh/m^2/day) from the period 1999–2013 is shown in Figure 4.6. This map shows an almost uniform distribution of GHI irradiation with the exception of slightly higher irradiation in the southern area. In contrast, the Geo-model shows that more GHI is concentrated in the northern part of the country.

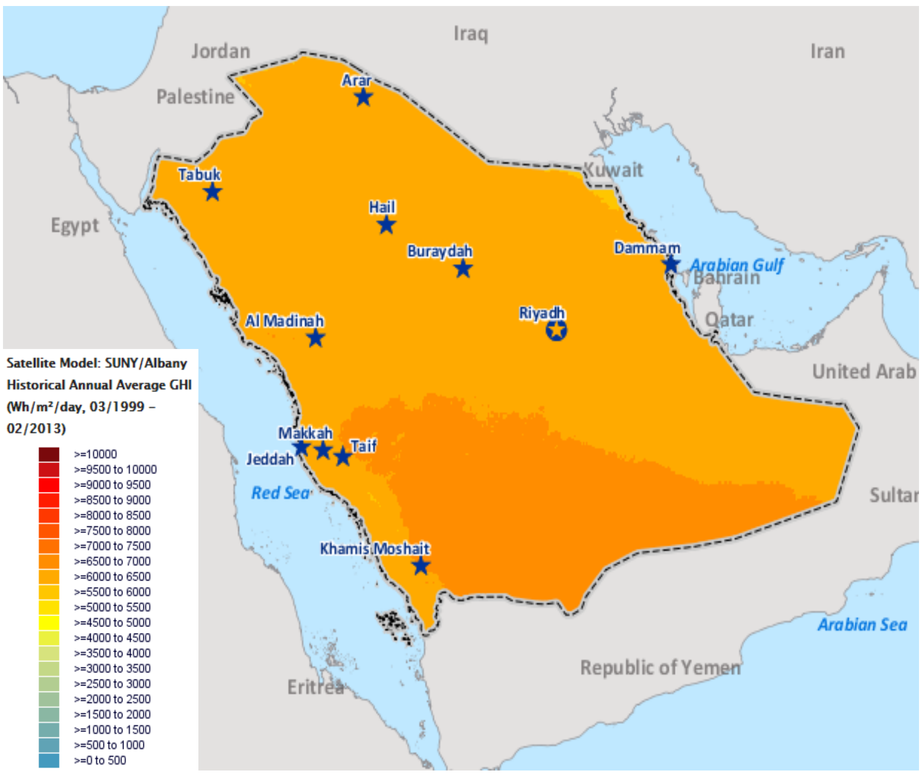


Figure 4.6 Historical annual average GHI map for the SUNY model (Wh/m^2/day)

A series of monthly maps was produced to look independently at each month and the amount of irradiation per area. The maps are shown in Figure 4.7, starting with January in the top left, to December in the right bottom corner. In general, the SUNY model shows an overall high GHI, with approximately 200 $Wh/m^2/day$ more than the Geo-model for most locations in the KSA. However, both models show corresponding places to have similar trends of insolation. In other words, sites with higher irradiation in the Geo-model tend to be the same in SUNY model. To illustrate, the southern part of the country seems to receive the highest GHI in both models and the eastern part the least. Thus, the overall GHI ranges between 5.7 $kWh/m^2/day$ in Al Jubail and 6.7 $kWh/m^2/day$ as the highest in Sharurah.

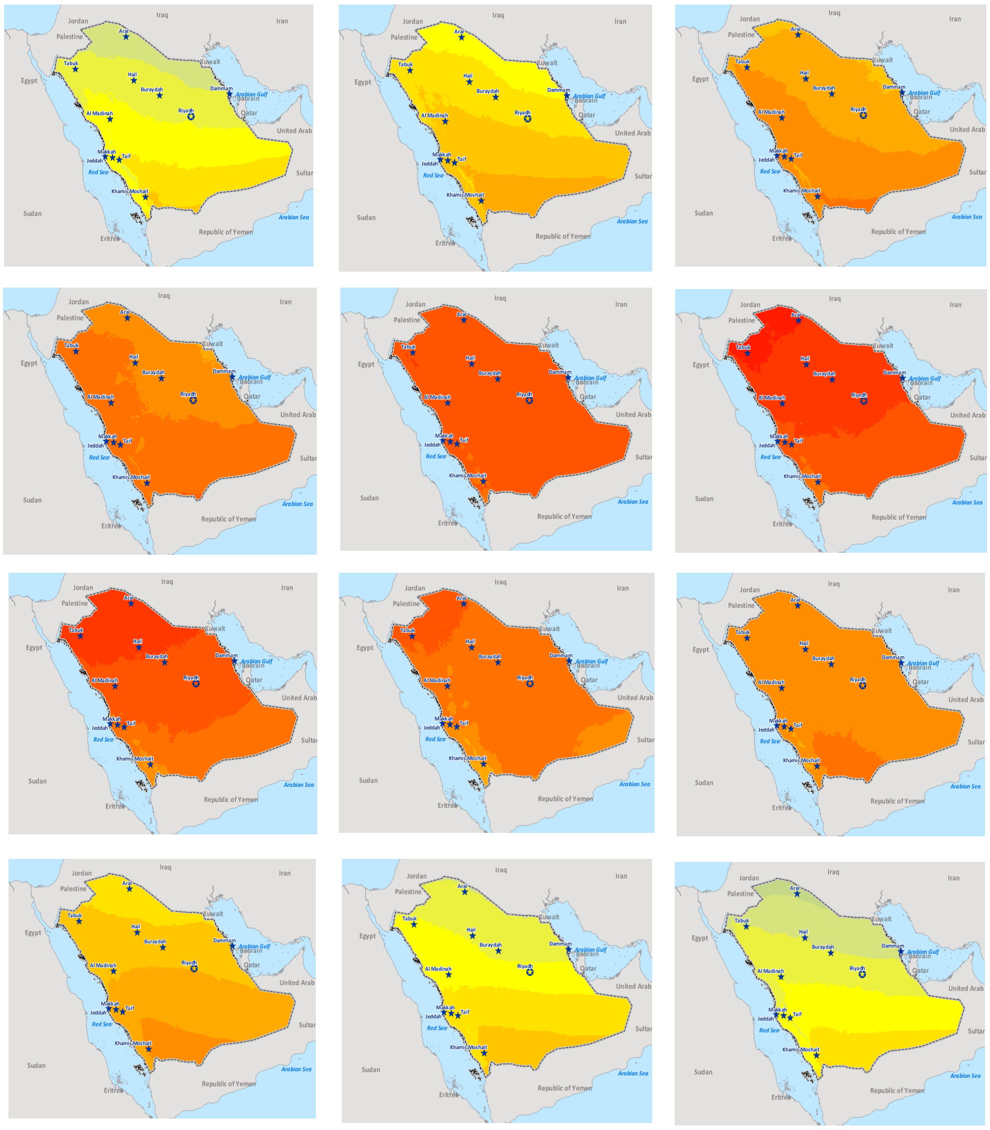


Figure 4.7 GHI monthly-averaged maps of SUNY model from Jan (top left) to Dec (bottom right)

The SUNY model has a similar trend of spatial variation as the Geo-model over the seasonal variation period. During the winter season the southern part of the country becomes the most favourable area for PV plants, as shown in the maps from October to April. This illustrates that Sharurah and Najran in the southern part of the country have the highest annual mean daily total irradiation all year around. However, the inland and coastal north-western area has higher GHI from May to September, with Tabuk the highest at 8.5

kWh/m^2/day in June. The eastern part of the country has the least GHI all year round, with the coastal areas the lowest. Hafar Al Batin in the eastern part showed higher irradiation in the SUNY model, with 6.0 kWh/m^2/day, compared to 5.7 kWh/m^2/day in the geo-model. This reflects the same pattern as it is higher than coastal sites such as Al Jubail and Al Khafji.

Layla and Afif have the highest GHI in the central area. Coastal areas, whether in the western or eastern area, show a similar pattern in both models, where GHI is higher inland and lower but not significantly so in coastal areas. In general, the SUNY and Geo-model shows similar solar characteristics and variation patterns all over the Kingdom. The numbers might be slightly higher in one or another, but ultimately both suggest similar regions that receive the highest insolation.

4.3.3.2 SUNY Model Direct Normal Irradiation

Based on the SUNY model, monthly-averaged daily total solar maps were produced for DNI in the KSA. A map of the historical annual average DNI in (Wh/m^2/day) for the period 1999–2013 is shown in Figure 4.8. Clearly, there are areas that receive more radiation than others, as has been noticed in the northern and southern areas, which are almost the same colour. Generally, these two areas are dominant in terms of DNI-receiving in both the geo-model and the SUNY model for the entire year. Tabuk in the north has the highest annual-averaged daily total DNI, with 6,956 Wh/m^2/day. Sharurah, Najran and Timaa come next and these are locations from both southern and northern areas that range from 6.5–6.9 kWh/m^2/day.

The central, south-western coast and inland western area exhibit almost the same overall DNI that ranges from 6.3-6.5 kWh/m^2/day. The eastern part of the country shows the least irradiation, particularly near the coastal area. To analyse variation month by month and investigate solar patterns, maps were produced from January–December, as shown in Figure 4.9. A pattern is occurring in both models that shows seasonal variation in the summer and winter periods. In winter time the southern area has more DNI than any other area in the country, while during the summer and very hot climate period, more DNI is concentrated in the north-western area. At the same time, in the SUNY and Geo-model, during the summer the south-western coastal area still receives less DNI than it receives in the winter.

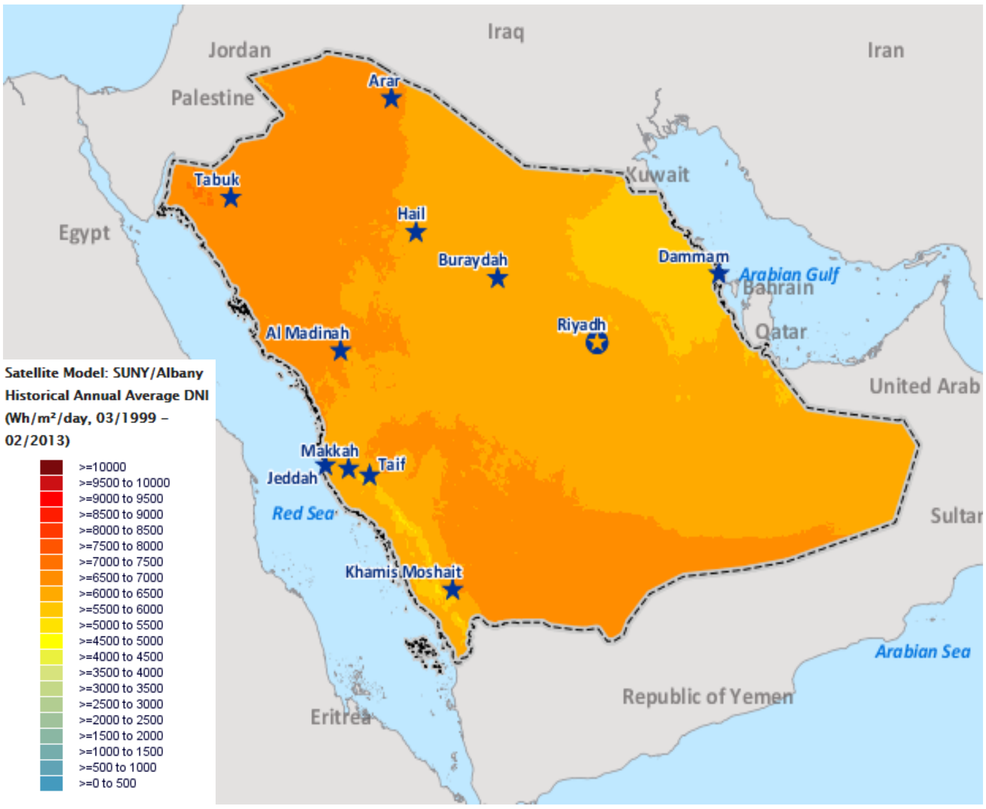


Figure 4.8 Historical annual average DNI map for the SUNY model (Wh/m^2/day)

In summary, the Geo-model and SUNY model present a similar pattern across the KSA, whether in space or time. The SUNY model showed higher numbers in general for most of the 43 sites selected in different regions. The difference between the figures is not significant, except in western and eastern areas. For example, in the Geo-model Al Khfji had 4.5 kWh/m^2/day, whilst in the SUNY model it had 5.6 kWh/m^2/day. Similarly, in the south-western coastal area Jazan had 4.2 kWh/m^2/day in the geo-model, but much higher in the SUNY model, with an irradiation of 6.4 kWh/m^2/day. It should be taken into consideration that the periods for running the two models are slightly different in terms of spatial and temporal resolution. The KSA also has a diverse topography, where some locations are 2,000 m above ground level and others are just 1 m. The south-western part of the country is mostly mountains, while the southern belt is just arid desert. There is no complex topography in the eastern part, but it is high in humidity and cloudiness, while there is more dust in the eastern inland areas.

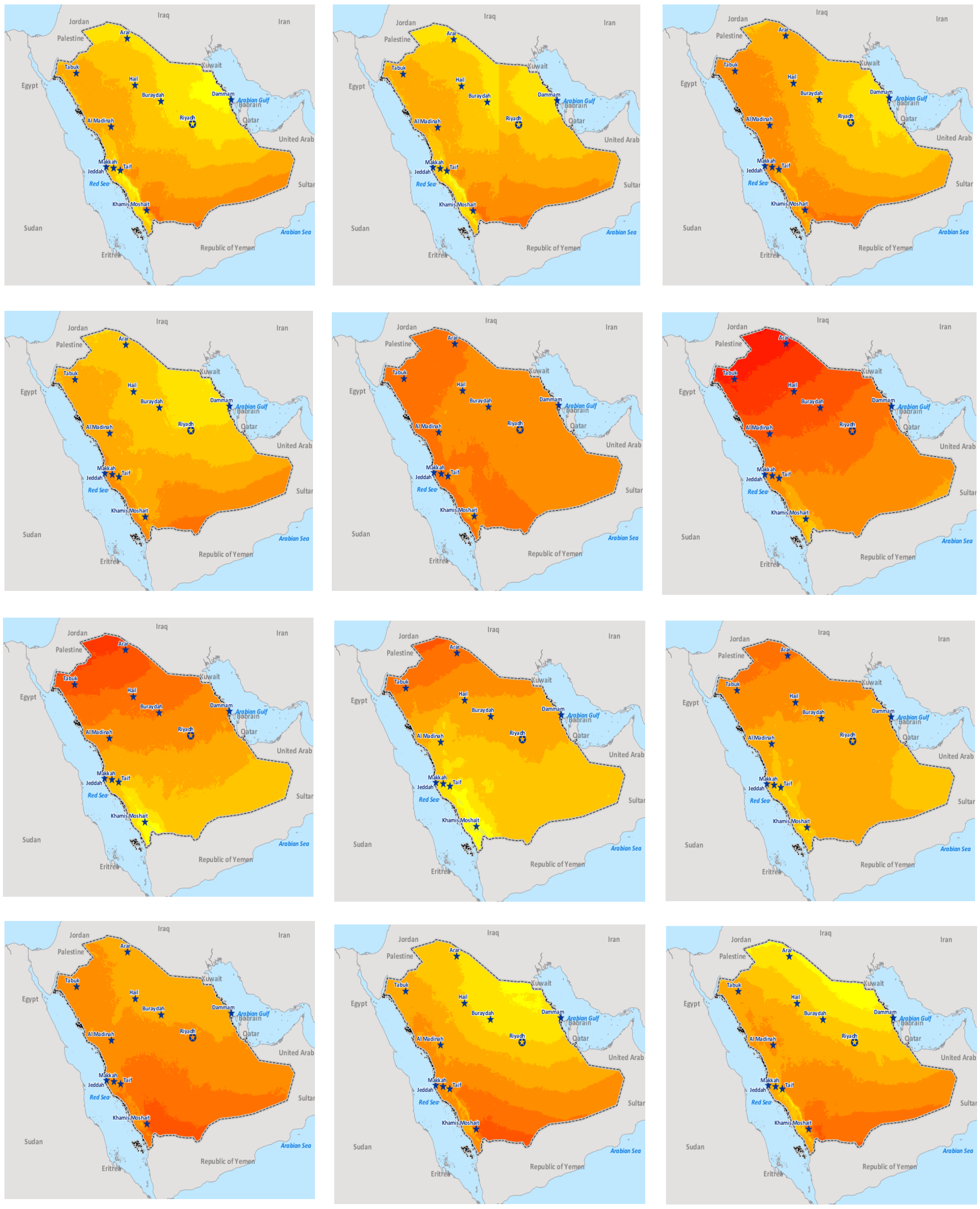


Figure 4.9 DNI monthly-averaged maps of SUNY model from Jan (top left) to Dec (bottom right)

4.3.3.3 SUNY Model Solar Components

Details of sites and the annual-averaged daily total of both solar components used in this study are provided in Table 4.3..

Region	Location	Avg. daily total GHI (Wh/m^2)	Avg. daily total DNI (Wh/m^2)
Central	Afif	6,398	6,342
	Al Dawadmi	6,344	6,242
	Al Uyaynah	6,308	6,160
	Al Kharj	6,329	6,121
	KACARE	6,348	6,190
	City	6,313	6,167
	KACARE HQ	6,217	6,096
	Majmaah	6,507	6,379
	Layla	62,82	6,162
	Shaqra	6,240	6,227
	Qassim		
Eastern	Al Ahsa	6,170	5,890
	Al Dhahran	6,104	5,954
	Al Khfji	5,841	5,661
	Al Jubail	5,961	5,707
	Arar	6,066	6,530
	Dammam	6,048	5,836
	Hafar Al Batin	6,053	6,042
Southern	Abha	6,472	6,317
	Al Baha	6,401	6,246
	Al Farshah	6,486	6,308
	Najran	6,750	6,783
	Jazan	6,364	6,388
	Sharurah	6,767	6,875
	Rania	6,544	6,563
	Wadi Addawasir	6,610	6,584
North & Western	Al Hanakiyah	6,410	6,538
	Al Jouf	6,181	6,635
	Al Qunfudah	6,328	6,277
	Al Wajh	6,285	6,454
	Duba	6,260	6,566
	Osfan	6,365	6,439
	Hada Al Sham	6,372	6,369
	Hail	6,240	6,426
	Hagl	6,134	6,575
	Jeddah	6,375	6,475
	Madinah	6,466	6,664
	Makkah	6,386	6,358
	Tabuk	6,386	6,956
	Taif	6,504	6,450
	Thuwal	6,374	6,476
	Timaa	6,364	6,756
	Umluj	6,337	6,503
	Yanbu	6,378	6,515

Table 4-3 Annual averaged daily total of SUNY model solar components

More than 40 different sites were selected from all four regions in order to have a comprehensive understanding of the spatial variation for solar irradiation obtained from the SUNY model. The DHI component was intentionally not included in the two satellite models because it will be a part of the ground-based monitoring stations analysis used later for solar power plant studies. COV will not be presented for this model since it revealed similar patterns to the Geo-model in most locations

4.3.4 Renewable Resource Monitoring and Mapping (RRMM) Programme

The RRMM programme was initiated following the royal decree in 2010 to establish a new body to lead atomic and renewable activities in the KSA. K.A.CARE was established in 2010 and later, at the beginning of 2013, the RRMM network was deployed to monitor solar radiation on several parameters throughout the kingdom. The programme has been carried out to create an atlas with the assistance of local contributions from Saudi universities and institutions, as well as international collaboration with NREL and the International Renewable Energy Agency (IRENA). In 2016, approximately 46 monitoring stations were installed out of an intended 53 [172]. The monitoring systems were classified into three different tiers and each tier was configured to serve a number of objectives. The objective of this programme is to support renewables R&D in the KSA to find out about prospective resources and technologies for the future energy mix through high resolution data. Distribution of ground-based solar monitoring stations with their tier classification is shown in Figure 4.10. More details about each station tier and the specific location and elevation are presented in Table 4.4 and Table 4.5 respectively.

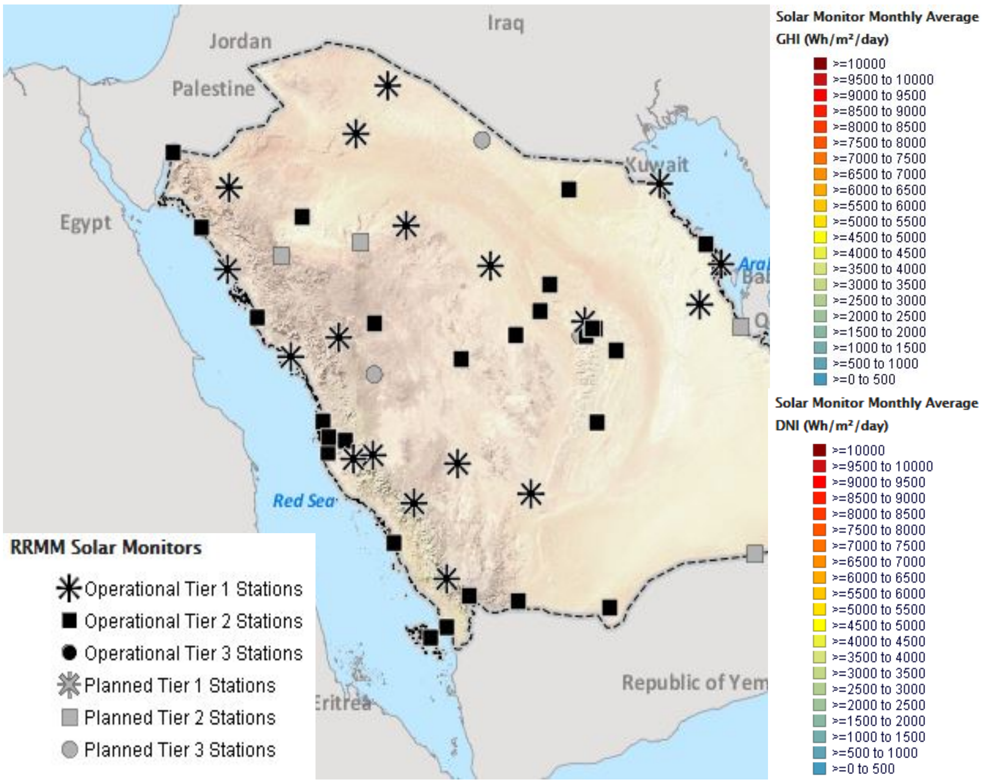


Figure 4.10 Monitoring station distribution and their classifications

To ensure quality and maintenance, K.A.CARE allocated the monitoring stations to partner hosts, such as research centres, universities and technical institutes. The tier of the station reflects its complexity and instruments. Tier 1 is the most complex configuration since it provides the highest quality and at the time of writing it is the most complete. Mid-range stations are considered to be tier 2, which focuses on providing fundamental solar resources, surface measurements and variability in complex topography. The third tier is simple stations and these are designed to be located in places with high potential to have solar power plants, with the task of defining resource variability. This type of station is very limited and at the time of writing none have been installed.

Station Type	Number of Stations Operating
Tier 1: Research with three different configurations	18
Configuration A: R&D laboratory: *full complement of radiometric instruments with independent and redundant solar radiation component data, plus basic meteorological instruments, and instruments measuring dust and horizontal variability.*	1
***Configuration* B:** Solar broadband and spectral monitoring: *all broadband solar radiometers, selected solar spectral radiometers and photometers, pyrgeometers, and basic meteorological instruments and instruments measuring dust and horizontal variability.*	3
Configuration C: Broadband baseline monitoring station: contains *fundamental broadband solar irradiances (DNI, GHI, DHI, and GTI), plus basic meteorological instruments.*	14
Tier 2: Mid-range stations: *provides fundamental solar resource and surface meteorology.*	28
Tier 3: Simple stations: *cluster of eight instruments taking only global horizontal and plane-of-array irradiance (GHI and GTI) measurements plus temperature readings, surrounding a single rotating shadowband radiometer (RSR).*	0

Table 4-4 Type and number of stations used in this study [172]

Solar data from 46 ground-based stations were obtained from K.A.CARE as comma-separated values text files (.CSV) to analyse along with the other data from satellite-based models. All the stations were configured to provide one-minute resolution for solar components. Monthly mean daily total data are available to the public for free; however, higher resolution data requires payment. Hourly and daily data from the beginning of operation in January 2013 to November 2016 were acquired for this research for free. The order quote for this data was around $342,859, but K.A.CARE provided it for free as a part of supporting researchers affiliated with universities in the KSA.

Region	Location	Latitude (N)	Longitude (E)	Elevation (m)	Tier
Central	Afif	23.92	42.94	1060	2
	Al Dawadmi	24.55	44.47	955	2
	Al Uyaynah	24.90	46.39	779	1A
	Al Kharj	24.14	47.26	465	2
	KACARE City	24.52	46.43	895	2
	KACARE HQ	24.71	46.68	668	2
	Majmaah	25.85	45.41	718	2
	Layla	22.27	46.73	567	2
	Shaqra	25.17	45.14	804	2
	Qassim	26.34	43.76	688	1B
Eastern	Al Ahsa	25.34	49.59	170	2
	Al Dhahran	26.30	50.14	75	2
	Al Khfji	28.48	48.48	5	1C
	Al Jubail	26.90	49.76	89	2
	Arar	31.02	40.90	570	1C
	Dammam	26.39	50.18	28	1A
	Hafar Al Batin	28.33	45.95	383	2
Southern	Abha	18.22	42.54	2173	1C
	Al Baha	20.17	41.63	1680	1C
	Al Farshah	17.77	43.17	1094	2
	Najran	17.63	44.53	1187	1C
	Jazan	16.96	42.54	1	1B
	Sharurah	17.47	47.08	760	2
	Rania	21.21	42.84	933	1C
	Wadi Addawasir	20.43	44.89	671	1C
North & Western	Al Hanakiyah	24.85	40.53	873	2
	Al Jouf	29.77	40.02	680	1C
	Al Qunfudah	19.15	41.08	20	2
	Al Wajh	26.25	36.44	21	1C
	Duba	27.34	35.72	45	2
	Osfan	21.89	39.25	119	2
	Hada Al Sham	21.80	39.72	245	2
	Hail	27.39	41.42	950	2
	Hagl	29.28	34.93	36	2
	Jeddah	21.49	39.24	75	1B
	Madinah	24.48	39.54	643	1C
	Makkah	21.33	39.94	295	1C
	Tabuk	28.38	36.48	781	1C
	Taif	21.43	40.49	1518	1C
	Thuwal	22.30	39.10	34	1A
	Timaa	27.61	38.52	844	2
	Umluj	25.00	37.00	10	2
	Yanbu	23.98	38.20	17	1C

Table 4-5 Summary of ground-based solar monitoring stations used in this research

An intensive review has been done of the raw data received from K.A.CARE to ensure there is no missing or corrupted data. K.A.CARE follows best practice in data gathering, procedures and maintenance using NREL standards [176] and more information about network operation and design can be found in reports by K.A.CARE [172]. Data received included different parameters, such as solar three components (GHI, DNI, DHI), ambient air temperature, wind speed, parametric pressure and relative humidity. Since monitoring stations for the third tier is not yet working, data for this study is from the first and second tier stations. Each station has at least 8,760 hours of data recording depending on the time it started operating. A few stations started operating in 2013, whilst others were installed in the following years. These stations used different instruments, such as an anemometer, air temperature probe, pyranometer, pyrgeometer, pyrheliometer and many others to capture parameters. One major instrument is a rotating shadowband radiometer used as a secondary device to provide solar components besides the pyranometer and pyrheliometer; this is the primary device for measuring solar components and basic meteorological measurements in mid-range stations. According to K.A.CARE, nominal uncertainty associated with these devices is ±2% for the pyranometer and pyrheliometer at one minute resolution, but ±5% for the rotating shadowband radiometer.

After investigating data received from K.A.CARE, three stations were excluded because they have incomplete data. One of these is Princess Norah University, which was decommissioned after constructing CSP for heating water and space [79]. The other two stations not available were King Saud University and Farasan; however, there was a Jazan station that could be used as a substitute for Farasan and two stations in the Riyadh area were used to substitute the King Saud University station. Hence, the total number of stations is 43, covering one year from 1st Jan 2015 to 31st Dec 2015. This was the most complete year in terms of data and installation of solar monitoring stations.

Analysis was carried out for this data similar to that described above for the satellite-based models, but this time with hourly resolution. DHI was included in this analysis to look widely at the characteristics of solar resources and their magnitude. An assessment of the daily irradiation in 2015 was done for the three solar components in all 43 stations to nominate the highest four places from the four operating areas for solar power plants. The analysis showed very similar results to those drawn from the satellite-based models. The maps in Figure 4.11 and Figure 4.12 present the monthly-averaged GHI and DNI with their geographic and temporal distribution respectively.

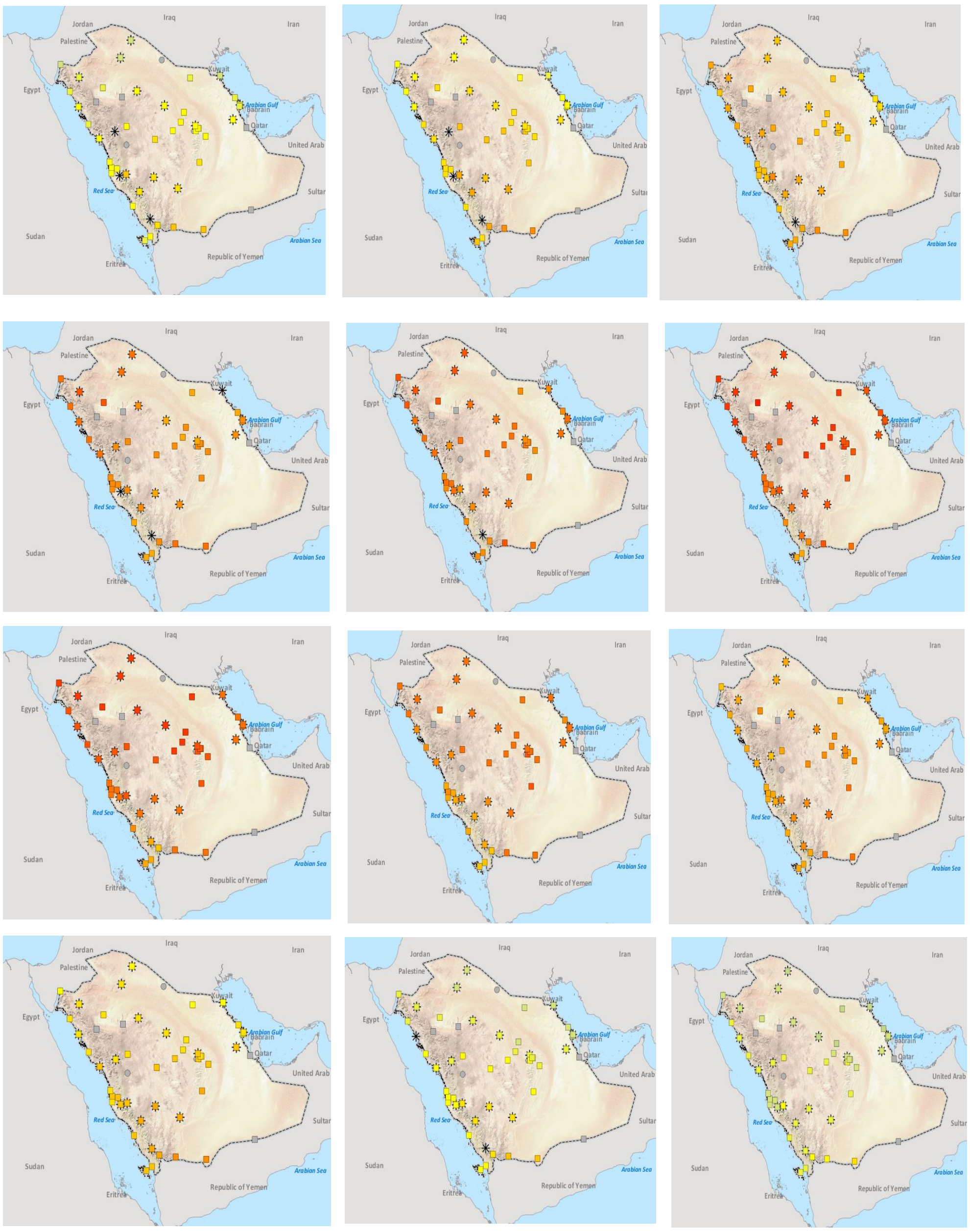


Figure 4.11 GHI monthly-averaged maps of RRMM for 2015 from Jan (top left) to Dec (bottom right)

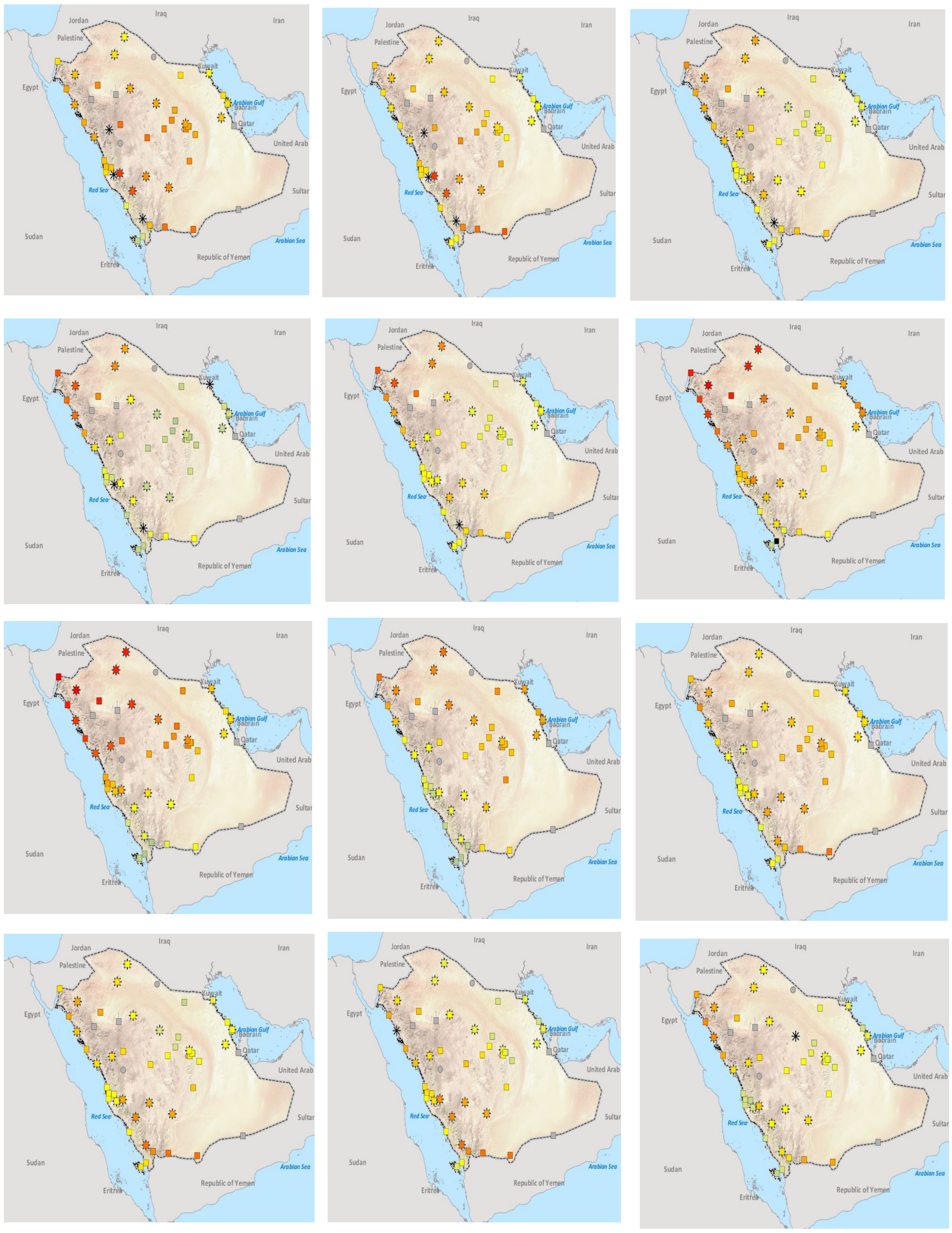
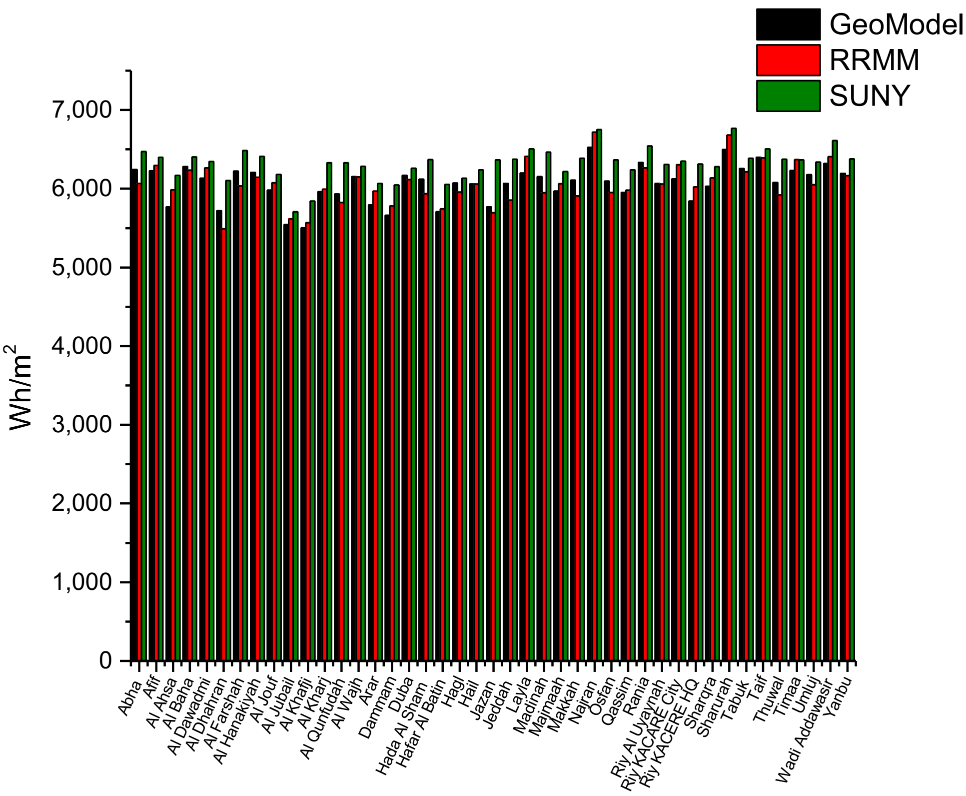


Figure 4.12 DNI monthly-averaged maps of RRMM for 2015 from Jan (top left) to Dec (bottom right)

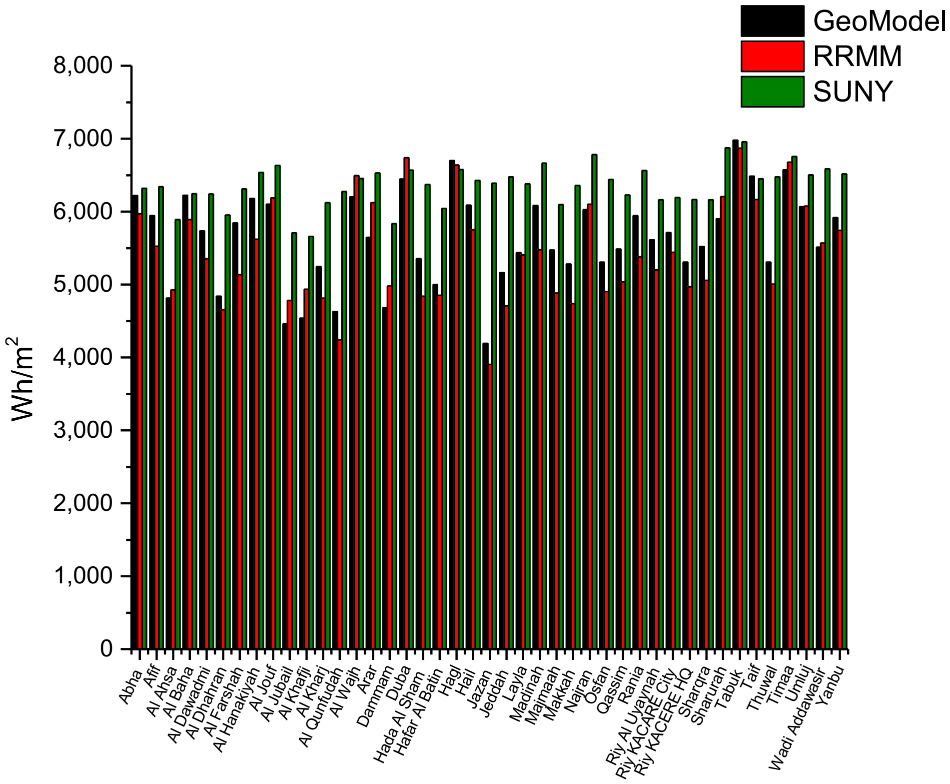
4.3.5 Comparison of Models and Observations

The satellite-based models and the RRMM programme which is basically measurements and observations have a good correspondence, present a clear pattern and confirm the highest irradiation by region. The north-western area has the highest irradiation, followed closely by the southern, then central, and finally the eastern area. Having DHI in this study emphasises that sites with higher DNI are less with DHI, which reflects a clearer sky and not much aerosol or dust. The maximum daily total GHI and DNI is seen to be higher in some areas with the RRMM approach. For example, the DNI reaches above 11 kWh/m^2/day in the north-western area and it is a similar case with GHI in the southern area. Data from this network is only available for a short period of time; otherwise an inter-annual study should be performed to look at its impact on solar resources.

The RRMM has been compared to the satellite-based models to visualise the differences between the three approaches, as depicted in Figure 4.13.



(a) Monthly mean daily total for 43 sites using three approaches of GHI



(b) Monthly mean daily total for 43 sites using three approaches of DNI

Figure 4.13 Comparing monthly mean daily total for 43 different sites using three approaches of GHI in (a) and DNI in (b)

The three approaches do not vary much in GHI across the entire country, but there is a high spatial variation in DNI, as noticed in Figure 4.13 (b). The SUNY model shows a higher DNI in some sites with a large difference from the other two cases, as, for example, in Jazan, Jeddah and Layla. It is important to emphasise time period differences between the different approaches.

4.4 Resource Data

The main objective for next analysis is to have reliable data to use when simulating solar power plants. After looking at and analysing all the available data from different satellite-based and ground-based sources, as discussed in the previous sections, it was found that RRMM is the most appropriate for this purpose. The input data should represent the long-term conditions of a time series solar resource; however, there is no reliable long-term data available and the only data that could serve the purpose of operational analysis for power plants is the year 2015 from the RRMM model. This is the most recent available data with higher temporal resolution and quality to be used for power plant development studies.

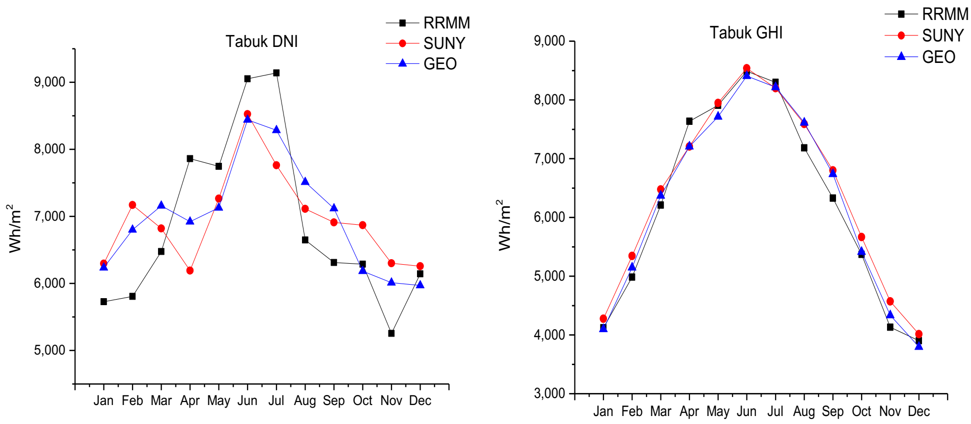


Figure 4.14 DNI and GHI comparison for the three models in the Tabuk site

For consistency, the country was divided into four regions when analysis took place for solar irradiation resources. These areas match those for the electricity sector and demand used in the third chapter. Importantly, the conditions at the specific sites used in those areas are representative of the wider areas. Since RRMM will be the main solar resource data used in CSP and PV power plants, four different sites, one from each region, will be nominated to have power time series at these locations and they will be integrated into the grid in the next chapter. After calculating the monthly averaged daily total irradiation for all three approaches, the best sites were confirmed based on their presence in the highest irradiation in all three approaches. Therefore, the sites chosen are Tabuk from the north-western region, Sharurah from the southern region, Afif from the central region and Hafar Al-Batin from the eastern area. The monthly averaged daily total irradiation for each site from the three models were compared with each other, Figure 4.14 shows Tabuk as an example.

4.5 Summary

In this chapter, solar resources were analysed using several available datasets and approaches, both old and new. The objective was to understand how good the solar resources in the KSA are. High time resolution data at meteorological stations was obtained for this purpose, which is the most recent, with more parameters included to investigate solar resources in depth. Solar resources were compared using satellite-based and ground-based measurements. Spatial and temporal variabilities for the resources were examined, including spatial maps for different datasets. Several sites were then nominated as representative locations for deploying solar technologies.

Chapter 5 **Solar Energy Generation**

5.1 Introduction

The previous chapter presented an analysis of solar energy resources. In this chapter, different solar power technologies are examined. The representative sites in each region are evaluated in terms of optimal technology configuration for PV, CSP and hybrid plants using a multi-objective optimisation.

5.2 Solar Power Plant Optimisation

In recent years, several studies have considered the advantages of solar power plants, whether CSP, PV or the two combined as a hybrid system. Indeed, energy system hybridisation is more common now and more than one type of technology can be hybridised in one system with a different configuration to achieve several purposes. Most of these technologies were found to be cost effective and to perform better when combined with another technology, depending on the objective of the power plant. For example, it has been cited by numerous authors that PV power plants alone have a low capacity factor (CF) because of the diurnal effects and intermittency that result in supply and demand mismatch [177]. Denholm and Margolis [178] stated that it would be difficult for PV to contribute significantly to the world energy mix unless a vast decrease took place in the cost of electricity storage.

Similarly, a CSP power plant is less economically viable since the cost of generation will be higher, especially when large TES is included [179]. Hybrid energy systems seem to be the most appropriate solution when trying to avoid these techno-economic issues related to single technology choice. Yang et al. developed a solar-wind hybrid system employing battery and using a sizing optimisation method with different objectives, showing that systems can be optimised technically and economically within the system reliability requirements [180]. In [181], Zurita et al. performed a techno-economic evaluation of a system encompassing a CSP with TES and a PV utility scale with a large-scale battery system to deliver a baseload of 100 MW. The study analysed different aspects, but most important is the inclusion of a large battery in the PV system that proved to be unprofitable.

A techno-economic study was presented by Al-Shamma'a and Addoweesh [182] using a genetic algorithm (GA) to evaluate a hybrid system with different configurations, including a wind, battery and diesel generator to meet the load for a rural area in the KSA. After the sizing optimisation was applied to nine different configurations, the study showed that a hybrid system of PV, wind and battery is the best choice to meet this demand, both economically and environmentally. Ramli et al. [183] presented an economic analysis of a PV-diesel integrated with flywheel storage after investigating several configurations with and without storage to supply the demand of Makkah City in the KSA. Simulation was done using HOMER software considering power generation and its cost with net present cost. The results showed a higher utilisation of the system when employing flywheel, lower emissions while decreasing diesel fuel consumption and lower net present cost.

This current study will focus on the optimisation of CSP, PV and hybrid systems. Hybrid systems have been studied in different places, but no known work has been published using this type of hybrid system within the KSA. A recent SWOT analysis was performed on six CSP technologies using system advisor modelling (SAM) as a simulator to select the most suitable CSP plant design for the KSA [184]. Several scenarios were assessed with defined financial, technical and weather parameters for one location: Riyadh. The study showed that parabolic trough has reached a mature state, while solar tower technology is becoming increasingly popular for its ability to incorporate large TES.

Solar tower technology has significant potential and this has been commercially proven with Ivanpah in the US being the largest operating CSP plant at 392 MW; however, it has not been widely deployed and several studies have discussed the utilisation of this technology. Parabolic trough technology has a higher installed capacity, including recent constructed plants in the Arabic region and countries adjacent to the KSA with good solar resources, such as in United Arab Emirates and Morocco with the Shams and Noor projects respectively. There are no solar tower plants operating in the Arabic region, but it has been reported that one third of recent commissioned project are solar tower plants [185].

5.2.1 Model and System Description

In most recent studies solar tower technology has been studied with the integration of TES and/or hybridised with PV [173], [177], [182–188]. Therefore, in the current study a hybrid system including CSP solar tower technology with its large-scale TES integrated with PV will be studied. This system will be tested in the four different sites nominated in the previous sections due to their solar irradiation and spatial diversity. Utilisation of this type of system aims to benefit from cost competitive PV installation, whilst also exploiting the advantages of CSP technology with TES, providing dispatchability and higher reliability to the system by supplying demand during times when no solar power is available. After studying the hybrid system, CSP and PV only systems will be studied to compare the results with ones obtained from the hybrid.

The optimisation model employed for this analysis is derived from the model developed at the University of Edinburgh by Bravo [193]. The mathematical model is a two-stage multi-objective optimisation to solve for an optimal operation and design for the system. It considers simultaneously optimising both operation and design to weigh technical and economic trade-offs. The structure of this hybrid power plant system includes two different technologies – solar tower technology with TES and PV technology – coupled in parallel, as shown in Figure 5.1. Hence, the entire system is composed of several subsystems. These subsystems are: area of the CSP heliostats solar field A_{CSP}^{SF} (m^2), storage capacity of TES E_{St}^{Max}(MWh), capacity of the power block PB_{Cap}^{Max} (MW), inverter, capacity of the PV power plant P_{PV}^{Max}(MW) and network. Four of these are defined as decision variables for the design of the power plant: A_{CSP}^{SF}, E_{St}^{Max}, PB_{Cap}^{Max} and P_{PV}^{Max}. Similarly, when optimising for operation there will be too many variables considering the hourly resolution profile that requires linear programming optimisation for each possible design. More details about the objectives of each stage of optimisation will be explained in the following sections and the optimisation method will be presented. This optimisation process has been executed using Python software and evolutionary algorithm NSGA-II with several packages, such as NumPy [194], Pyomo [195], Pandas [196], DEAP [197] and Gurobi [198] used as optimiser and solver [193].

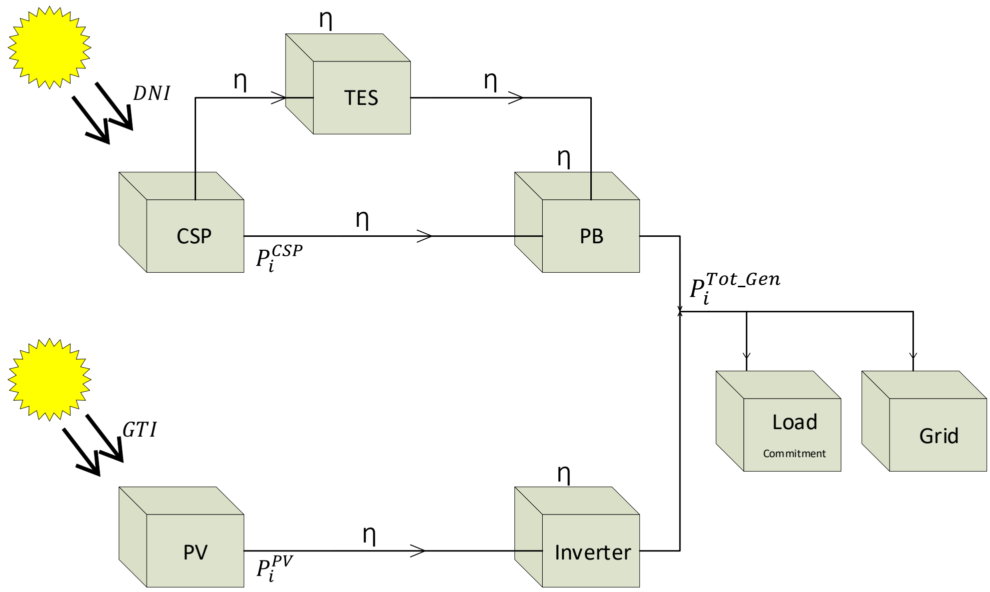


Figure 5.1 Structure of the hybrid system showing the power flow model

The technologies used in this study are described in Chapter 2, including their advantages and disadvantages. The CSP plant in this study will have different capacities in all four sites, utilising two-tank molten salt storage for TES and molten salt for HTF, which, once heated by concentrators (heliostats), will either be used immediately to produce heated steam and drive the Rankine cycle to generate electricity, or stored in the other tank to be used later. Molten salt has been used in both HTF and TES based on its usage in most of the operating and under-construction projects since it has showed higher storage and efficiency, lower thermal losses, and better capacity factor [184], [199]. According to [200], two-tank molten salt storage is the most utilised system within CSP technology. Synthetic oil is not employed as HTF in the solar power tower as commonly as in parabolic trough since it is considered expensive, toxic and entailing thermal degradation properties that limits efficiency improvement [201], [202]. The PV power plant works in the same manner, while no batteries are included. Module used is SunPower SRP-E19-310-COM with a nominal efficiency 19.01% and fixed mono crystalline silicon. The inverter used here is the SMA America:SC750CP-US324V[CEC2021] and its efficiency is 98.3%. Technical characteristics are derived from the SAM model [203].

When operating CSP, power flows from the CSP block to either TES or PB through heat lines after calculating power received at the solar field according to equation 5.1. In addition to the flow line from CSP to PB, these two lines are variables that will be optimised at the operational stage considering the objectives of this stage. The size of PB and TES are optimised during the design stage; therefore, once both are at their maximum, surplus energy will be curtailed at the CSP plant.

$$P_i^{CSP} = (DNI_i \, . \, \eta^{Solar\ field} . \, A^{CSP}) - P_i^{Curtailed} \qquad 5.1$$

where P_i^{CSP} is the power from CSP at period (i), DNI_i is the direct normal irradiation at a certain hour, η is the efficiency of the solar field, A^{CSP} is the area of the solar field, and $P_i^{Curtaild}$ is the surplus power curtailed at a certain hour. Stored energy is calculated at TES using equation 5.2.

$$E_i^{TES} = E_{i-1}^{TES} \, . \, \eta^{TES} + \left(P_i^{CSP \rightarrow TES} . \, \eta^{CSP \rightarrow TES} - P_i^{TES \rightarrow PB}\right) . \, \Delta t_i \qquad 5.2$$

$$E_{min}^{TES} \leq E_i^{TES} \leq E_{max}^{TES}$$

where $E_{i-1}^{TES}$is storage energy with a time step, η^{TES} is storage efficiency, $P_i^{CSP\rightarrow TES}$ is power flowing from CSP to energy storage at a certain hour, $\eta^{CSP\rightarrow TES}$ is power flow from CSP to TES efficiency, $\mathrm{P_i^{TES\rightarrow PB}}$ is power flowing from TES to BP at a certain hour, and Δt_i is the delta period hour. Then total power received at PB is calculated, as shown in equation 5.3.

$$\mathrm{P_i^{PB} = (P_i^{CSP\rightarrow PB} \,.\, \eta^{PB} + P_i^{TES\rightarrow PB} \,.\, \eta^{TES\rightarrow PB}) \,.\, \eta^{PB}} \qquad 5.3$$

$$\mathrm{P_{min}^{PB} \leq P_i^{PB} \leq \; P_{max}^{PB}}$$

where $P_i^{PB}$is PB power at a certain period (h), $P_i^{CSP\rightarrow PB}$is the power flowing from CSP to PB at a certain period (h), η^{PB} is PB efficiency, $P_i^{TES\rightarrow PB}$is power flowing from TES to PB at a certain period (h) and $\eta^{TES\rightarrow PB}$is the power flow from TES to PB efficiency.

When operated, the PV power plant performs similarly to CSP, while the capacity of this plant is also decided by the design optimisation in all four sites with no batteries included. Therefore, whatever DC power is received from the solar panels is converted through the inverter to AC and sent to load. Power that is transferred from the PV power plant to the grid is calculated using equations 5.4 and 5.5.

$$\mathrm{P_i^{PV} = \left(GTI_i \,.\, \eta^{Solar\ field} . A^{PV}\right) - P_i^{Curtailed}} \qquad 5.4$$

$$\mathrm{P_i^{PV\rightarrow grid} = P_i^{PV\rightarrow Inv} . \eta^{PV\rightarrow Inv} . \eta^{Inv}} \qquad 5.5$$

where $P_i^{PV}$is the power from PV plant at a certain period (h), GTI_i is global tilted irradiation at a certain period, $\eta^{Solar\ field}$ is solar field efficiency, $A^{PV}$is solar field area, and $P_i^{Curtaild}$ is surplus power that cannot be converted because it is beyond the inverter capacity. Equation 5.5 considers the efficiency of the related components.

The load commitment in this study is set to be 100 MW, which requires that amount of power to be constantly supplied every hour. The surplus energy is sent to the grid; however, one important analysis of this study is considering the total generation of both plants in case it is integrated into the grid. The reason for setting a commitment in the configuration is to maximise CF and exploit the synergies of both power plants. Ultimately, the power from both plants is calculated using equation 5.6.

$$P_i^{Tot\_Gen} = P_i^{PB} + P_i^{PV \rightarrow grid} \qquad 5.6$$

where $P_i^{Tot\_Gen}$ is the total generation at a certain period (h), P_i^{PB} is the power from PB, which depends on the maximum cycle of PB, and $P_i^{PV \rightarrow grid}$ is the power from the PV power plant.

In this configuration, two-stage multi-objective optimisation, which considers hourly operation profile as one stage and design as another stage with respect to different variables, will be processed. This optimisation process will result in optimal Pareto with non-dominated solutions of different designs enabled by certain objectives that will be defined through an operation and design optimisation process. The operational hourly profile of each component of this system will be obtained for further analysis in Chapter 6.

5.2.2 Input Parameters

Solar resource irradiation is key to evaluating the system under site condition in this study. Therefore, DNI and GHI for the different sites nominated (Afif, Hafar Al-Batin, Sharurah, Tabuk) are considered for 2015 with hourly resolution. The resource data do not represent best or worst case, but instead the most accurate available high resolution obtained after solar resource analysis was carried out in the previous section. Solar panels for the PV plant are tilted and fixed; therefore, in this case, GHI data received from K.A.CARE were used to acquire global tilt irradiation (GTI) since it is not available.

This process is conducted using the SAM environment, which is a tool developed by NREL [204] [203]. First, data from the received CSV files were used to construct typical meteorological year (TMY3) weather files that SAM only deals with. There were several parameters needed to construct these files; some of them were available and others had to be calculated in order to complete this process. These parameters are: wind direction, wind speed, pressure, air temperature, relative humidity, GHI, DNI, DHI, elevation, longitude, latitude and dew temperature T_{dew}, which was calculated using equation 5.7 according to [205].

$$T_{dew} = Temp - (RH)/5 \qquad 5.7$$

where T_{dew} is dew temperature, $Temp$ is ambient temperature, and RH is relative humidity. These parameters were prepared and entered for all four locations in TMY3 to calculate for GTI. Afterwards, the hourly profile for GTI was modelled and compared to GHI. This was done for all sites so that tilt is equal to latitude since the panels are fixed. To illustrate this step, Figure 5.2 shows the calculated GTI compared with GHI for the Tabuk site.

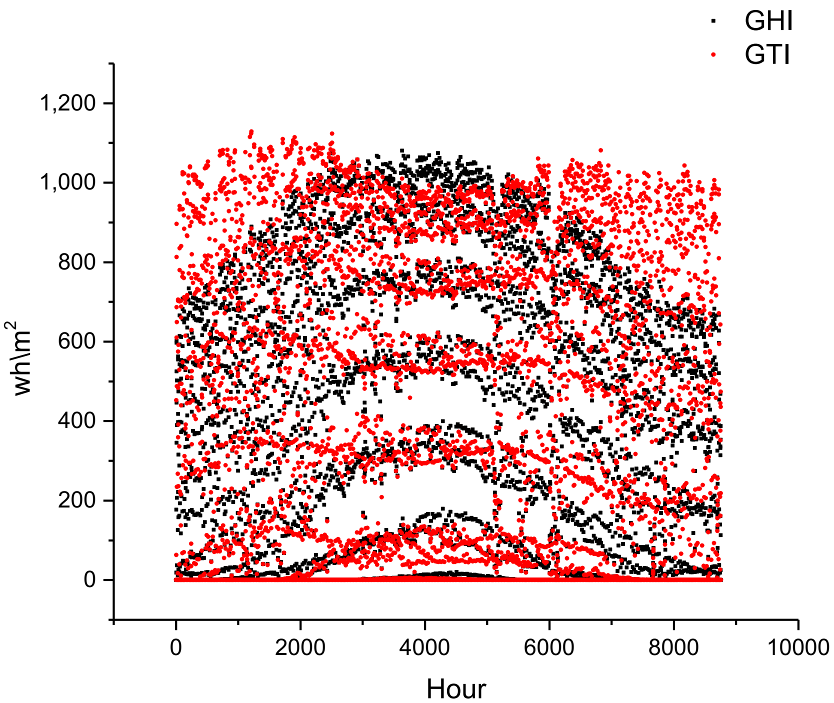


Figure 5.2 GTI after calculation compared to GHI for Tabuk site

Furthermore, input parameters related to technical and financial aspects are of importance in analysing the performance of the hybrid system and at the same time using this for validation purposes. SAM provides different financial and technical information related to different technologies, including the presented CSP and PV technologies. This was used to construct and model different CSP and PV power plants to estimate the technical and financial parameters, such as efficiencies related to each element and financial parameters related to investments and the economics of power plants in general. The efficiencies used in the model for each component and line of the subsystem are listed in Table 5.1 and other technical and financial parameters can be found in the system advisor model (SAM) [203]. Finally, the nameplate capacity for both power plants was decided by design optimisation with a firm 100 MW load commitment. The assumed discount rate is 7% over the 25 year lifetime of the project [185].

<table>
<tr><th>CSP Plant Efficiencies (η)</th><th>PV Plant Efficiencies (η)</th></tr>
<tr><td>Solar field = 0.487</td><td>Panels = 0.181</td></tr>
<tr><td>Pipelines = 0.99</td><td>From PV to inverter = 0.850</td></tr>
<tr><td>TES = 0.99</td><td rowspan="2">From Inverter to network = 0.973</td></tr>
<tr><td>PB = 0.371</td></tr>
</table>

Table 5-1 Power plants efficiencies used in the model

5.2.3 Optimisation Process

This process is composed of two-stage multi-objective optimisation, as is mentioned above. The first phase is to optimise the operation of the power plant through the linear programming method; however, this is nested into the design optimisation that uses GA [206] to simultaneously evaluate both stages. The flowchart of this process is shown in Figure 5.3.

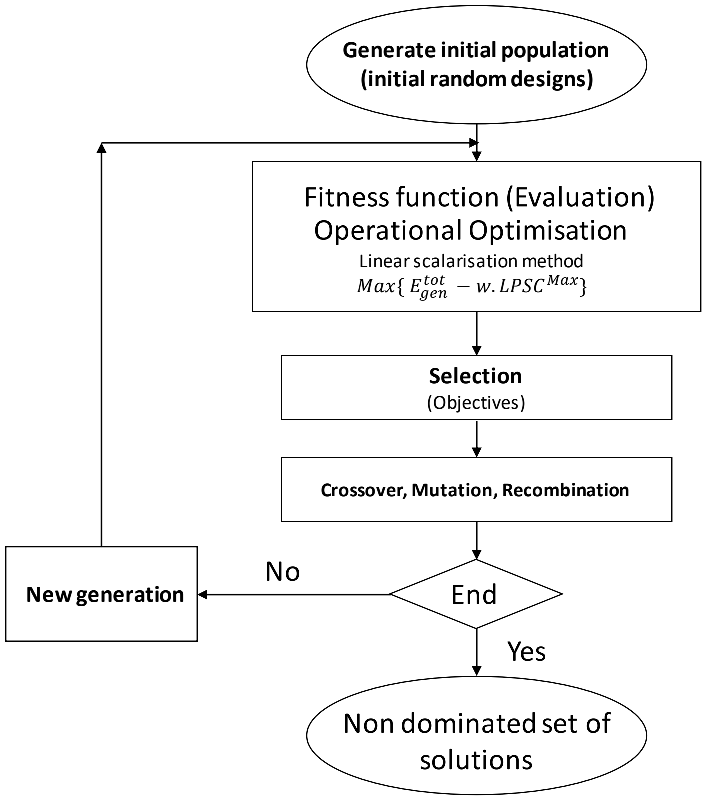


Figure 5.3 Optimisation process flowchart

The way the system operates has been generally explained in section 5.2.1 and this current section will explain how this model is optimised with respect to certain objectives. The process begins with generating initial random population and initial random design of a certain number of individuals, which is defined by the user. In this case, the number of individuals has been defined as 100, which can each be looked at as an independent hybrid solar plant system. The operational optimisation has looked at the techno-economic trade-off considering two objectives: (i) maximising energy supply; and (ii) minimising loss power supply (LPS), as shown in the following equations.

$$\max\{\mathrm{E}^{\mathrm{Tot\_gen}}\} = \max \sum_{\mathrm{i}=0}^{\mathrm{T}} P_i . \Delta \mathrm{t_i} \qquad 5.8$$

$$\min \{\mathrm{LPS}\} \qquad 5.9$$

where P_i is the power supplied in a certain period, LPS is the loss power supplied, which calculates the mismatch between supply and load commitment. This relation is defined as below:

$$LPS_i = \begin{cases} P_i^{Load} - P_i^{Tot-gen} & , P_i^{Tot_{gen}} < P_i^{Load} \\ 0 & , P_i^{Tot_{gen}} \geq P_i^{Load} \end{cases} \quad 5.10$$

This LPS step leads to calculating the loss of power supply probability (LPSP), which is one approach to achieving the optimal configuration of the system [180]; this is defined as the probability that an inadequate energy occurs when the system is not able to deliver the required generation [182]. This is one of the design stage objectives by which to measure the reliability of the system and its optimality with respect to techno-economic study. Thus, it can be defined as follows:

$$LPSP = \frac{\sum_{i=0}^{T} LPS_i .\Delta t_i}{\sum_{i=0}^{T} P_i^{Load} .\Delta t_i} \quad 5.11$$

This operational optimisation considers several technical and financial variables at the same time, which are looked at as key performance indicators, in addition to what has already been mentioned above. For example, CF of both plants, loss power supply capacity (LPSC), capacity of each block (CSP, PV, storage), solar multiple (SM) and storage hours. SM is an important concept where higher SM gives higher CF and this is the ratio of the thermal power generated to the capacity size of solar field and PB [199].

Having two objectives in the operational optimisation with too many variables requires a linear programming method, which only manages to deal with a single objective. In this case, a multi-objective problem has been treated as a single objective using a weighted-sum: the scalarisation method [207]. Another approach that could be used is the epsilon method; however, this method has some drawbacks as it is an inefficient way to get the Pareto front, as well as taking longer for iterations [208]. Hence, the scalarisation method was chosen for this step to get the Pareto front. This method has been automated to find the best operational profile and thus only one result was chosen from the optimal frontier. Automation is done through three iteration process; the first two involve running each objective of the two mentioned above. Once maximum generation and minimum LPS are recorded, the linear scalarisation technique is applied. The single objective equation and scalarisation technique respectively are shown below.

$$\max\{E_{gen}^{tot} - w.\,LPS^{max}\} \qquad 5.12$$

$$w = \begin{cases} \frac{E_{j=1}^{supply} - E_{j=2}^{supply}}{LPS_{j=1}^{max} - LPS_{j=2}^{max}} & , LPS_{j=1}^{max} \neq LPS_{j=2}^{max} \\ 1 & , LPS_{j=1}^{max} = LPS_{j=2}^{max} \end{cases} \qquad 5.13$$

Both objectives are weighted through the scaling factor w, where j is the min and max number of iteration for the optimisation.

The design optimisation phase is the next step, which uses GA with the fitness function inside to run the operational optimisation simultaneously for each design. In this stage, three objectives have been defined to minimise the design optimisation: (i) levelled cost of energy (LCOE); (ii) LPSP that defines how much the LPSC is; and (iii) investment. Decision variables for the design optimisation have been mentioned above whereby each component's size should be chosen during this process. Upon deciding the best sizes, the design optimisation optimises for the three objectives.

5.3 Results and Discussion

The model was run twice separately for two different system configurations, once for a hybrid solar power plant and once for a CSP-alone solar power plant. The latter was configured by setting the PV power plant to zero since this provides an opportunity to evaluate CSP power plants in the KSA along the hybrid systems. This was applied to the four different sites nominated with respect to their conditions using the input parameters mentioned above. This presents the opportunity to test these plants all over the KSA since the study has already divided the country into different regions, each with its own characteristics in terms of topography, solar resources, and electricity demand.

5.3.1 Hybrid System

In this section, Pareto solutions for the four sites representing the different operating areas will be presented. Since different variables were evaluated along multiple objectives for each design, there will be a large range of potential hybrid power plants. It is up to the user to choose the most suitable solar plant in terms of technical and economic performance.

5.3.1.1 Afif

This is from the central operating area and it is selected to evaluate the hybrid system with the conditions of the region. The non-dominated solutions are shown in Figure 5.4 on a three dimensional surface. Every point is a possible solution and it is up to the decision maker to decide which one is best by considering other related circumstances.

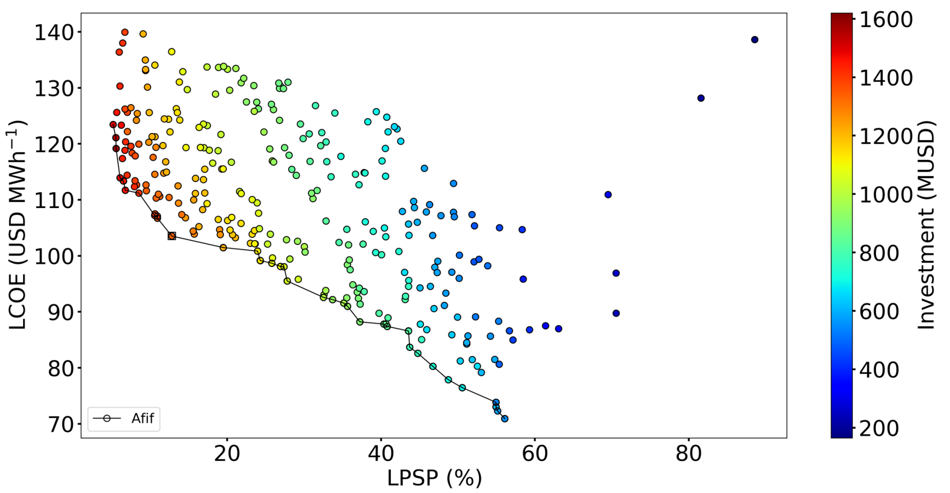
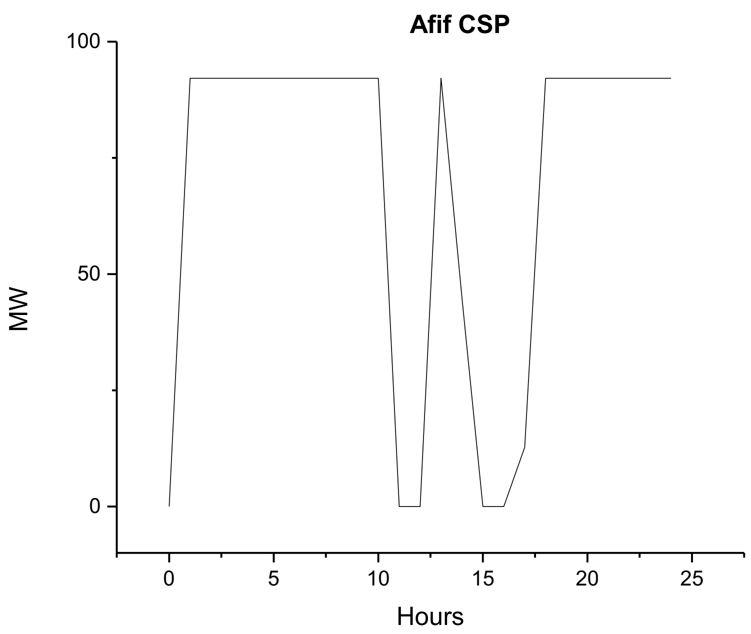


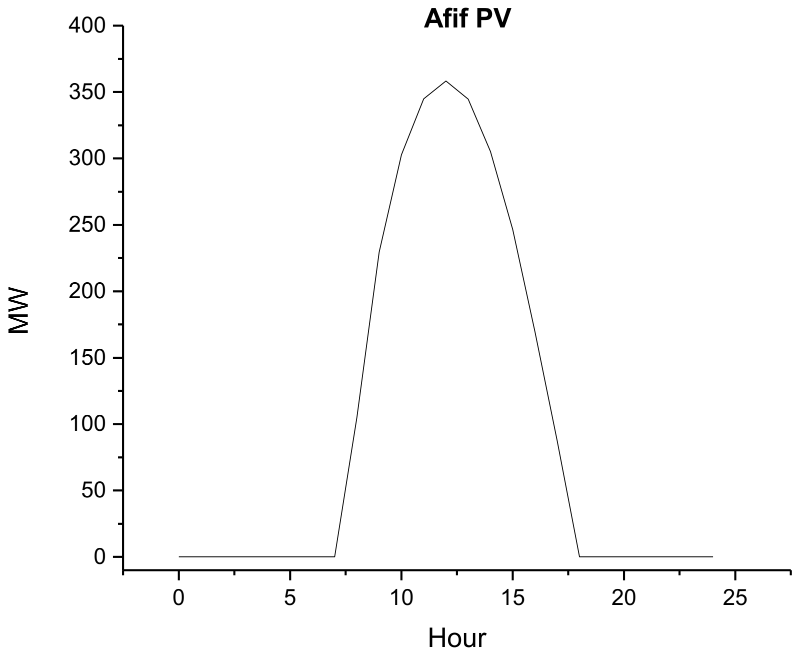
Figure 5.4 Pareto solutions for different possible designs for Afif

One hybrid solar power plant has been chosen to evaluate the hourly operational profile for components of high interest. This point is squared in Figure 5.4 with *LPSP* 12.81%, *LCOE 103 USD*MWh^{-1}. It is important to consider that the slope is very steep after this point with higher *LCOE* and investment, but with lower *LPSP*, which is a better technical performance against trade-off economic properties.

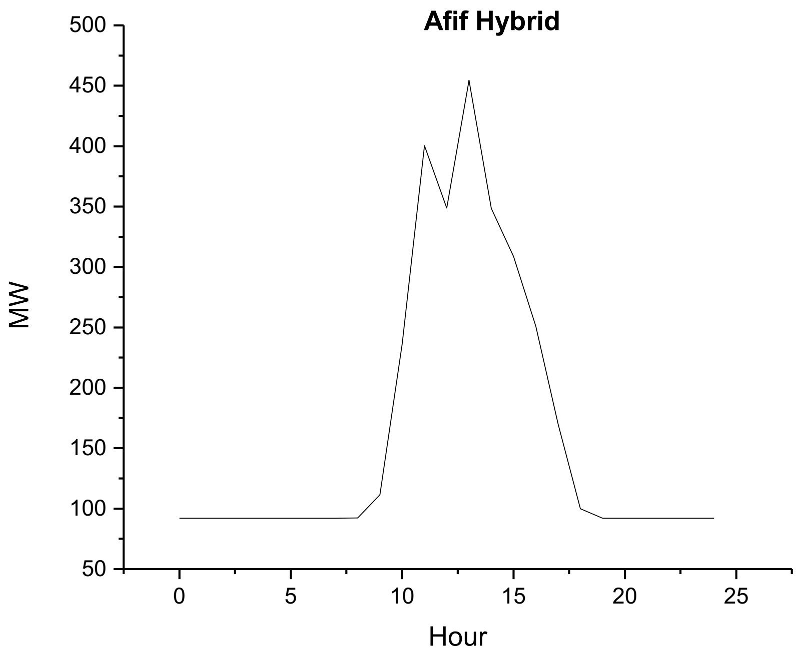
A single-day hourly profile of the second of January (chosen randomly) of the contribution from each part of the power plant is shown in Figure 5.5. The profile of the CSP plant in Figure 5.5(a) shows that the full 92 MW capacity of the power block is generated for most of the day benefiting from thermal energy storage. This drops from 11-12 pm and from 3-5 pm when the PV plant supplies power and the thermal energy storage gets charged. The PV power plant peaks during the day and generated power reaches around 360 MW as shown in Figure 5.5(b). The profile of the hybrid system is shown in Figure 5.5(c) as the combination of both CSP and PV power plants. The advantage of this plant is very clear having the system meeting the load even at night and during the day the power reaches 450 MW. A full year profile and power hourly distribution are shown in appendix B.



(a)



(b)



(c)

Figure 5.5 One day profile of hybrid system with contribution of each plant PV+CSP (Afif)

5.3.1.2 Hafar Al-Batin

A similar process was performed for Hafar Al-Batin from the eastern operating area and this is selected to evaluate the hybrid system with the conditions of the region. The non-dominated solutions are shown in Figure 5.6 with a three-dimensional surface.

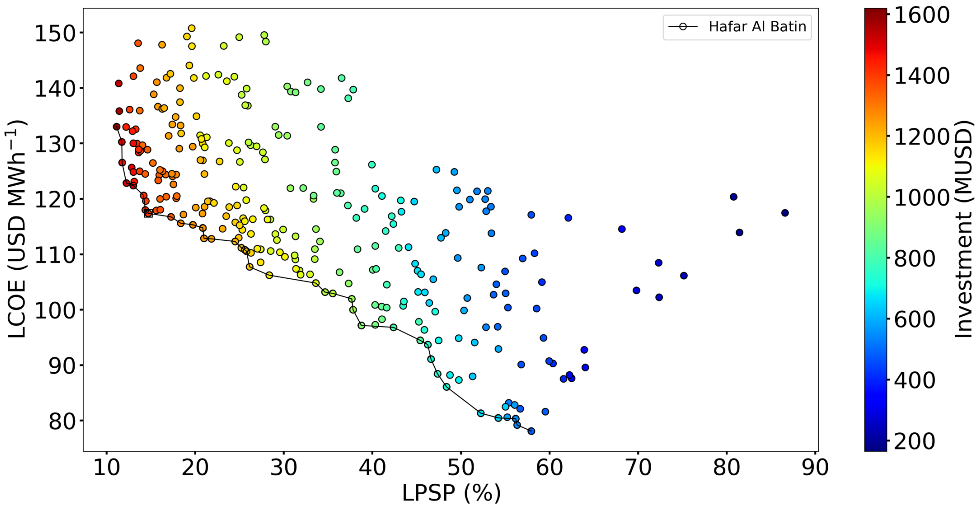
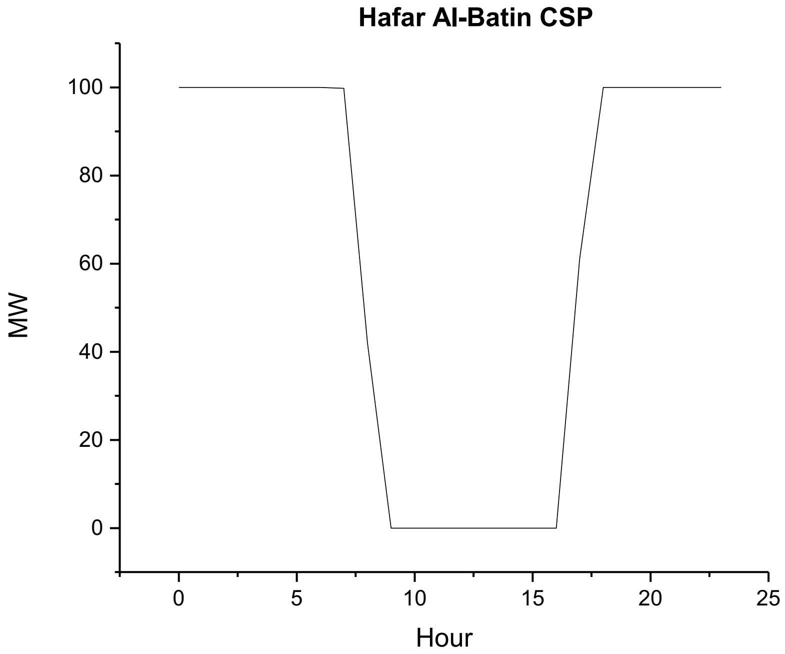


Figure 5.6 Pareto solutions for different possible designs for Hafar Al-Batin

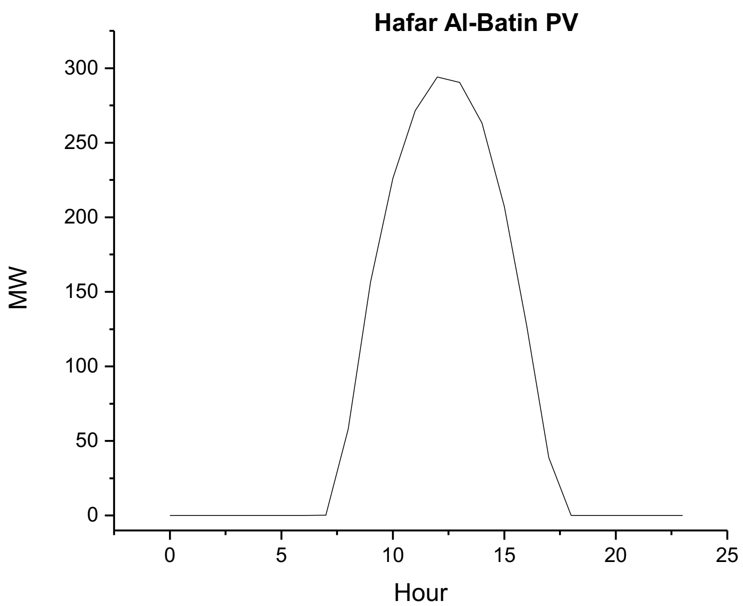
Again, the chosen solar power plant is squared in Figure 5.6 with *LPSP* 14.71% and *LCOE 117.38 USD*MWh^{-1}. It is important to consider that the slope becomes very steep after this point with higher *LCOE* and investment, but with just a slightly lower *LPSP*, which is a better technical performance, but not as good for the financial performance.

Figure 5.7 shows a single day hourly profile arising from this design. It is a the same January day as for the previous power plant and will be the same for the rest for consistency. CSP and PV here have smoother cut-offs but again have similar pattern with previous power plants. A full year profile and hourly power distribution are shown in appendix B. The CSP plant output clearly depends on the capacity of the power block and cannot exceed it. At the same time, the user could choose a larger capacity for the power block but this might result in an oversized power plant and higher risk of not maintaining minimum output levels.



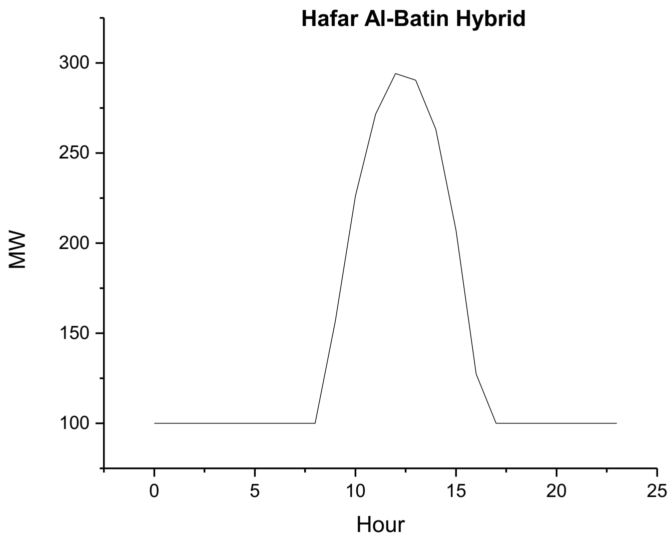
Hafar Al-Batin CSP
MW
Hour
0
20
40
60
80
100
0
5
10
15
20
25

(a)



Hafar Al-Batin PV
MW
Hour
0
50
100
150
200
250
300
0
5
10
15
20
25

(b)



(c)

Figure 5.7 One day profile of hybrid system with contribution of each plant (Hafar Al-Batin)

5.3.1.3 Sharurah

Sharurah is from the southern operating area and has been considered using a similar process to evaluate the hybrid solar plant with this region's conditions. The non-dominated solutions are shown in Figure 5.8. The solar power plant of interest was decided by squaring it in Figure 5.8, with *LPSP* 7.08% and *LCOE 102.55 USD*MWh^{-1}. This solar plant is clearly in a better location since it has much lower *LPSP* and *LCOE* than the previous two power plants in the central and eastern regions. Other measures depend on further indictors to compare this system with others, such as total generated power, area of heliostat, CF, etc. A single day generation profile is presented in Figure 5.9 showing similar patterns to Afif; full year generation and hourly power distribution is shown in appendix B.

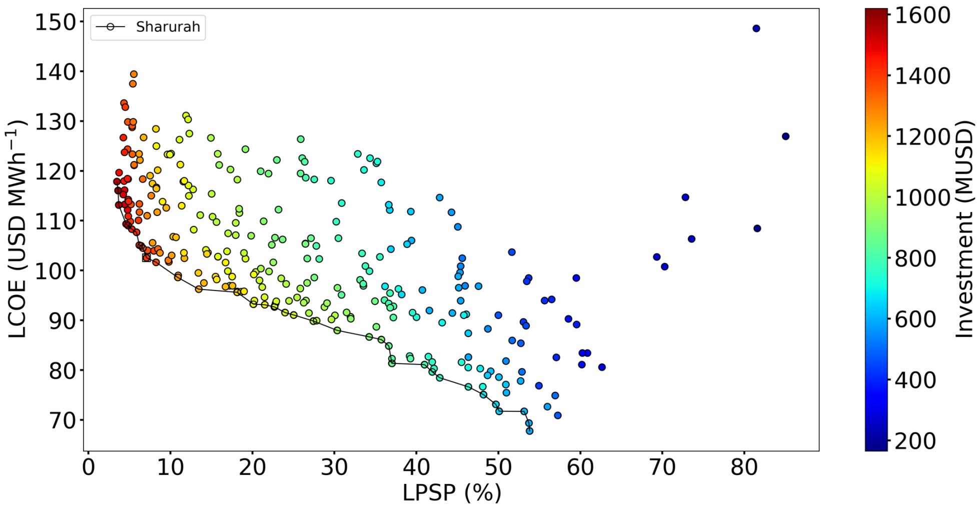
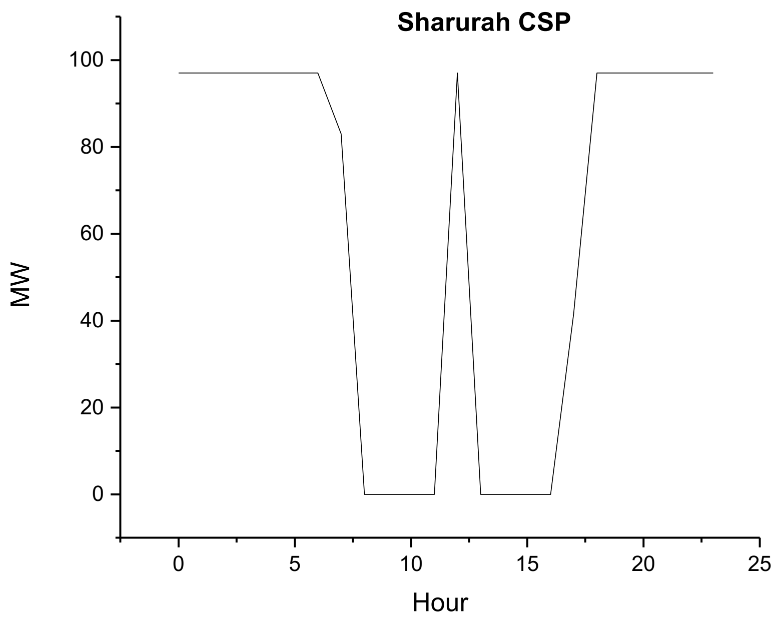
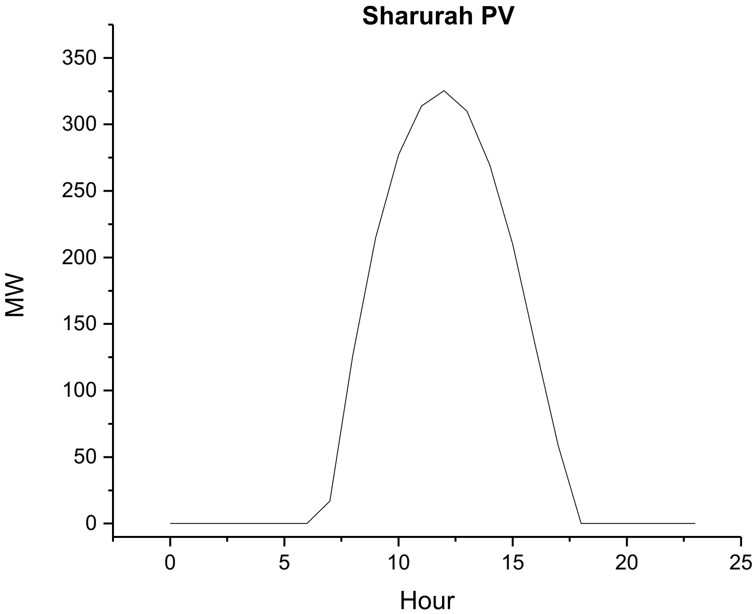


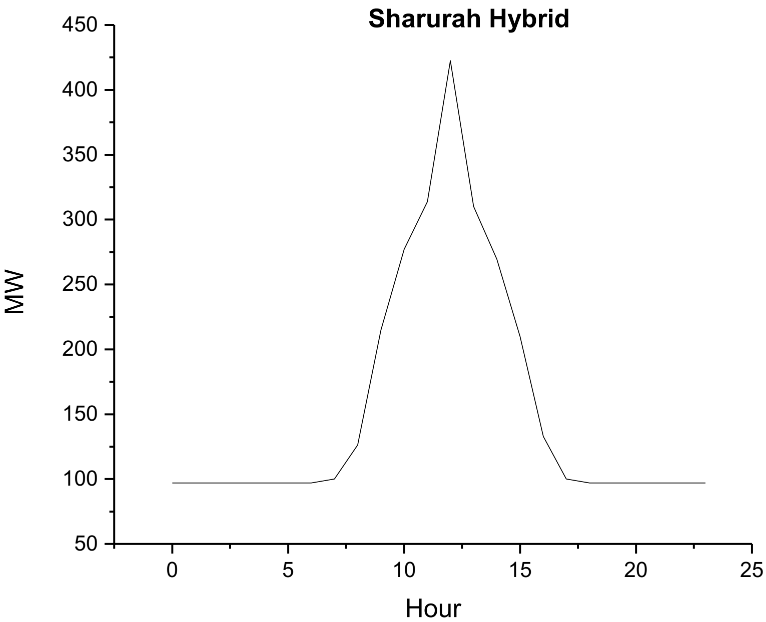
Figure 5.8 Pareto solutions for different possible designs for Sharurah



(a)



(b)



(c)

Figure 5.9 Hourly profile of hybrid system with contribution of each plant (Sharurah)

5.3.1.4 Tabuk

This is the final site used in this analysis. Tabuk is from the western operating area and has been considered using a similar process to evaluate the hybrid solar plant with this region's conditions. The non-dominated solutions are shown in Figure 5.10.

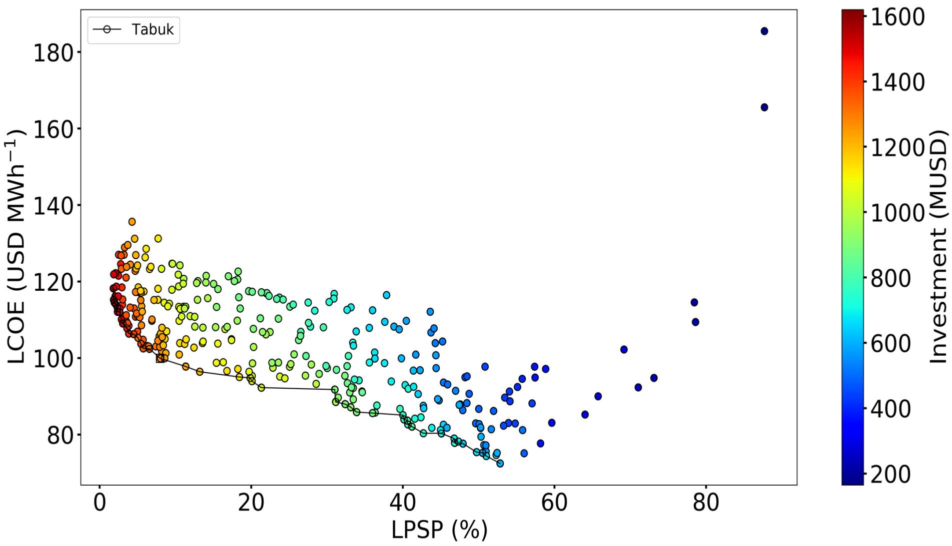
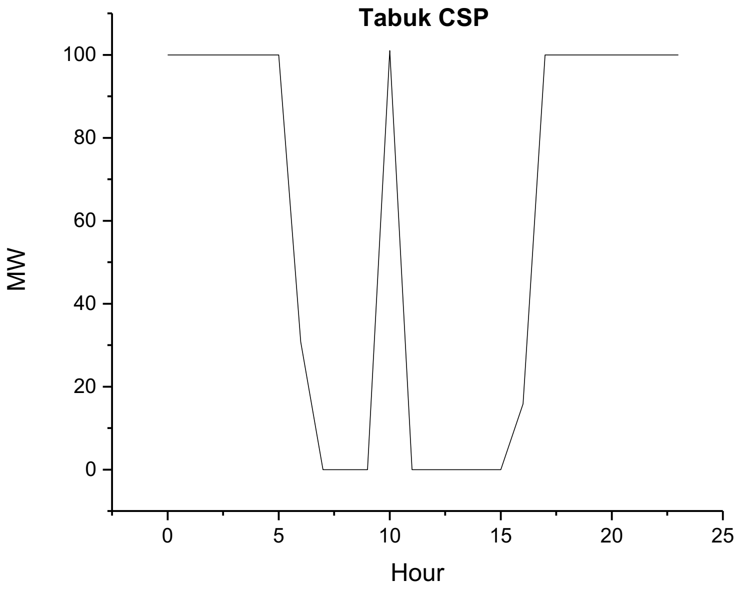


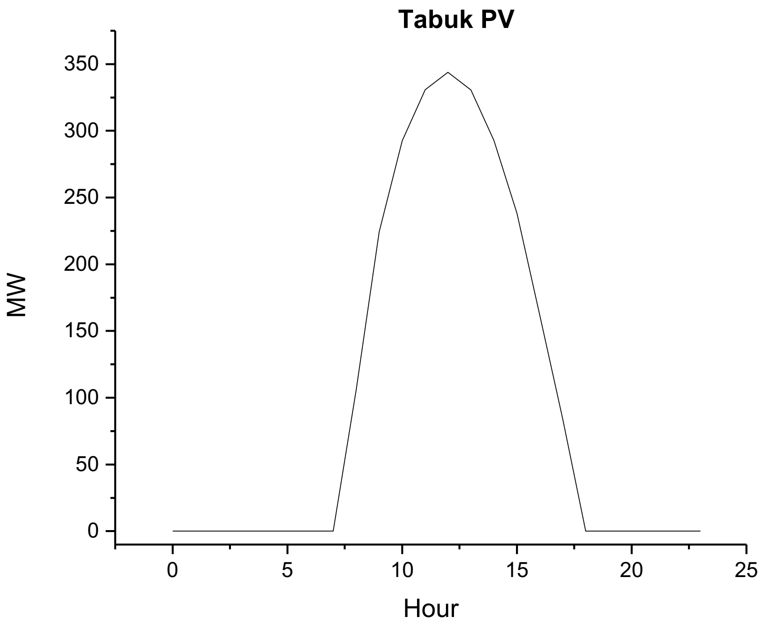
Figure 5.10 Pareto solutions for different possible designs for Tabuk

The solar power plant of interest was decided by squaring it in Figure 5.10, with *LPSP* 7.99% and *LCOE 99.93 USD*MWh^{-1}. This location has the lowest *LCOE*, with a low *LPSP*, which is justified by the good solar resources in this area. The single day hourly generation of this plant is shown in Figure 5.11. Notably the periods of reduced CSP output are longer and there is a short period where the total plant output falls below 100 MW. The full year power generation profile and hourly distribution is shown in appendix B.



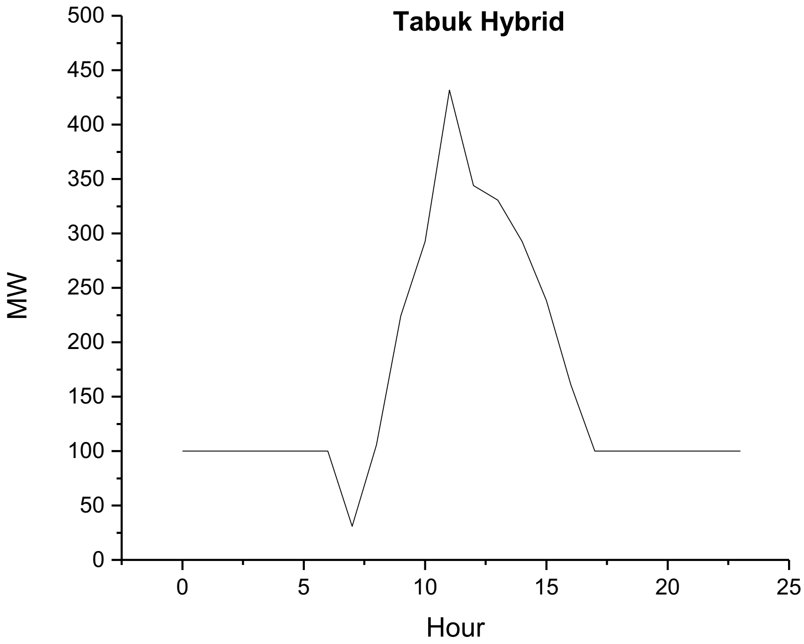
Tabuk CSP
100
80
60
40
20
0
MW
0
5
10
15
20
25
Hour

(a)



Tabuk PV
350
300
250
200
150
100
50
0
MW
0
5
10
15
20
25
Hour

(b)



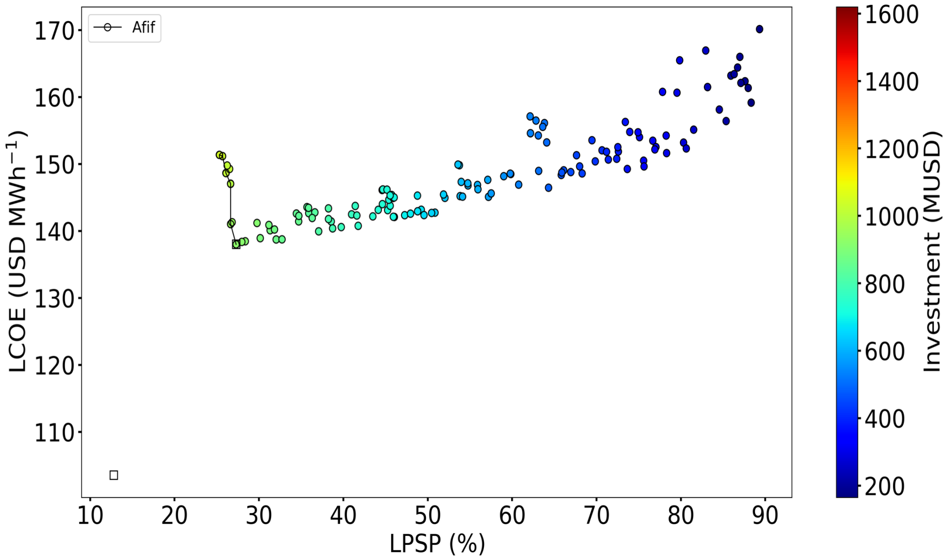
(c)

Figure 5.11 Hourly profile of hybrid system with contribution of each plant (Tabuk)

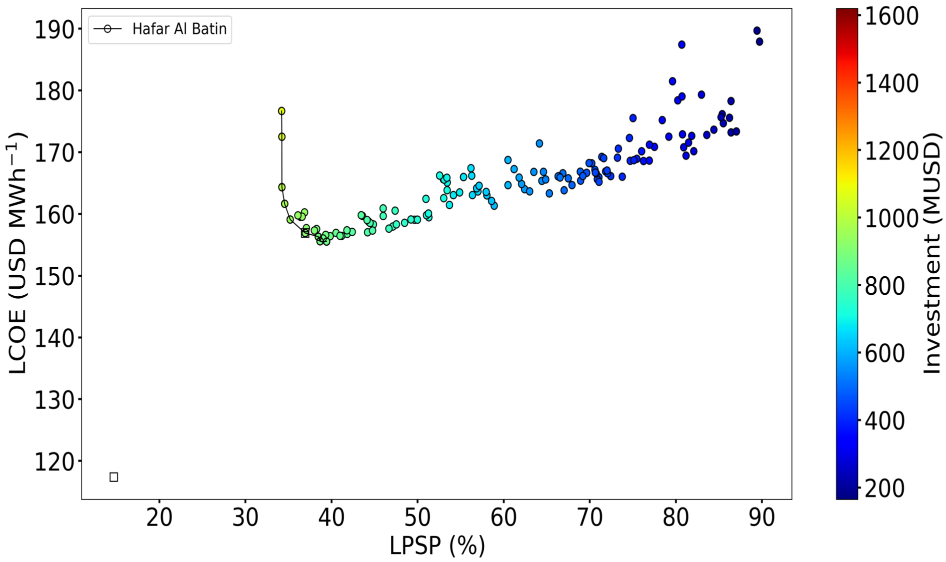
5.3.2 Concentrated Solar Power Plant

It is also worth considering CSP-alone power plants in the KSA using the same sites and optimisation methodology. Optimal Pareto solutions are shown in Figure 5.12 for all of these and it can be seen that the slope of the Pareto solutions is too steep in almost all of them. Investment in these plants is not as high as it is in hybrid solar power plants. However, these plants have a very high *LCOE* and *LPSP* when compared with hybrid systems.

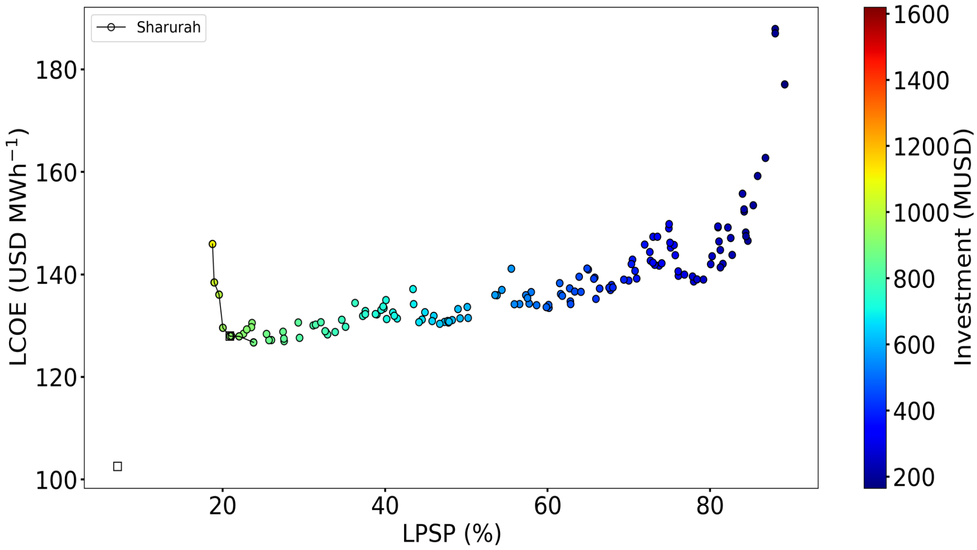
Solar power plants are squared in Figure 5.12 and there is a little square in the left corner of each optimal Pareto showing the hybrid system solar plant on the same graph to compare the two different systems. The purpose of this is to show the results and decision makers can decide which type of solar power plant best serves their needs. If the purpose is to spend less on investments, then CSP-alone is a better choice; however, hybrid systems provide better economic and technical performance.


Afif
LCOE (USD MWh^{-1})
LPSP (%)
Investment (MUSD)
170
160
150
140
130
120
110
10
20
30
40
50
60
70
80
90
1600
1400
1200
1000
800
600
400
200

(a)


Hafar Al Batin
LCOE (USD MWh^{-1})
LPSP (%)
Investment (MUSD)
190
180
170
160
150
140
130
120
20
30
40
50
60
70
80
90
1600
1400
1200
1000
800
600
400
200

(b)



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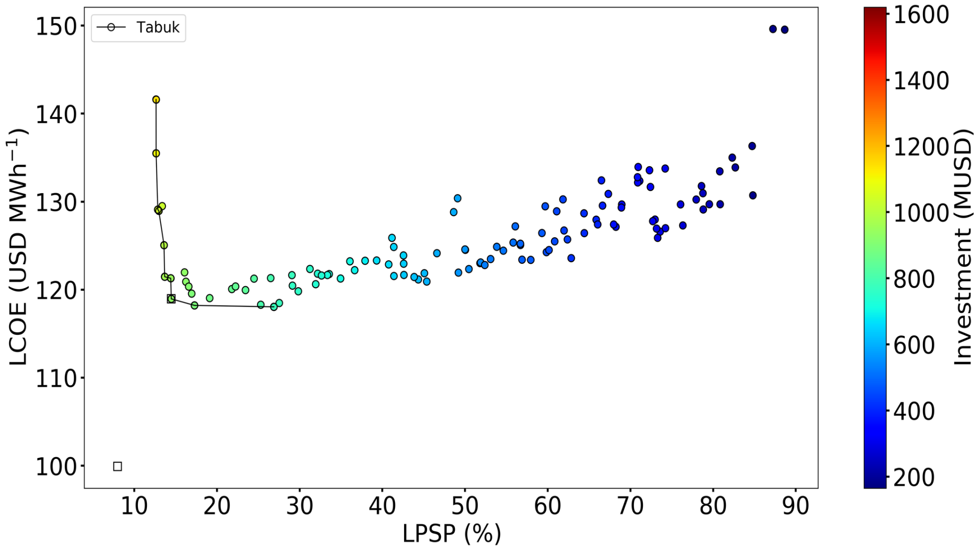


(d)

Figure 5.12 CSP-alone Pareto solutions for different locations in the KSA

5.3.3 Conclusion

More variables and objectives could be analysed using this model, but what is considered depends on the purpose of the study. Environmental objectives and/or constraints that serve a certain goal can be added to investigate different scenarios and conditions if needed. However, the main purpose here is met by objectives used to examine the trade-offs between financial and technical measures. This is shown through the Pareto front, which considers every point as an independent solar power plant and one of these has been nominated as a candidate. The power generated from each plant at these different sites will be used in the next chapter's analysis by integrating these plants into the Saudi power system.

Hybrid power plants and CSP-alone power plants were optimised in two different cases to provide insights into each system. Locations played a major role in this analysis since investments and other indicators are much lower for some sites. This shows the places that have the highest potential to deploy these technologies. Overall, the choice of which type of solar power plant is the most suitable depends on the purpose of deployment and decision makers' weighting of technical and financial trade-off. CSP-alone power plants are shown to have more SM and hence higher CF, but higher *LPSP* and *LCOE*. Hybrid systems have higher total generation and much lower *LPSP*, which leads to less mismatch between supply and demand and thus a more constant supply. These indicators are summarised in Table 5.2 and Table 5.3 for hybrid systems and CSP-alone systems respectively.

Objective	**Operating Area**			
	Afif (COA)	**Hafar Albatin (EOA)**	**Sharurah (SOA)**	**Tabuk (WOA)**
Investment (MUSD)	1,334.23	1,414.54	1,397.76	1,269.68
PV investment (MUSD)	540.118	513.878	514.508	495.063
CSP investment (MUSD)	794.115	900.659	883.250	774.616
LCOE (USD/MWh)	103.54	117.38	102.55	99.93
PV capacity (MW)	380	334	345	361
CSP capacity (MW)	92	106	96.9	101
CSP capacity factor (%)	52	44.58	56.77	53.34
PV capacity factor (%)	24.41	23.24	25.78	24.66
E_{total} (GWh)	763.82	747.17	813.94	805.97
LPSP (%)	12.81	14.17	7.08	7.99
Storage Hours (h)	14.92	14.25	15.27	13.93

Table 5-2 Summary of some indicators for the hybrid system power plants

Objective	Operating Area			
	Afif (COA)	Hafar Albatin (EOA)	Sharurah (SOA)	Tabuk (WOA)
Investment (MUSD)	922.91	914.73	926.66	930.10
LCOE (USD/MWh)	138.00	156.91	127.96	118.96
CSP capacity factor (%)	74.23	66.41	77.55	84.44
CSP capacity (MW)	97.9	94.9	102	101
E_{total} (GWh)	636.88	552.50	693.02	749.16
LPSP (%)	27.30	36.93	20.89	14.48
Storage Hours (h)	15.17	16.72	15.56	15.42

Table 5-3 Summary of some indicators for the CSP-alone power plants

5.4 Summary

In this chapter, two-stage multi-objective optimisation was used with multiple variables and indicators to evaluate the two different systems. Hybrid and CSP-alone solar power plants were tested in four different sites. An optimisation model generated a non-dominated set of solutions, each of which is a possible power plant, and in this process one point was carefully picked up considering technical and economic trade-offs. This model can be applied in different sites to examine the possibility of deploying these technologies. In addition, different scenarios can be investigated by applying new constraints or objectives to the model depending on the purpose of the policy or decision maker.

Chapter 6 **Power System Modelling**

6.1 Introduction

In the previous chapter, solar generation time series for 2015 have been generated, which will be employed in the power system analysis in this chapter. The Saudi power network will be modelled in this chapter to integrate renewables and assess their value within the system. Time series demand for the year 2015 with available generation data will be used in this chapter. The study will include an assessment of the impact of solar generation on meeting the demand, as well as the economic dispatch of the system. An analysis will be undertaken to investigate the impact of large solar generation penetration into the system. This will illustrate the operating cost of the system at different times of the year and the system production prices. Economic dispatch will also illustrate the impact of solar power and an increase in fuel prices on the fuel used to supply energy in the KSA. Three different types of solar power plants will be used in this study, including PV, CSP and hybrid solar power plants.

6.2 System Description

Part of this work involves building a representative network for the Saudi power system to simulate different studies and perform power system analysis. There is no publically available information or studies that provide a holistic representation of the Saudi electricity system due to the sensitivity of the data. This research will provide a Saudi test network to be used by researchers for research and development purposes.

For the purpose of this study, data were gathered from SEC after a field trip to understand the nature of the Saudi grid and the entire electricity generation system. The system considered consists of more than 3000-buses, including more than 600 conventional generation units based on the 2015 Saudi power system. A highly simplified 8-bus network of the transmission high voltage 380kV level has been used for the analysis carried out in this work. A schematic in Figure 6.1 shows the representative network that will be used in this study to perform power system analysis; this can be compared against the geographic map of the system in Figure 2.1. In the next sections, more details will be provided about the network formulation and parameters arranged throughout this process. Some of these technical operating parameters might not be used in the current study, but they will be available for any extended future research. These parameters include the unit commitment model and transmission constraints, which will provide for another stage of studying the Saudi power system.

6.2.1 Network Data

The considered network is based on the Saudi 380kV high voltage level grid. While there are over 3,000 buses in the system, this is too large for efficient analysis in this thesis. There are formalised 'network reduction' methods available in the literature which seek to produce a much simpler network topologies that are electrically similar to the real system. Here a very simple approach has been followed. The aim was to have a minimum of one bus for each zone and a bus for each major city whilst capturing the main inter zone transmission corridors. This implicitly assumes that the flow within the zones are unconstrained and it is understood that this is a reasonable assumption as the main constraints in the system are between zones. The connection between each zone involve multiple lines, each with their own flow limit. The resulting network, encompassing 8-buses, represents the major transmission system in the KSA, including 4 major areas and 4 important cities considered as a subset of COA, 17 lines and 20 demand centres. Network buses and lines are shown in Tables 6.1 and 6.2 respectively. The loads at each node and line capacities are shown in appendix C. There is one interconnection to the surrounding gulf countries, but it is ignored in this study due to the negligible amount of power exported from the KSA to these countries or vice versa at this time, and to ensure the simplicity of the model at this stage. The work at this point is focused on developing and validating a test network that could run an economic dispatch and manage the integration of solar power plants. Further development of this model could include extra components, such as including interconnection to the GCC or Africa through Egypt. It will be possible to make additions to the model to examine different purposes and comprehend it in relation to multiple aspects.

The Saudi power system is still largely state owned and bundled; thus, this study deals with a vertically integrated power system environment.

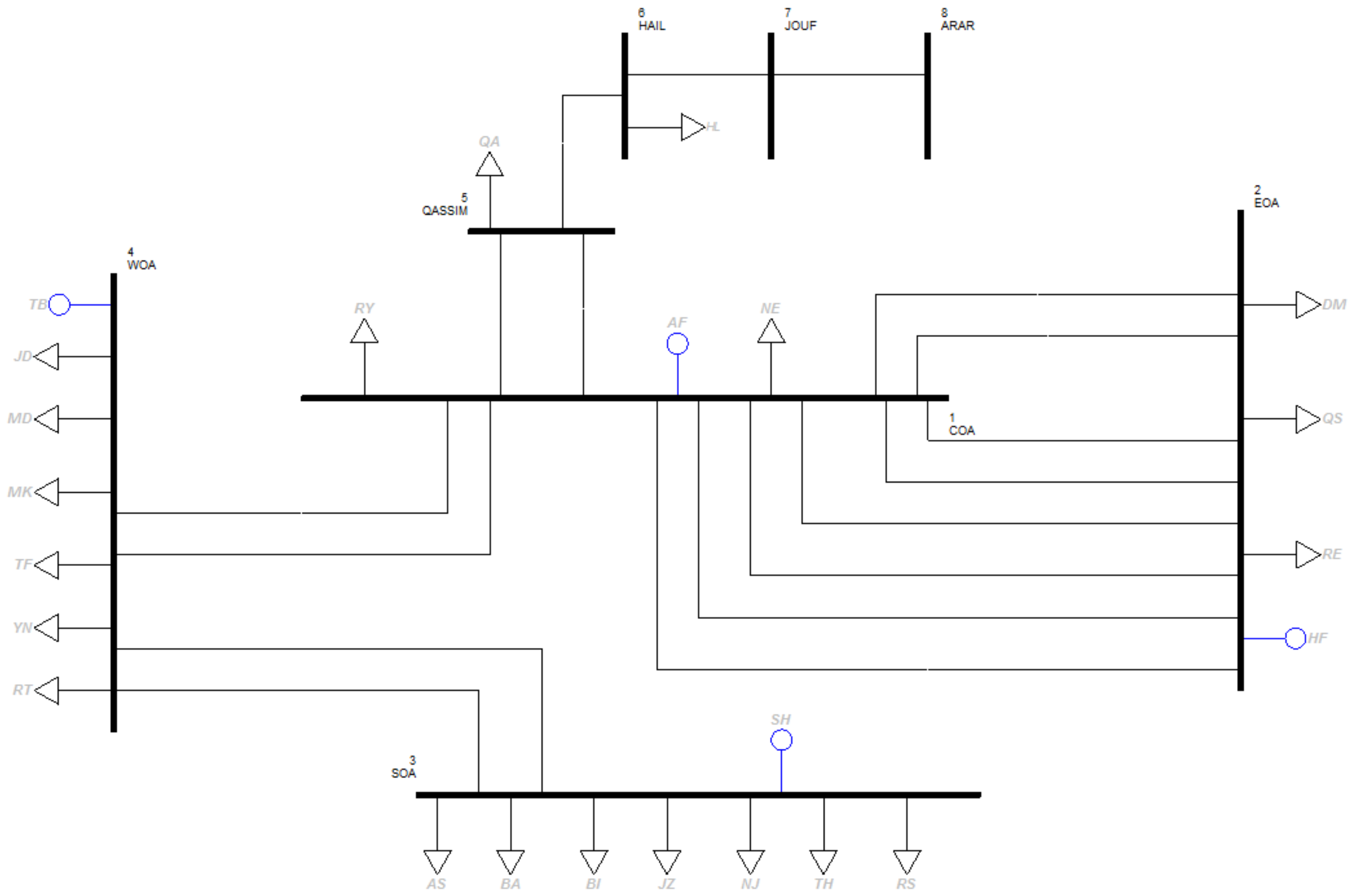


Figure 6.1 One line diagram 380kV test network for KSA

Zone ID	Zone Name	Area
1	COA	COA
2	EOA	EOA
3	SOA	SOA
4	WOA	WOA
5	Qassim (Qas)	COA
6	Hail	COA
7	Jouf	COA
8	Arar	COA

Table 6-1 380kV test network busses

Line ID	Line Name	From	To	Capacity	Reactance
1	EOA to COA	2	1	1,000	0.3389
2	EOA to COA	2	1	1,650	0.5593
3	EOA to COA	2	1	1,650	0.4711
4	EOA to COA	2	1	1,650	0.4711
5	EOA to COA	2	1	1,650	0.4259
6	EOA to COA	2	1	1,650	0.4259
7	COA to WOA	1	4	1,650	1.529
8	COA to WOA	1	4	1,650	1.529
9	SOA to WOA	3	4	1,650	0.9516
10	SOA to WOA	3	4	1,650	0.9156
11	EOA to COA	2	1	1,650	0.9969
12	EOA to COA	2	1	1,650	0.9969
13	COA to Qas	1	6	1,800	1.0170
14	COA to Qas	1	6	1,800	1.0170
15	Qas to Hail	6	7	1,800	0.6780
16	Hail to Jouf	7	8	800	0.2712
17	Jouf to Arar	8	9	800	0.2712

Table 6-2 380kV test network lines

6.3 Model Formulation and Data

This section introduces the approach and data for assessing the Saudi power system when integrating solar power as a renewable. The approach considers a whole-system with an economic dispatch (ED) framework. This is a mature method in short-term planning and therefore it will assist in simulating and investigating the contribution of solar integration and assessing other aspects related to the system, such as operation cost, curtailment, and other parameters. Several studies have already been published using stochastic and deterministic approaches. However, studies show that system operators avoid using stochastic optimisation not only due to the computational time it takes, but also because of non-transparent procedures related to determination and weighting scenarios [209]. Therefore a deterministic approach is employed here.

The ED is implemented using the mathematical method of mixed-integer linear programming (MIP) [210]. This method has gained importance based on the advantages it provides, in this case for the ED model. These advantages are related to strong capabilities in handling complex constraints, solution feasibility, and level optimality. The model was first developed at the University of Edinburgh through a simulation algorithm using the AIMMS optimisation environment [211]. However, in this study the model is taken from its simple state two-bus model and developed to meet the objective of this study. This involves, but is not limited to: generation parameters, network parameters and their corresponding variables, and constraints for economic dispatch, such as solar constraints where the model is developed to incorporate three different types of solar power plants. In the following subsections, the model using input data is discussed in detail.

6.3.1 Conventional Generation Units

Power in the KSA is generated from different sources, for which all generators are included in this study except from IPPs. Generation is divided by type with regard to generation technology: OCGT, CCGT, ST and diesel

(DE), as listed in Table 6.3. Fuel types used by these generation technologies are shown in Table 6.4 and each technology is assigned a certain type of fuel. For example, OCGT accepts gas, crude and diesel. CCGT is working with gas and crude. ST power plants are run with gas and HFO. Diesel engines are run with diesel. This diversity will be considered throughout this analysis, and is complicating factor; most other studies tend to use well defined fuel types relating to specific technology types. The conventional thermal generation capacity is 63.6 GW as of 2015 and in the data prepared for this study. OCGT dominates the capacity generation mix in the KSA and these generators have the capability to respond quickly to any variation in demand, which means providing reserve because of their short time for start-up. Parameters related to generators are included in this study; this comprises marginal cost and technical limits.

Gen Type	Units	Capacity (MW)
OCGT	537	33,618
CCGT	27	13,358
ST	36	16,542
DE	15	119
Total	**615**	**63,637**

Table 6-3 Conventional thermal generation capacity connected to grid

Code	Fuel Type	Units	Capacity (MW)	Mix (%)
1	Crude	245	20,249.3	32%
2	Diesel	151	6,259.5	10%
3	Gas	195	27,461.9	43%
4	HFO	24	9,666	15%
Total	**-**	**615**	**63,636.7**	**100%**

Table 6-4 Fuel type used by generation technology

6.3.2 Solar Power Plants

Solar generation poses a challenge for system operators when used as a primary energy source due to its uncertain and variable nature that needs to be predicted and forecast. In this analysis, time series from the solar power plants modelled in the fourth chapter will be used and integrated into the system. Hybrid, PV and CSP power plants will be employed independently in this study. Different scenarios will be considered and solar output power will be scaled in terms of GW and location to investigate its impact on the system.

6.3.3 Demand Time Series

Hourly demand time series is used as an input to the model. The employed time series corresponds with solar power plants and generation data for the year 2015. Peak load of the demand time series is 59.9 GW. Demand for each operating area is included (COA, EOA, WOA, and SOA).

6.4 Economic Dispatch Model

The economic dispatch model is a one-stage process used to minimise the generators' production cost and hence they are used here to consider the overall system operating cost. This comprises the sum of all committed generators meeting the system demand profile and dispatching in the least cost order. To find the optimal generation, ED will use the incremental cost and constraints of operations [212]. Typically, constrained optimisation is not included, which means no transmission constraint are applied.

In this study, a deterministic approach to the economic dispatch model will be used with different constraints related to the characteristics of each generation unit and system energy balance. This approach has been chosen because the problem associates with a large number of variables and constraints. Deterministic time series are used with perfect foresight assumed, i.e. there is not forecast error.

6.4.1 Objective Function

The ED model will use the input data presented in Section 6.3 and optimise it using the CPLEX 12.6 solver in the optimisation environment. The objective of this model is to minimise the system operating cost to meet the load using a moving horizon principle to provide a solution with an optimal cost for each hour over the entire year. The planning horizon is a year; this model calculates the system cost of energy produced on an hourly and daily basis.

$$C = min \sum_{t=1}^{T} \sum_{g=1}^{G} MC_g \ x \ P_{g,t} + H_{curt(g,t)} \ x \ C_{curt(g)} + C_{uns} \ x \ Uns_{b,t} \qquad 6.1$$

where *C* is the system total operating cost in dollars ($), *MC* is the marginal cost of each generator ($/MWh), which includes fuel and variable operating and maintenance costs, $P_{g,t}$ represents the hourly power output of each dispatchable generation unit (MW), $H_{curt(g,t)}$ is the hourly curtailed solar power from each power plant (MW), $C_{curt(g)}$ is the cost of solar power curtailment ($/MWh), C_{uns} is the cost of the penalty for unserved load ($), $Uns_{b,t}$ is the hourly unserved load at each bus (MW).

Considering Equation 6.1, there are several terms that should be minimised, which is the overall objective of this model. This aims to minimise the variable cost in the first term, curtailment cost in the second term and cost of the unserved load in the third term. Curtailment could happen for several reasons, including oversupply, where available supply exceeds actual demand or would reduce minimum levels of other generation below an acceptable level; congestion; and system balancing, where some grid operators curtail because it is cheaper than shutting down and starting up some power plants [213]. Sometimes, this cost is paid to the owners of these generators for curtailing generation from solar power plants; however, it is used here for the opportunity cost to discourage curtailment and use as much solar power as possible. The load shedding penalty has been set at $1,000 in case of any unserved load and this value is a typical of ISO settings [214].

6.4.2 Constraints

The ED model is subject to several constraints that account for certain measures and ensure the system is running within its operational limits.

System power balance constraints

This constraint is to balance supply and demand in every period:

$$\sum_{g}^{G} P_{g,t} + R_t - H_{curt(g,t)} = d_{b,t} - Uns_{b,t} \quad 6.2$$

where d is the demand at each bus b, R_t is the potential solar resource available which may be curtailed to balance the system when there is an excess. There is a fixed cost of $20/MWh paid when curtailing solar generation.

Generation power output constraints

Conventional generators must be operated within their limitations well above their minimum generation limit $P_{g,min}$ and they must not exceed their maximum power capacity $P_{g,max}$ [215]:

$$P_{g,min} \leq P_{g,t} \leq P_{g,max} \quad 6.3$$

When operating part loaded, the efficiency of conventional generators operate reduces, which can be captured using heat rate that varies with output. Here, all heat rates are considered uniform across the operational range.

A range of other constraints can be applied to examine operation of a power system with solar power, including power flow and unit commitment. Although not used in the case study, they are part of the model used and are presented here for completeness.

6.4.3 Power Flow Constraints

Economic dispatch can be extended to incorporate the constraints imposed by flow limits on power lines. The DC optimal power flow technique was applied instead of AC power flow, which provides less accuracy due to the assumption of lossless energy transfer; however, it is widely used for its reduced computational intensity as the difference between DC and AC models is approximately 5% at high voltages [216].

Power lines have an upper limit on their ability to transfer power. This is normally dictated by the heating effect of power flow and is strongly dependent on ambient temperature. Alternatively limits may be defined by voltage, stability or post-fault flow constraints.

$$-S^{max} \leq n(P_g - d_b + Uns_{b,t}) \leq S^{max} \qquad 6.4$$

where n is the matrix of node arc which relates power injection power flow branches, d_b is the demand vector at a certain bus, S_{line} is power rating (MVA) of the branch.

6.4.4 Unit Commitment Constraints

The model can consider maintaining a defined reserve requirement to be provided by thermal power plants. This provides a way to run the system in a reliable manner, allocating some spare capacity in case unexpected imbalance occurs in the system. According to the North American Electric Reliability Corporation's (NERC) definition, reserve is categorised as spinning reserve and non-spinning reserve [217]. Spinning reserve is not commonly used with economic dispatch processes, but rather with unit commitment. This is the case for systems with large renewable integration in order to counteract the uncertainty of renewables [218].

Unit commitment adds another layer of constraints, governing the minimum amount of capacity that must be held in reserve such that production can be raised or lowered rapidly. Reserve is spread across the fleet of conventional generators and should be carried across the minimum number of units. This allows more realistic operating patterns to be modelled reflecting security requirements, unit flexibility and the costs associated with starting and stopping units. There are several sets of constraints including: reserve volumes, unit state, minimum up and down times and ramp rates [219]. Other aspects can feature in the problem including capturing the costs of unit start up and shutdown, although these are not included here.

Reserve requirements

The reserve requirements are for capacity to be available at all times to allow production to change upwards ($ResUp_t$) or downwards ($ResDn_t$). These set limits to the system power balance:

$$\sum_{g}^{G} P_{g,max} + R_t - H_{curt(g,t)} \geq d_{b,t} - Uns_{b,t} + ResUp_t \qquad 6.5$$

$$\sum_{g}^{G} P_{g,min} + R_t - H_{curt(g,t)} \leq d_{b,t} - Uns_{b,t} - ResDn_t \qquad 6.6$$

where $P_{g,max}$ and $P_{g,min}$ are the maximum and minimum outputs of the conventional generators.

Unit status and output constraints

Not all conventional units are required to be operating to meet demand and to maintain reserve. The unit status $s_{g,t}$ is defined as zero when off – uncommitted – and 1 when on – committed.

The limits on unit output also apply but these are adapted to reflect the operational state of each unit:

$$P_{g,min} \cdot s_{g,t} \leq P_{g,t} \leq P_{g,max} \cdot s_{g,t} \qquad 6.7$$

Unit minimum up and down time constraints

Once a unit is operating it is not desirable to shut it down immediately due to technical and economic considerations. Minimum up time refers to the minimum amount of time the plant must run for. Similarly, once the power plant is shut down it cannot be turned back on immediately and this is what is referred to as minimum down time. Minimum up/down times can vary from hours to days depending on the technology and in this Saudi model the variation is from 0 to 48 hours. The constraints are:

$$(X_{g,t-1} - UT_{g,min}) \cdot (s_{g,t-1} - s_{g,t}) \geq 0 \qquad 6.8$$

$$(-X_{g,t-1} - DT_{g,min}) \cdot (s_{g,t} - s_{g,t} - 1) \geq 0 \qquad 6.9$$

where $X_{g,t}$ is the number of hours unit g has been online(+) or offline (-), and $UT_{g,min}$ and $DT_{g,min}$ are the minimum up and down times.

Ramp up/down rates

Thermal power generators are designed to increase or decrease their output to at a certain maximum rate depending on thermal and mechanical restrictions designed to protect the turbine from damage. This is referred to as ramp up and down rates:

$$P_{g,t} - P_{g,t-1} + s_{g,t-1}\left(P_{g,min} - RUP_g\right) + s_{g,t}\left(P_{g,max} - P_{g,min}\right) \leq P_{g,max} \qquad 6.10$$

$$P_{g,t-1} - P_{g,t} + s_{g,t}\left(P_{g,min} - RDN_g\right) + s_{g,t-1}\left(P_{g,max} - P_{g,min}\right) \leq P_{g,max} \qquad 6.11$$

where RUP_g and RDN_g are the maximum ramp up and down rates. This is given in units such as percentage of unit capacity per minute as units of time, or as MW/h.

Thermal generators are divided into three categories in terms of ramping capabilities: i) high ramping units such as open cycle gas turbine GT (OCGT), which ramps up/down very quickly; ii) units with less ramping capabilities such as combined cycle CCGT; iii) units that continuously operate at their full potential to meet baseload, such as steam turbines (ST) in the KSA, or nuclear power plants in other countries.

6.5 Base Case Economic Dispatch

It was decided to run a base case economic dispatch as a first step to understand the business as usual case for the system. This considers the fuel cost order used by SEC, and then the prices are varied to look at the changes that occur in the system when fuel prices change. Fuel is sold to SEC at prices that are significantly cheaper than international prices due to a subsidy from the Saudi government. Using the model to vary the fuel prices will provide an opportunity to illustrate subsidy lifting scenarios, as well as the operating cost for the system with and without solar energy. The total annual energy demand for this study is 343 TWh.

As mentioned above, there are four types of fuel used in the Saudi electricity system. The prices in order of cost are: HFO is the cheapest, then gas, crude and then diesel, which is the most expensive; this represents the merit order of these technologies while considering their operational costs. Access from SEC granted the use of the real fuel prices for the year 2015, as shown in Table 6.5; the prices are in dollars per million British thermal units (MBTU).

The model considers the fuel type with respect to technology type, as shown in Table 6.6. This provides a marginal cost range for each technology with respect to fuel to illustrate the complexity of the merit order used by SEC and help understand the following graphs on when to run economic dispatch. OCGT operated by SEC accepts different types of fuel and the case is similar with CCGT and ST. OCGT can be fuelled with gas, crude and diesel. CCGT, for example, will accept gas and crude. Steam turbines are fed with gas and HFO. This is not done by arbitrary matching, however, but rather with certain units specified within the data to show which is accustomed to accommodating a certain fuel type.

Fuel Type	Price ($/MMBTU)
HFO	0.59
Gas	0.75
Crude	1.17
Diesel	2.83

Table 6-5 Fuel prices used in this study

	Min.	Max.	Mean	Median
OCGT/Gas	7.5	53.3	14.5	12.5
OCGT/Crude	5.7	26.6	13.9	12.6
OCGT/Diesel	10.4	47.6	9.6	13.2
CCGT/Gas	5.3	8.1	6.8	6.4
CCGT/Crude	5.1	11.1	9.6	10.6
Steam/Gas	7.2	8.6	7.8	7.6
Steam/HFO	4.7	5.9	5.1	5.0
Diesel/Diesel	8.4	52.5	23.9	21.7

Table 6-6 Technologies' marginal cost range ($/MWh)

The initial run looked at the system performance under the current standard fuel prices. A period of 36 hours in a summer day is shown in Figure 6.2. HFO supplies some part of the baseload with ST technology that is less flexible to going on/offline as it is the cheapest. Since it is a summer day diesel is seen in the dispatch, which will not be visible for a winter day. The full year ED is shown in Figure 6.3. Fluctuations in the dispatch show a merit order that looks different from most of what was found in the literature and this comes from the overlapping between different technologies' marginal costs, representing the complexity of a real system.

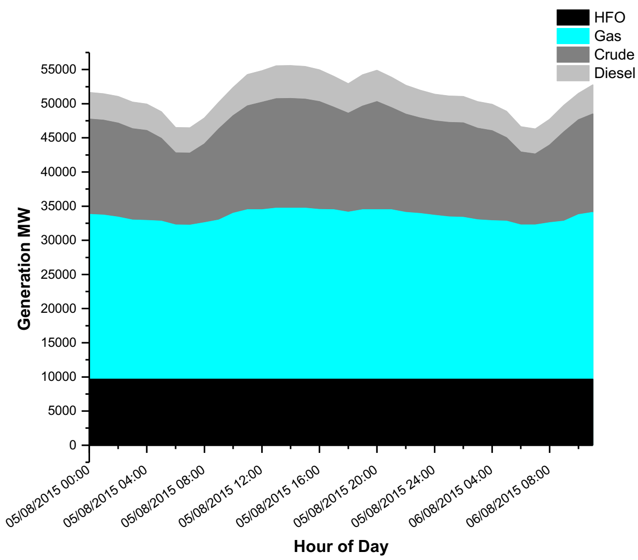


Figure 6.2 Base case 36 hours economic dispatch without solar

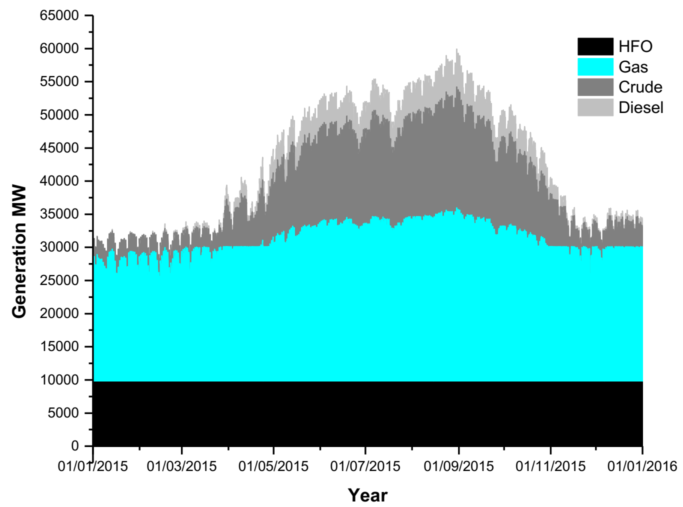


Figure 6.3 Base case full year economic dispatch without solar

Table 6.7 shows the average system marginal price (SMP) for the system and current operating cost. SMP is the cost paid for operating when producing an electricity unit in each hour and the strike price is determined by generating the last megawatt unit to meet the demand [220]. Sometimes this concept is called the shadow price in the electricity market. In this model, one single SMP is produced for the entire country each hour with respect to the hourly dispatch period. Solar power is treated as a must-run generator. The SMP is influenced by several factors, which makes it different from one hour to another because of the consumption pattern variation. Therefore, demand changing, as apparent in the daily cycle or seasonal variation, besides the marginal cost of each generator, drives the SMP in this work. In the real market there are lots of factors that may impact the price of SMP, but this is difficult to count for in a real situation [221]. In this case, the system operating cost is dominated by fuel prices and variable operating and maintenance costs.

Fuel types used in the base case full year economic dispatch are shown in Table 6.8. This is dominated by gas fuel at 176 TWh, about 51.4% of the fuel used over the entire year. HFO follows, with 24.6%, which is mostly used for baseload with ST generators. Crude is next with 18.8%, and finally diesel with only 5.2%.

Price	Average SMP ($/MWh)	Operating cost (million $)
Base case	10.56	2,608

Table 6-7 Full year base case system operating cost and SMP

Type	Heavy (GWh)	Gas (GWh)	Crude (GWh)	Diesel (GWh)
Base case	84,674	176,549	64,674	17,729

Table 6-8 Annual fuel variations in base case ED

Several runs were carried out for different sensitivity scenarios: i) increasing all fuel prices by 25%; ii) doubling all fuel prices; iii) doubling fuel prices, one at a time. This allows different indicators of the system to be envisaged for different scenarios. The system operating cost increases by 25% when increasing fuel prices by 25%, but this becomes almost 150% when fuel prices increase by 100%. This is increasing non-linearly because each fuel type and generator has its own independent price.

Fuel is sold to SEC at less than the international price and thus varying fuel prices will allow to see which fuels impact the operating cost the most. These prices are expected to increase in the future to match the international market and liberate the electricity market in the KSA. When the price of crude is doubled, for example, the system is forced to use as much gas as possible and then use diesel when there is no other option. The operating cost will go very high, by approximately 98%, but fuel will not change much from the base case. Doubling the diesel price will not make much difference in terms of operating cost due to its limited use and already high price; however, it will significantly lower the usage of diesel in the system. Fuel variations after doubling the price of each are shown in Table 6.9. This does not show fuel variation for the 25% and 100% increased price scenarios because change only happens in the cost, while fuel variation is unnoticeable in this case.

Table 6.10 shows the numbers related to increasing fuel prices by 25%, 100%, and one at a time. First, all prices increased by 25% and then 100%. Second, diesel was increased by 100% and other types were not altered; this was run in a similar manner for every fuel type. These prices are significantly affected by the system complexity. When doubling gas or HFO prices, used fuel does not change much, but there is around 11.7% difference, meaning HFO has a higher operating cost. This is because the system makes a comparison between used technologies and fuel prices and tries to opt for low marginal cost technologies.

Type	Heavy (GWh)	Gas (GWh)	Crude (GWh)	Diesel (GWh)
Base	84,674	176,549	64,674	17,729
Diesel	84,674	182,300	76,408	81
Gas	84,674	106,972	148,842	3,020
HFO	84,674	106,927	148,842	3,020
Crude	84,674	176,726	64,303	17,760

Table 6-9 Fuel variations upon fuel prices variation over a full year

Price change	Average SMP ($/MWh)	Operating cost (million $)
Increase (%25)	13.21	3,256
Double (%100)	26.42	6,497
Diesel	11.5	2,619
Gas	16.4	3,681
HFO	16.4	4,112
Crude	21.51	5,180

Table 6-10 System operating cost varying fuel prices

6.6 Photovoltaic Power Plant Integration

The preceding sections have focused on preparing a valid test network and using it to simulate the system as a basic and reference case with current conditions and no renewable integration. This section focuses on the integration of a PV solar power plant into the power system. Marginal O&M for the solar PV plant is assumed to be zero, as found in different studies [222] and in the SAM model [203].

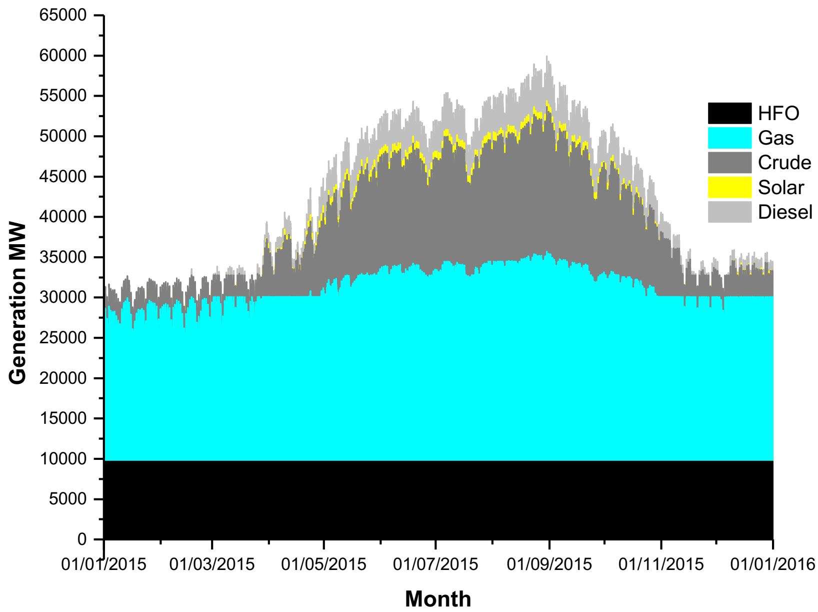
A series of PV power plants will be located within each system area, COA, EOA, SOA and WOA, corresponding to the locations identified in Chapter 4: Afif, Hafar Al-Batin, Sharurah and Tabuk, respectively. Many studies employ a 'standard capacity' for PV plant and scale this at different locations, while accounting for the different resource time series. In this work, the PV capacity comes directly from the hybrid CSP-PV analysis in Chapter 5 and as a result slightly different power plant characteristics apply to each location, in addition to the different resource time series.

The design optimisation stage in Chapter 5 optimises for the solar field depending on the irradiation received by each site. The maximum power generated from each plant is: 380 MW, 334 MW, 345 MW and 361 MW, corresponding to Afif, Hafar-Al-Batin, Sharurah and Tabuk respectively. The overall maximum power generated from these four plants is approximately 1.4 GW. Then, different levels of solar generation are considered in relation to the system, assuming two plants in each area, 10 plants, 20 plants and 40 plants, which is an extreme case to reflect a solar power-rich system. These correspond to installing 2.8 GW, 14 GW, 28 GW and 56 GW, representing capacity penetrations of PV in the four areas.

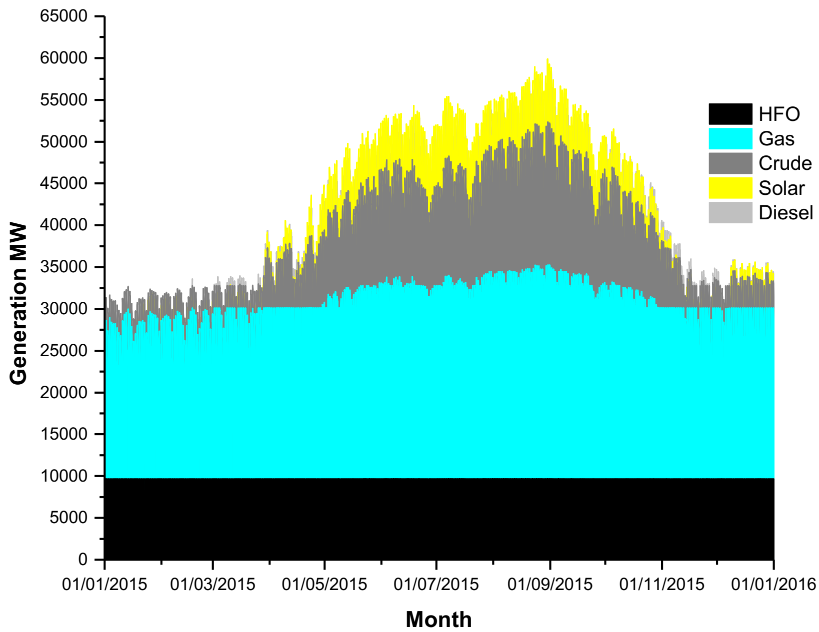
6.6.1 PV Full Year Simulation

Simulations were carried out using the base case fuel costs for each of the deployment scenarios. Figure 6.4 shows one low penetration case with a single PV installation in each area, 1.4 GW with all combined, and one higher penetration case (14 GW). Curtailment takes place in the higher penetration cases 20 and 40 plants, where it impacts the operating system cost. At the same time, thermal generation output is not stable and it can be affected by a high penetration of PV since it is only available for half of the day. The variability of solar PV drives variability in thermal generation output.

It is noted that greater PV generation coincides with the summer period, when the peak demand occurs. High PV penetration offsets generators with high operational costs, but once PV output is absent again these high cost generators will need to be used for balancing. Therefore, increasing PV penetration tends to decrease the operating cost, but beyond a certain level this is not as valuable because curtailment costs will start to increase. This is presented in Table 6.11, which shows the results of simulations considering different scenarios of generation penetration. Curtailments begin once there are 20 PV power plants in each area, although the overall costs still decrease. This decrease reverses with 40 PV plants in each area, when the system operating cost begins to increase with curtailment costs outweighing savings; the level of curtailment is significant at approximately 13% of potential production. In the low penetration case, with one plant in each area, solar power provides only 0.9% of the demand, which lowers the annual overall operating cost by 1.6%. 10 PV power plants shows clear displacement of diesel fuel towards the mid-year. Fuel decreases by 20%, 17% and 9.5% for diesel, crude and gas respectively. Solar penetration in this case is approximately 9.5% of the demand and this lowers the annual overall operating cost by approximately 8.9%. Table 6.12 presents the fuel variation over the year for each solar penetration scenario. The solar column shows the net solar power after curtailment.



(a) Full year economic dispatch with one PV plant in each area



(b) Full year economic dispatch with 10 PV plants in each area

Figure 6.4 Full year economic dispatch for low and a high case PV penetration

Power plants/area	Average SMP ($/MWh)	Operating cost (million $)	Solar (GWh)	Curtailment (GWh)
1	10.43	2,569	3,143	0
2	10.55	2,543	6,287	0
10	10.15	2,377	31,436	0
20	9.5	2,224	62,866	7
40	5.4	2,352	111,311	14,436

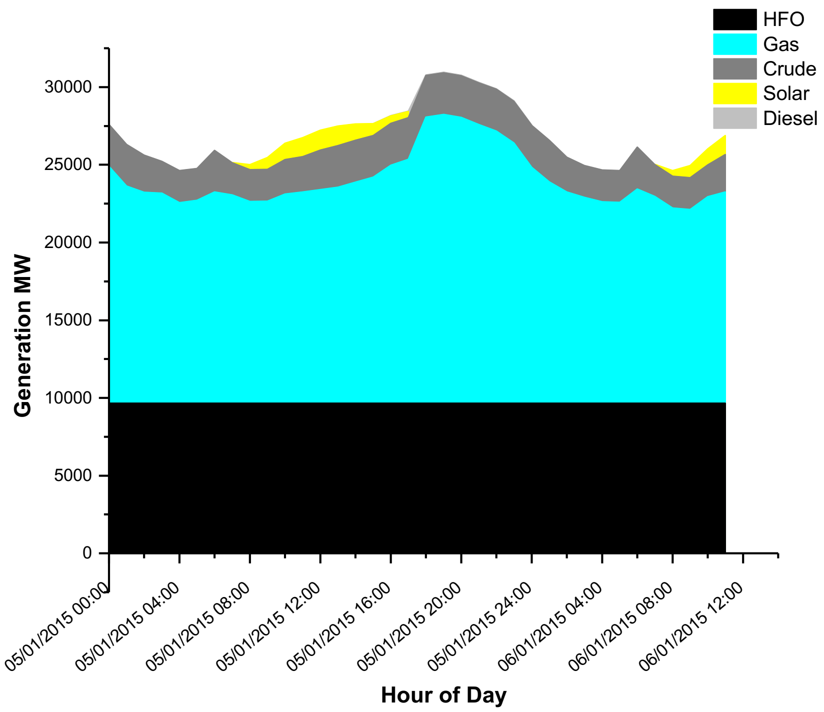
Table 6-11 System indicators simulating different scenarios over a full year integrating PV

Type	Heavy (GWh)	Gas (GWh)	Crude (GWh)	Diesel (GWh)	Solar (GWH)
Base	84,674	176,549	64,674	17,729	0
1 plant	84,674	174,850	63,395	17,401	3,143
2 plants	84,674	173,442	62,009	17,051	6,287
10 plants	84,665	159,640	53,488	14,232	31,436
20 plants	81,707	141,732	45,748	11,410	62,866
40 plants	67,201	115,709	39,164	10,077	111,311

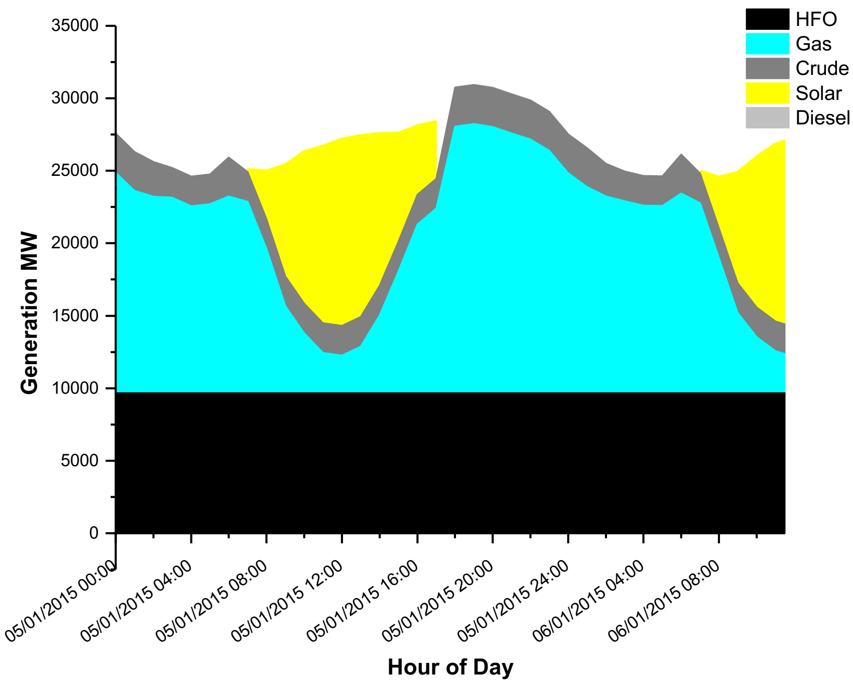
Table 6-12 Annual fuel variations simulating for different levels of PV solar power plants

6.6.2 PV Winter Day Economic Dispatch

KSA suffers from high seasonal variation, specifically between the winter and summer seasons. A snapshot of exactly 36 hours, the planning period for the model, from the winter season is shown in Figure 6.5 for the two cases with 1 and 10 plants in each area for lower and higher penetration respectively. This allows a closer look at the PV addition during the winter season for two different levels of penetration.



(a) One day economic dispatch with one PV plant in each area in winter



(b) One day economic dispatch with 10 PV plants in each area in winter

Figure 6.5 Winter season one day economic dispatch integrating PV

The impact of solar is clear in both cases with PV providing power between 7am and 5pm, peaking at around 12pm. The volumes of energy are very different between the cases: at the low penetration level a modest ~ 1.3 GW contribution reduces the amount of gas used during this period; while in the higher case, the contribution peaks at around 12.9 GW, resulting in a very marked reduction in gas and crude to a lesser extent. The shape very strongly resembles the 'duck curves' seen in other work. For the low case 1 PV plant in each area, and for 10 PV plants in each area, with a total of 14 GW in all areas, the operating cost drops by 1.1% and 8% respectively.

Table 6.13 shows the fuel variation over a 36 hour horizon with different levels of PV solar power. This saves 12,308 MWh and 58 MWh of gas and diesel respectively by adding just one plant in each area. If adding 10 plants in each area, this saves 112,811 MWh, 7,569 MWh and 115.3 MWh of gas, crude and diesel respectively. The fact that the impact is spread across multiple fuels reflects the diversity of their use in Saudi.

More than 20 plants will result in curtailment, resulting in negative prices for hourly marginal cost, which essentially represents the fuel saved from conventional power plants replaced by renewables. This will at the same time add curtailment costs.

Type	Heavy (MWh)	Gas (MWh)	Crude (MWh)	Diesel (MWh)	Solar (MWh)
Base	347,976	526,853	89,469	352.5	0
1 plant	347,976	514,544	89,760	295	12,049
10 plants	347,976	414,042	81,900	237.2	120,494

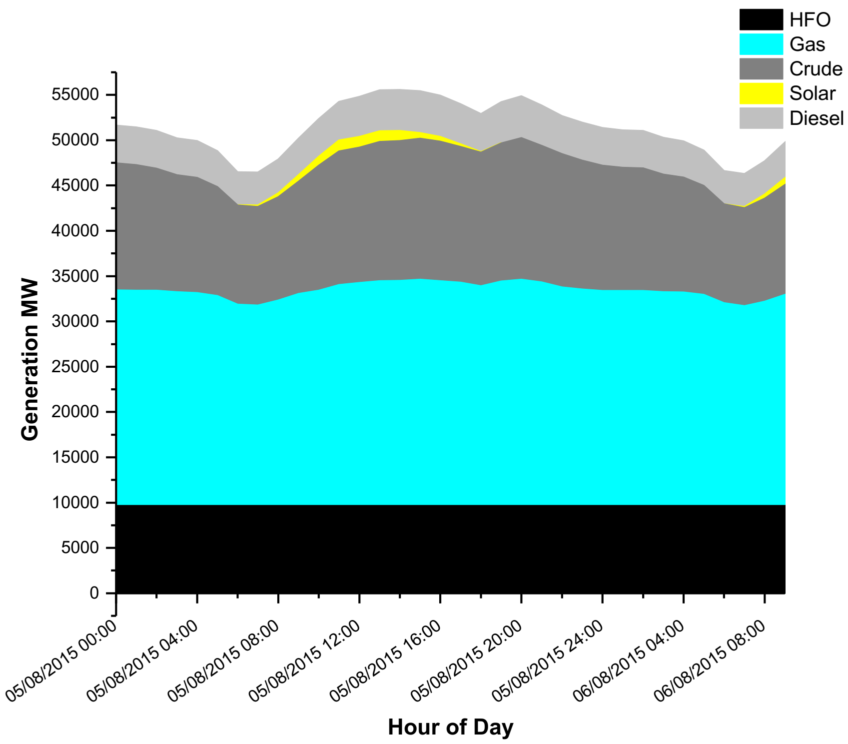
Table 6-13 Fuel after different levels of PV penetration over a horizon of 36 hours in winter season

6.6.3 PV Summer Day Economic Dispatch

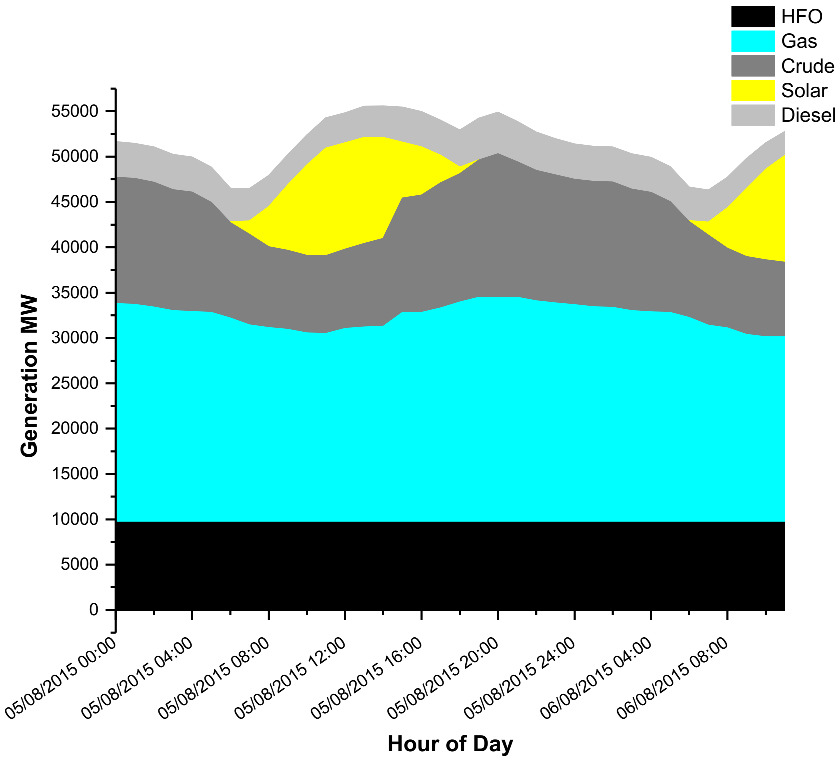
This section is intended to show PV solar performance in the summer season by following similar procedures to those outlined above. Summer marks the peak demand and solar power plants produce the highest amount in this time, which makes it the best time to investigate PV contribution.

Figure 6.6 provides a snapshot of 36 hours of the two cases with low and high penetration level, 1 and 10 PV solar power plants in each area. It clearly shows that the system uses more expensive fuels to cover the high demand, in this case more crude and diesel.

The impact of a longer day is clear in both cases, with PV providing power between 6am and 7pm, peaking at around 11pm. The volume of energy is very different between the cases: at the low penetration level around ~ 1.2 GW contribution reduces the amount of diesel, crude and then gas used during this period; while in the higher case, the contribution peaks at around 11.8 GW, resulting in a very significant reduction in the same fuels. Diesel is used for the summer day, while it is not used for the winter day. The overall effects are more modest in the summer and solar output is low, which is related to the choice of day.



(a) One day economic dispatch with one PV plant in each area in summer



(a) One day economic dispatch with 10 PV plants in each area in summer

Figure 6.6 Summer season one day economic dispatch integrating PV

Due to the coincidence of demand peak and high solar output, PV will displace the more expensive fuels, diesel and crude as the most expensive fuels. This case saves about 3,363 MWh, 7,247 MWh and 1,409 MWh of gas, crude and diesel respectively for the low penetration case. This becomes 37,778 MWh, 66,784 MWh and 15,614 MWh of gas, crude and diesel respectively with the high level penetration; the effect on crude is most significant. Table 6.14 shows the fuel change over the period of 36 hours using the two different scenarios.

Type	Heavy (MWh)	Gas (MWh)	Crude (MWh)	Solar (MWh)	Diesel (MWh)
Base	347,976	857,874	492,604	0	150,368
1 plant	347,976	854,513	485,356	12,017	148,959
10 plants	347,976	820,096	425,819	120,177	134,754

Table 6-14 Fuel after different levels of PV penetration over a horizon of 36 hours in summer season

6.7 Concentrated Solar Power Integration

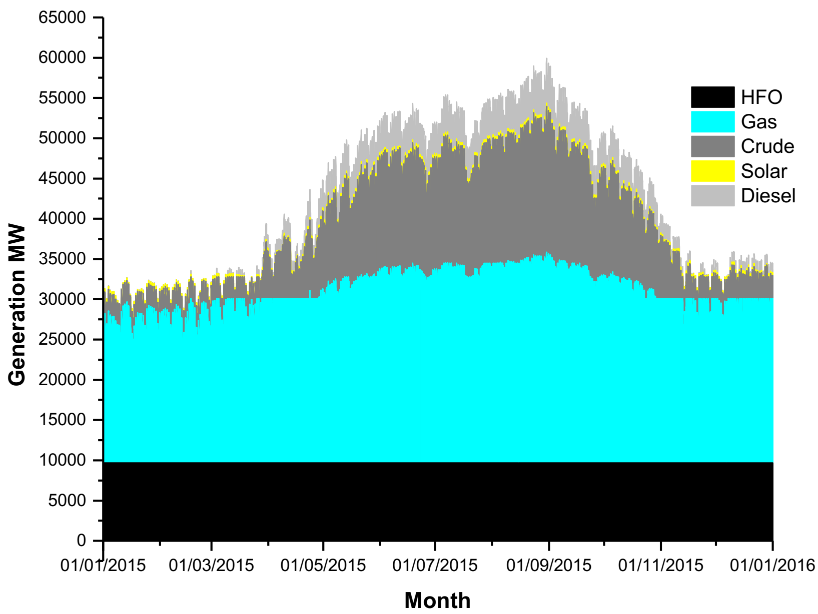
Analysis is now repeated for the concentrated solar power (CSP) plant. This behaves very differently since the power plant is designed to meet certain criteria outlined in Chapter 5. Specifically this related to the extent to which the plant could provide a target 100 MW of firm power, and examples were chosen with relatively high levels of reliability which involved substantial energy storage capability. The characteristics of the plants in each area are different depending on the capacity of the thermal storage and power block. The power transferred to the grid is controlled by the size of the power block and the turbine, which in this case is 97.9 MW, 94.97 MW, 100 MW and 100 MW for Afif, Hafar Al-Batin, Sharurah and Tabuk respectively.

Marginal O&M in this case is assumed to be 3.5 $/MWh [203]. These four different plants will be integrated into the system in the first run; then the number of plants will be increased to 2, 10, 20, and finally 40. As the power capacity differs from the PV plants, it should be noted that the actual capacities are lower at approximately 400 MW for all four areas, increasing to 800 MW, 4 GW, 8 GW and 16 GW.

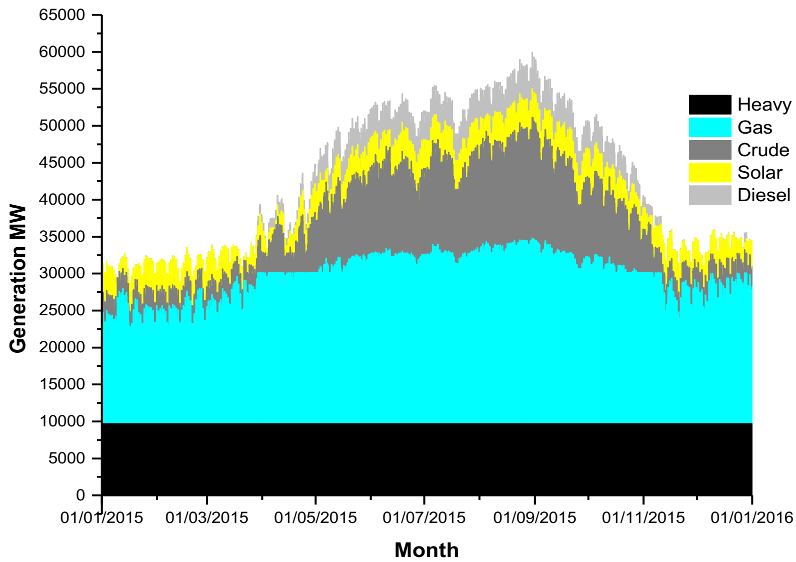
6.7.1 CSP Full Year Economic Dispatch

In the case of CSP, there will not be much variation in thermal generation output compared to PV since the aim was a near constant solar power supply

In comparison to PV integration, CSP provides a constant solar output during the winter and summer seasons, as shown in Figure 6.7, considering the two cases – low and higher penetration. Thermal energy storage backs up any interruption happening due to solar absence meaning the production in the winter is clearly visible even at the low penetration level. The effect at high level is quite pronounced in reducing gas use during winter, and very significantly reducing crude and diesel use in summer.



(a) Full year economic dispatch with one CSP plant in each area



(b) Full year economic dispatch with 10 CSP plants in each area

Figure 6.7 Full year economic dispatch for low and higher cases of CSP penetration

The results for the different scenario simulations are presented in Table 6.15. As power generated from CSP increases, the cost of the system falls gradually. The impact of CSP on the operating cost can be compared to PV integration. The output power from CSP power plants is not large compared to PV power plants; therefore, no curtailment takes place, even in the highest scenario penetration of 40 plants in each area, adding up to 16 GW in all areas. This means CSP has a lower operating cost and average SMP, with more solar output added to the system. The difference is not large. The operating cost is lowered by almost the same percentage in both technologies, going from one to two plants or from 10 to 20; however, this percentage is different in the highest penetration scenario, where it increases by 1.06% with PV and decreases by 12.8% with CSP. This increase for PV is due to the curtailment that does not take place in the CSP 40 plants. A new higher scenario is then added, with 80 plants in each area, and a total of 32 GW in all areas combined. This is purposely added to test for curtailment. Clearly, CSP reduces the system cost per MW more than PV does.

The annual fuel variations with different scenarios of CSP are presented in Table 6.16. It is noticeable that CSP can substantially lower the use of diesel and crude due to its ability to operate continuously. A significant fuel saving occurs when increasing plants from 20 to 40 in each area. This decreases diesel fuel by 51% and crude by 32%. Although PV has higher gigawatts in the similar plant scenarios, it has a lower effect on diesel and crude, thereby decreasing diesel by 11% and crude by 14%.

Power plants/area	**Average SMP ($/MWh)**	**Operating cost (million $)**	**Solar (GWh)**	**Curtailment (GWh)**
1	10.69	2,571	2,572	0
2	10.64	2,550	5,144	0
10	10.20	2,402	25,720	0
20	9.71	2,238	51,441	0
40	8.69	1,951	102,883	0
80	3.7	1,635	202,478	3,288

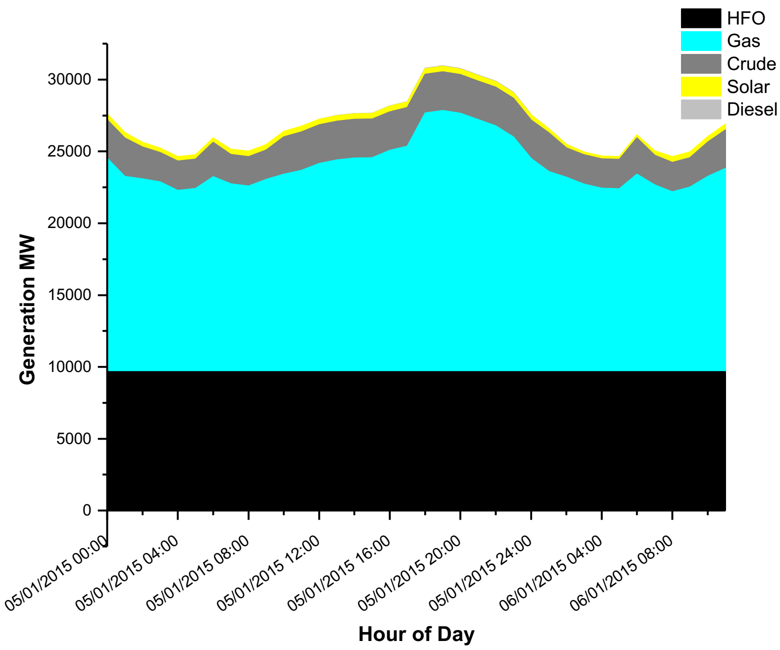
Table 6-15 System indicators simulating different scenarios over a full year integrating CSP

Type	Heavy (GWh)	Gas (GWh)	Crude (GWh)	Diesel (GWh)	Solar (GWH)
Base	84,674	176,549	64,674	17,729	0
1 plant	84,674	175,418	63,334	17,466	2,572
2 plants	84,674	174,125	62,369	17,150	5,144
10 plants	84,674	163,235	54,860	14,973	25,720
20 plants	84,674	149,141	46,184	12,022	51,441
40 plants	83,773	119,612	31,333	5,861	102,883
80 plants	63,969	58,498	16,650	1,868	202,478

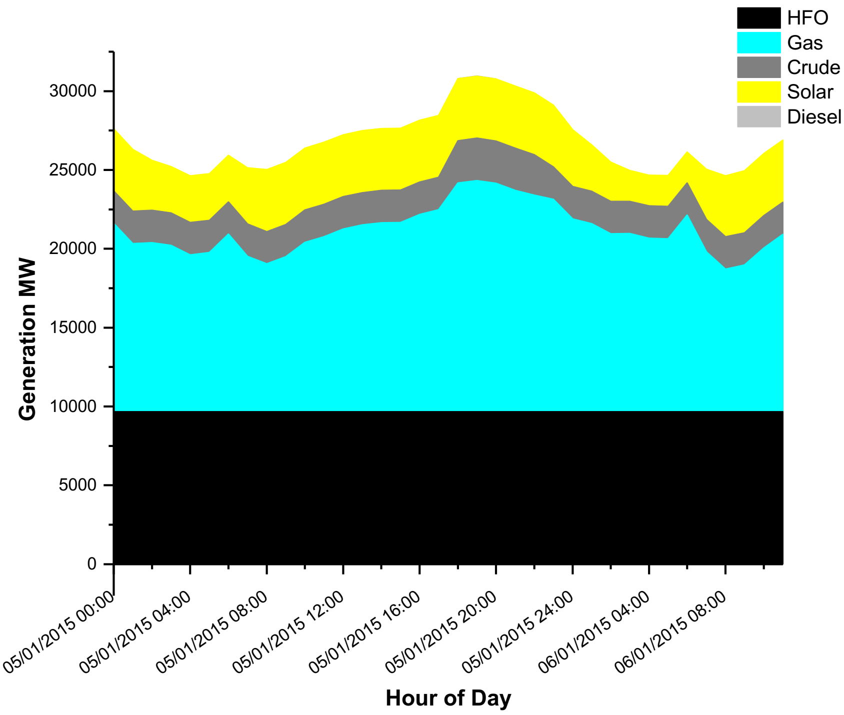
Table 6-16 Annual fuel variations simulating different levels of CSP solar power plants

6.7.2 CSP Winter One Day Economic Dispatch

This section shows how the system operates over 36 hours, the period in planning, with CSP over a winter day. This is shown in Figure 6.8, with low and high penetration cases. Adding one CSP plant in each area will save about 21% of diesel fuel, and 10 will decrease the diesel fuel required by 93% in that time. Table 6.17 show the amount of fuel saved using the two different penetration levels.



(a) One day economic dispatch with one CSP plant in each area in winter



(b) One day economic dispatch with 10 CSP plants in each area in winter

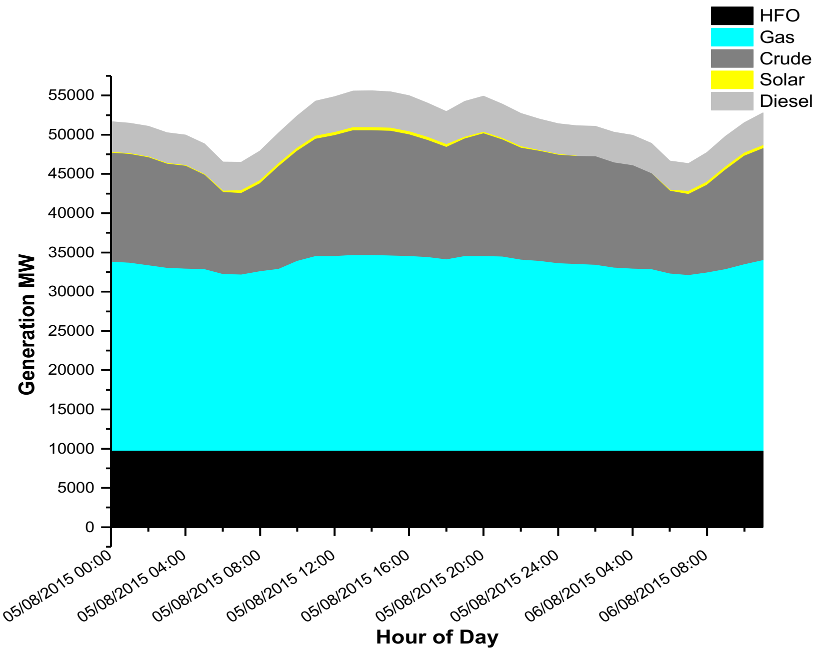
Figure 6.8 Winter season one day economic dispatch integrating CSP

Type	Heavy (MWh)	Gas (MWh)	Crude (MWh)	Solar (MWh)	Diesel (MWh)
Base	347,976	526,853	89,469	0	352.5
1 plant	347,976	516,853	87,051	12,492	278
10 plants	347,976	414,953	76,779	124,924	18.5

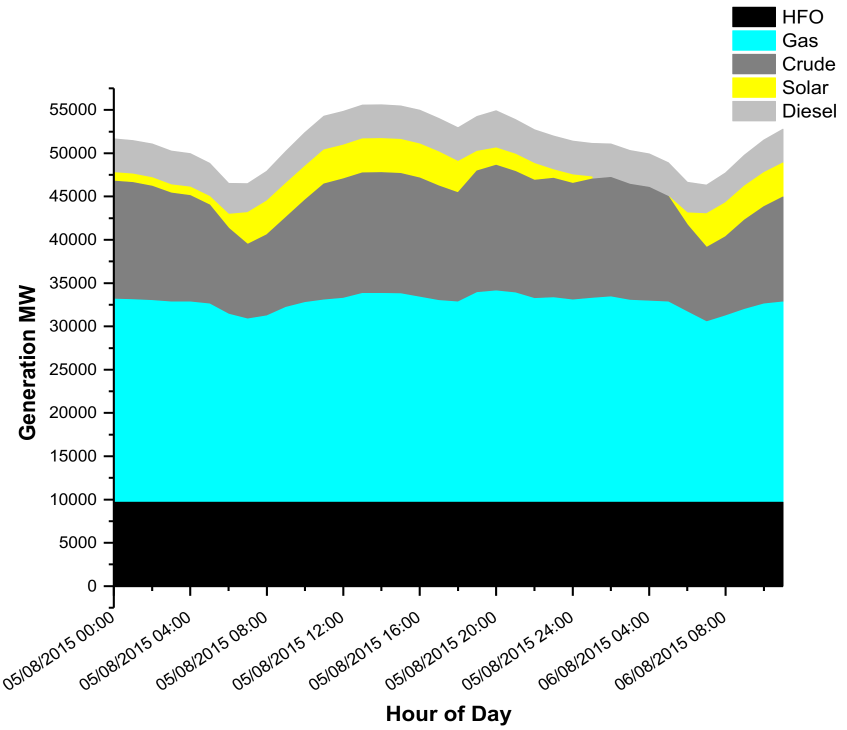
Table 6-17 Fuel after different levels of PV penetration over a horizon of 36 hours in winter season

6.7.3 CSP Summer One Day Economic Dispatch

Even though CSP power plants are supposed to provide constant power, this can sometimes be intermittent because of weather variability. Over the 36 hours of this day in August, solar power did not provide power for about 3 hours in the morning. The output dropped substantially before this incident, discharging the storage, as shown in Figure 6.9.



(a) One day economic dispatch with one CSP plant in each area in summer



(b) One day economic dispatch with 10 CSP plants in each area in summer

Figure 6.9 Summer season one day economic dispatch integrating CSP

Following this, similar procedures to penetrate different levels of CSP were carried out. The results of the simulations are shown in Table 6.12. The fuel amount saved from integrating a 10 CSP power plant in each area was 26,512 MWh, 45,851 MWh and 13,144 MWh for gas, crude and diesel respectively.

Type	Heavy (MWh)	Gas (MWh)	Crude (MWh)	Solar (MWh)	Diesel (MWh)
Base	347,976	857,874	492,604	0	150,368
1 plant	347,976	857,096	488,747	8,548	146,454
10 plants	347,976	831,362	446,753	85,486	137,224

Table 6-18 Fuel after different levels of CSP penetration over a horizon of 36 hours in summer season

6.8 Hybrid Solar Power Plant Integration

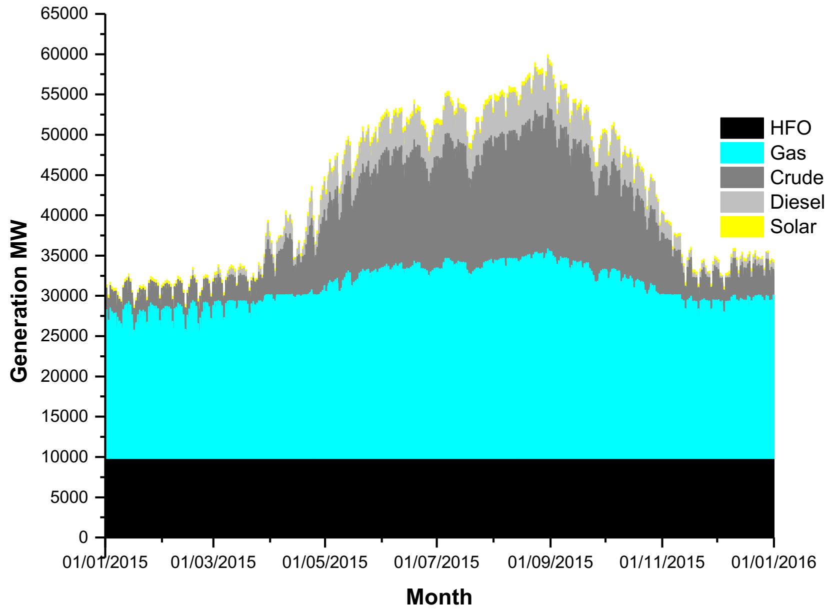
After trying two different technologies integrated into the Saudi power system, the integration of a hybrid solar power system was attempted. The procedures applied to PV and CSP were similarly applied to the hybrid system. The objective was to see how this impacted the operating cost of the system and how much fuel would be saved. Each power plant in this system consists of hybridised PV and CSP power plants, as outlined in Chapter 5. The four hybrid solar plants together were able to produce about 1.7 GW as a maximum. The number of plants was then increased in the same manner performed with the previous two technologies; two plants per area is equivalent to 3.4 GW power from all areas, etc.

6.8.1 Hybrid Full Year Economic Dispatch

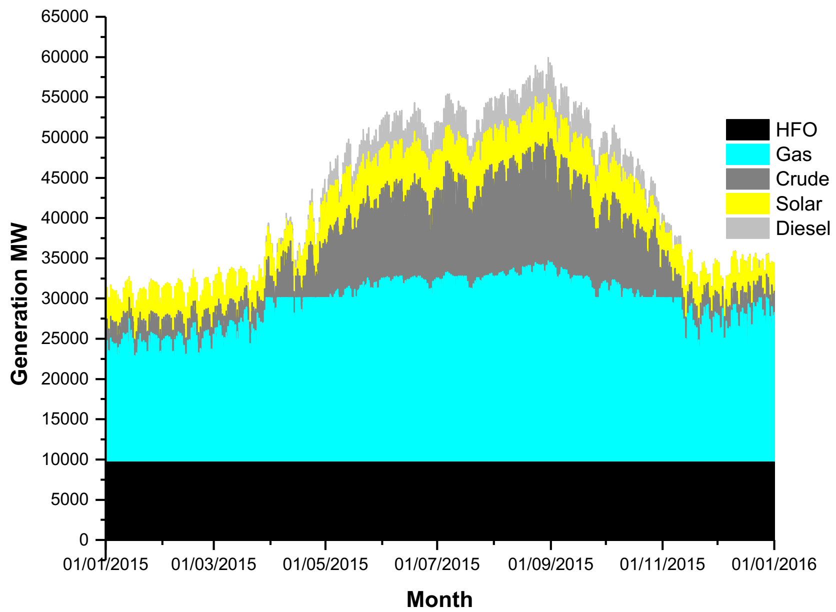
Simulations for hybrid solar power plant integration were carried out to analyse the system in comparison to the previous two technologies' integration. The figures for the two cases are shown in Figure 6.10 and the results for all solar penetration scenarios are presented in Table 6.19. In the low case, the solar power generated is visible all year round since the capacity of each hybrid power plant is up to 500 MW in each area. The impact is very clear in the higher case, where much of the diesel and crude are displaced, particularly during summer.

The system operating cost with one hybrid solar power plant in each area is higher by 0.155% and 0.077% than PV and CSP respectively. By adding one more hybrid solar power plant, so there are two in each area, it becomes cheaper than a system with two PV power plants by 0.51% and by 0.78% for CSP. In the case of the largest scenario, with 40 plants in each area, operating the system with a hybrid plant is cheaper than with PV by 13.7%. The curtailment cost for the system is 3.068 million dollars for the 20 power plants in each area, while it is 355 million dollars for the 40 plants scenario. The system average marginal price is cheaper in the hybrid solar power plant case and it is the cheapest for the system, whether integrating one type of the other two technologies or without any solar power.

Solar power coincides with peak demand hours, which is much cheaper compared to thermal generation. Adding only one hybrid solar power plant in each area will save about 1,719 GWh, 527.2 GWh and 2,624 GWh of crude, diesel and gas respectively, which reduces the annual cost of the system by 1.4%. Saving fuel and reducing the annual operating cost becomes particularly significant when more hybrid solar power plants are added, as shown in Table 6.20. This shows there needs to be up to 20 plants, as beyond that will impose a greater cost on the system due to curtailment. The system operating cost for these power plants are presented below in Table 6.19.



(a) Full year economic dispatch with one hybrid power plant in each area



(b) Full year economic dispatch with 10 hybrid plants in each area

Figure 6.10 Full year economic dispatch for low and higher cases of hybrid penetration

Power plants/Area	Average SMP ($/MWh)	Operating Cost (million $)	Solar (GWh)	Curtailment (GWh)
1	10.35	2,573	4,871	0
2	10.45	2,530	9,742	0
10	9.76	2,260	48,710	0
20	8.57	2,008	97,266	153
40	3.68	2,029	177,071	17,769

Table 6-19 System indicators simulating different scenarios over a full year integrating a hybrid solar power plant

Type	Heavy (GWh)	Gas (GWh)	Crude (GWh)	Diesel (GWh)	Solar (GWh)
Base	84,674	176,549	64,674	17,729	0
1 plant	84,674	173,925	62,792	17,202	4,871
2 plants	84,674	171,704	60,696	16,647	9,742
10 plants	84,599	150,580	47,338	12,236	48,710
20 plants	80,899	122,899	34,641	7,757	97,266
40 plants	65,030	80,355	18,618	2,389	177,071

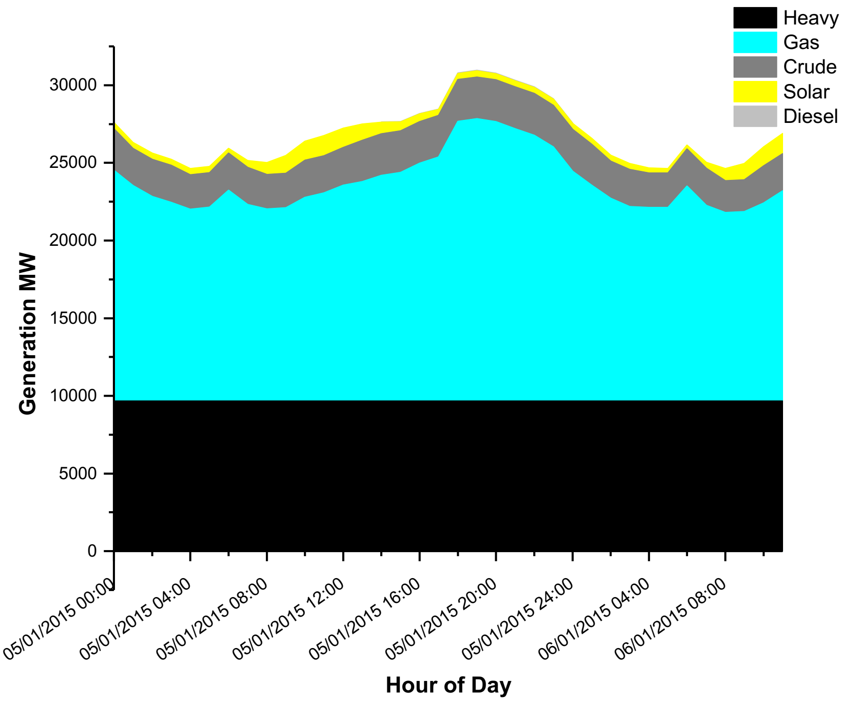
Table 6-20 Annual fuel variations integrating different levels of hybrid solar power plants

6.8.2 Hybrid Solar Power Plant Winter Day Economic Dispatch

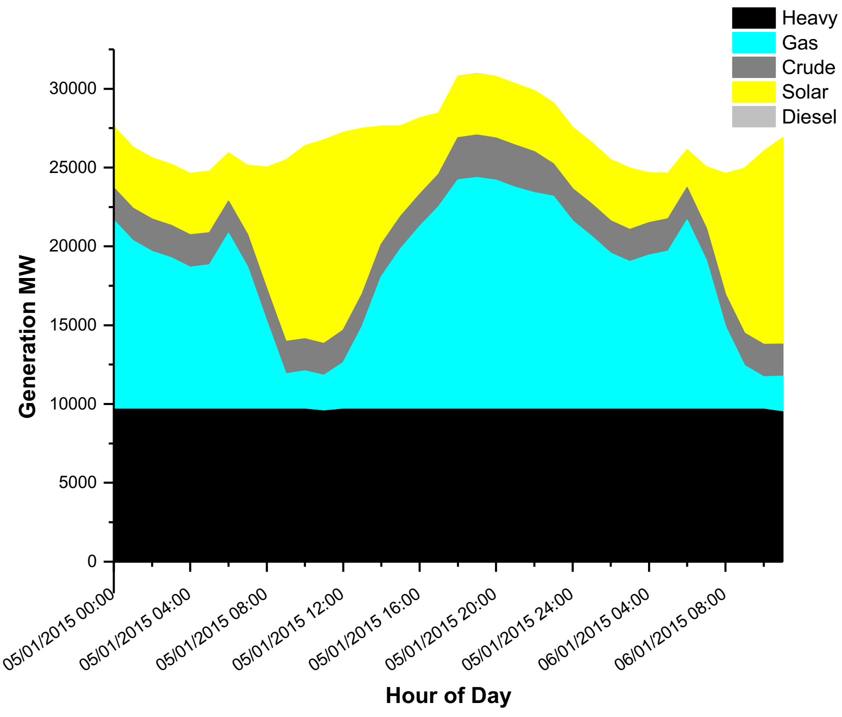
A snapshot of 36 hours was taken for two different levels of penetration – 1 and 10 plants in each area – as shown in Figure 6.11. This was done to stay consistent in terms of comparing this technology with the previous ones although capacities are higher. In both scenarios solar power peaks from 7am to nearly 4pm, when the power mostly comes from PV, and for the rest of the day there is no interruption where CSP is working. There is diesel in the low case scenario but it is displaced by solar in the higher case. Integration of hybrid solar power plants showed better performance during this time compared to PV and CSP. The fuel saved in the course of this period is shown in Table 6.21.

Type	Heavy (MWh)	Gas (MWh)	Crude (MWh)	Solar (MWh)	Diesel (MWh)
Base	347,976	526,853	89,469	0	352.5
1 plant	347,976	506,529	88,345	21,506	294.5
10 plants	347,699	325,078	76,791	215,063	18.5

Table 6-21 Fuel after different levels of PV penetration over a horizon of 36 hours in winter season



(a) One day economic dispatch with one hybrid solar plant in each area in winter

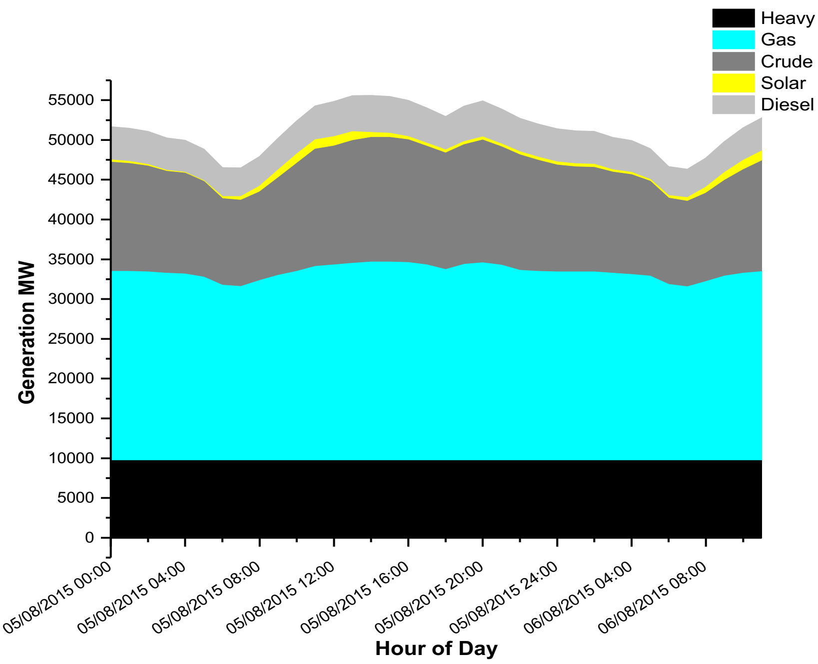


(b) One day economic dispatch with 10 hybrid solar plant in each area in winter

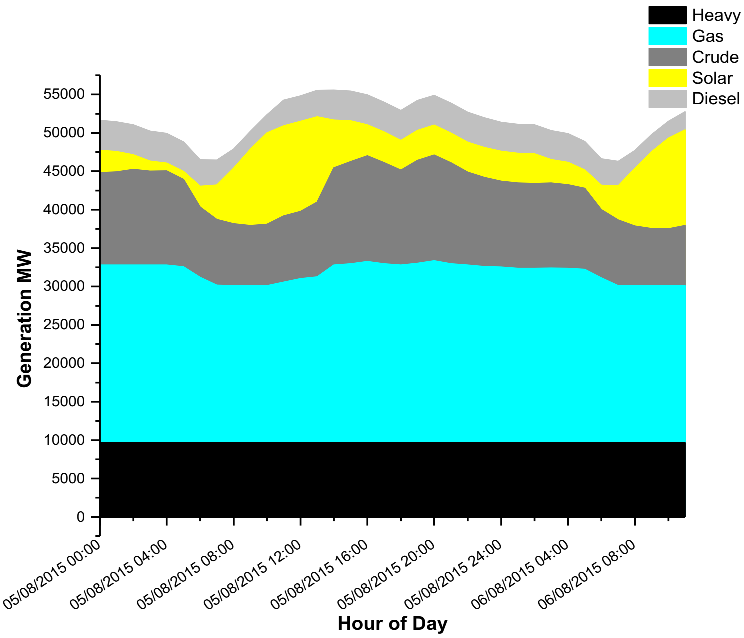
Figure 6.11 Winter season one day economic dispatch integrating a hybrid plant

6.8.3 Hybrid Solar Power Plant Summer Day Economic Dispatch

Here the work intends to show two different cases with different levels of penetration over a 36 hour horizon in the summer, as shown in Figure 6.12. There was an interruption in the CSP scenario used above, but it is clear here that PV helped the CSP to charge the storage and supply constant power for the entire day. Hybrid solar power plants integrated into the system do a better job in displacing fossil fuels than solar technology by itself. This is accompanied with better prices for running the system. The amount of fuel saved over this period, integrating 10 power plants in each area, is 59,559 MWh, 108,373 MWh and 26,050 MWh for gas, crude and diesel respectively. A change in fuel usage is presented in Table 6.22 for the two scenarios compared to a basic case where no solar power is integrated.



(a) One day economic dispatch with one hybrid solar power plant in each area in summer



(b) One day economic dispatch with 10 hybrid solar power plants in each area in summer

Figure 6.12 Summer season one day economic dispatch integrating a hybrid plant

Type	**Heavy (MWh)**	**Gas (MWh)**	**Crude (MWh)**	**Solar (MWh)**	**Diesel (MWh)**
Base	347,976	857,874	492,604	0	150,368
1 plant	347,976	852,193	480,747	19,398	148,508
10 plants	347,976	798,314	384,231	193,982	124,318

Table 6-22 Fuel after different levels of hybrid solar power plant penetration over a horizon of 36 hours in summer season

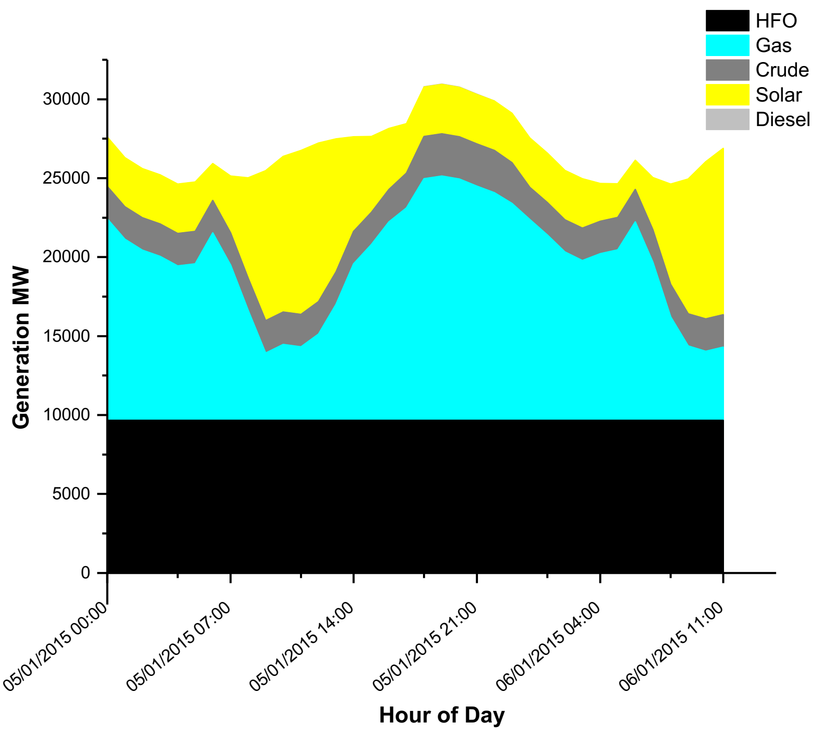
6.8.4 Hybrid Solar Power Plant Economic Dispatch: Sensitivity Study

Since the system performs better with a hybrid solar power plant, the impact of varying the crude price and solar output in each area is investigated in this section. The reason for this is because more thermal generators in the system are set to accept crude and in terms of cost crude comes second after diesel. Simulations are performed for winter and summer cases over a 36 hour horizon. There are 6 plants in Afif and Hafar Al-Batin and 10 plants in Sharurah and Tabuk since they have better irradiation.

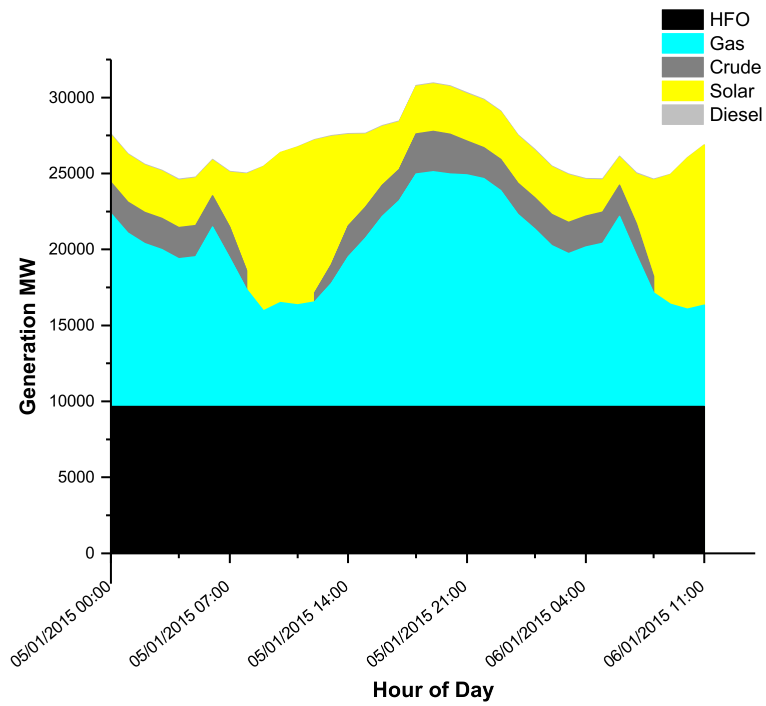
Winter day economic dispatch

The system response to a change in crude price was assessed while varying solar output amongst areas, as shown in Figure 6.13. This is based on the assumption that the government decides to lift the subsidy or some of the subsidy from crude. It is clear that the system has chosen the cheapest fuel, gas in this case, and then once no more gas is available it will opt for diesel.

The average system marginal price and operating cost will increase substantially whenever fuel prices are increased. The results of the simulation over this period are presented in Table 6.23, showing the impact on the system cost. In Table 6.24, the amount of change in fuel before and after increasing the prices is presented. The effect of spatial variation in solar power output is area specific; for example, in this case, it depends on which area has more crude generators and it will be displaced by solar power.



(a) Winter one day economic dispatch with 32 hybrid solar plants



(b) Winter one day economic dispatch with 32 hybrid solar plants doubling crude price

Figure 6.13 Winter one day economic dispatch with/without increasing crude fuel price

Plants	Average SMP ($/MWh)	Operating cost (million $)
Base (no solar)	8.18	5.957
32	7.41	5.229
32/ Δ Crude price	12.38	6.586

Table 6-23 System indicators with and without solar and if crude fuel price increased (winter case)

Price change	Heavy (MWh)	Gas (MWh)	Crude (MWh)	Solar (MWh)	Diesel (MWh)
Base	347,976	527,971	88,387	0	316.7
Yes	347,976	382,213	59,339	173,247	1,875
No	347,976	356,784	77,617	173,247	62.50
Change	-	+ 25,429	-18,278	-	+1,812

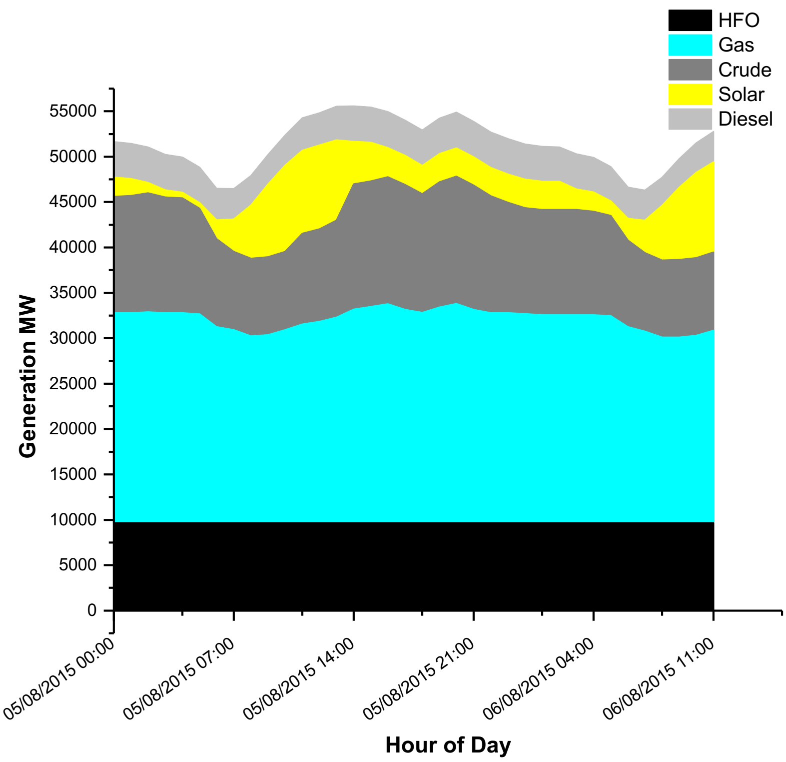
Table 6-24 System with three different cases without solar, with solar, and with solar and increasing crude price (winter case)

Summer day economic dispatch

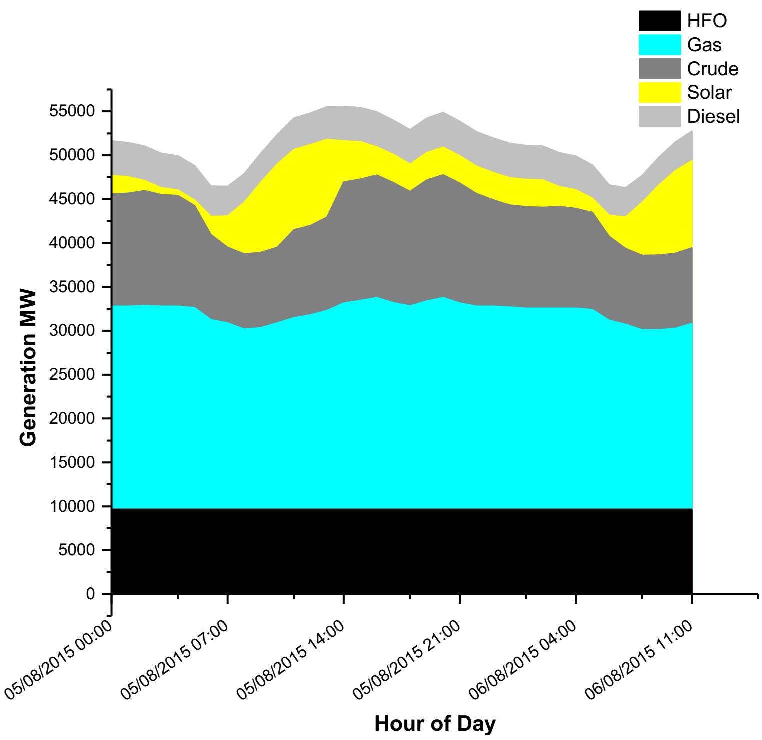
A snapshot of a summer day was included in the study of the system response to solar and crude fuel increase. This is illustrated in Figure 6.14, which shows little variation in fuel even when increasing crude fuel prices.

System prices largely increased, as shown in Table 6.25. The operating cost for the system was decreased over the horizon period by 8.07%, with 32 hybrid solar power plants integrated. However, the system operating cost increased by 55.3% after doubling the crude fuel price. The average of the system marginal price doubled.

The amount of crude and gas saved was limited because there was no chance of substituting, except using more diesel. Table 6.26 shows the variation in the amount of each fuel type. The increase in the system operating price emerges from using more diesel, which is already an expensive fuel, and a large amount of crude at its new price since there is no alternative fuel to substitute.



(a) Summer one day economic dispatch with 32 hybrid solar plants



(b) Winter one day economic dispatch with 32 hybrid solar plants doubling crude price

Figure 6.14 Summer one day economic dispatch without/with increasing crude price

Plant	Average SMP ($/MWh)	Operating cost (million $)
Base (no solar)	12.10	15.597
32	12.12	14.234
32/ Δ Crude price	24.23	24.236

Table 6-25 System indicators with and without solar and if crude fuel price increased (summer case)

Price change	Heavy (MWh)	Gas (MWh)	Crude (MWh)	Solar (MWh)	Diesel (MWh)
Base	347,976	859,490	493,278	0	148,077
Yes	347,976	808,632	406,545	152,256	133,421
No	347,976	809,192	407,149	152,256	132,248
Change	-	-560	-604	-	+1,173

Table 6-26 System indicators with and without solar and if crude fuel price increased (summer case)

Hybrid power plants doubling crude fuel price (10 plants/area)

This case is designed to compare 17 GW integrated into the system, 10 power plants per area, with a similar scenario but increasing the crude price. As shown in Figure 6.15, solar power displaced almost all crude during the winter season and it began to require a few megawatts of diesel. Solar power even slightly touched on the gas fuel during the winter season. During the summer season from May to mid-October the system used least crude and instead more gas and diesel.

Crude usage over the full year decreased by approximately 70% in the doubled fuel price scenario. On the other hand, other types of fuel increased by 77% and 13% for diesel and gas respectively. Fuel variation after increasing crude prices is shown in Table 6.27. SMP and operating cost increased by 27% and 8% respectively.

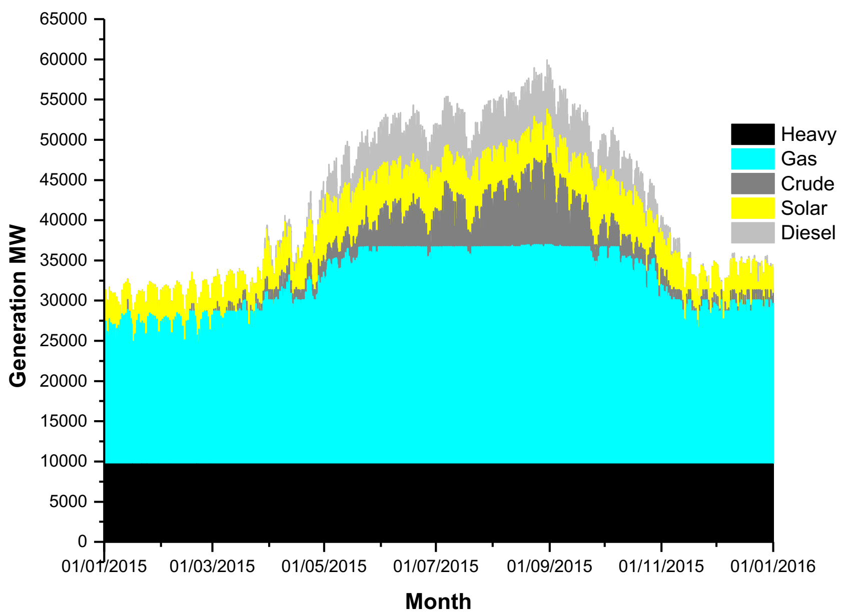


Figure 6.15 Full year simulation of 10 hybrid power plants into the system with doubling crude prices

Type	Heavy (GWh)	Gas (GWh)	Crude (GWh)	Diesel (GWh)	Solar (GWh)
Base	84,674	176,549	64,674	17,729	0
10 plants	84,599	150,580	47,338	12,236	48,710
10 plants Δ price	48,663	174,105	14,237	21,748	48,710

Table 6-27 Fuel variation over a full doubling crude prices

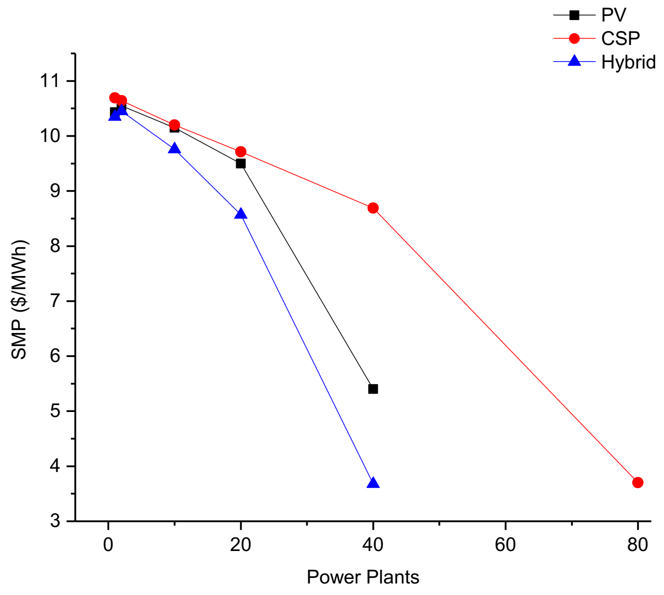
6.9 Comparative Study

Several indicators have been used in this chapter to measure the impact of different solar technologies on the power system. It is of interest to compare the values of these technologies although they have different capacities.

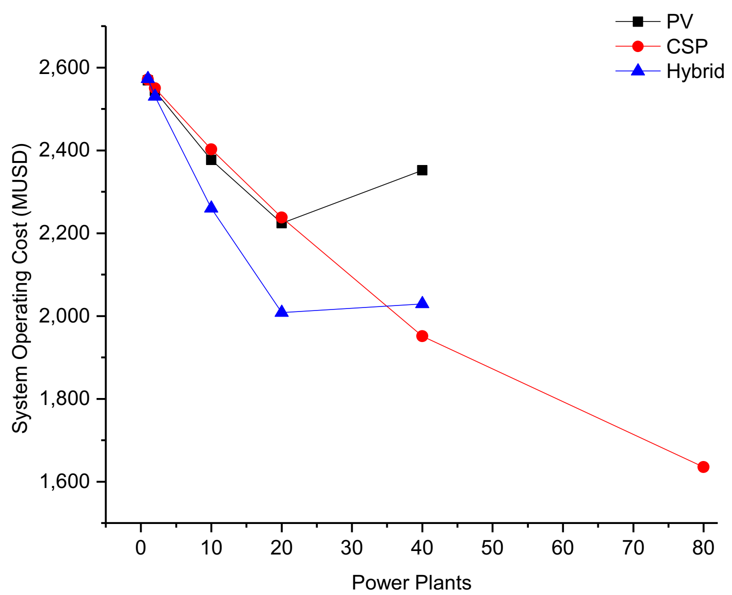
As shown in Figure 6.16 (a), SMP decreases with the increase of solar power. A greater decrease takes place in the hybrid system with the 68 GW scenario and 40 plants per area. The hybrid consists of both PV and CSP technologies. CSP in the 32 GW scenario, 80 plants per area, has a number close to that of SMP in hybrid; however, CSP requires a much greater investment, as discussed in Chapter 5.

The system operating cost for the three different technologies is shown in Figure 6.16 (b). The reverse effect is higher with the PV technology, showing the curtailment impact on the operating system. The effect is not as significant in the hybrid because the system benefits from solar all day and the curtailment cost therefore has less effect on the hybrid scenario. It looks smoother with CSP, but this is because CSP has less capacity from PV, even in the 80 plant CSP scenario, which leads to less curtailment and therefore less impact.

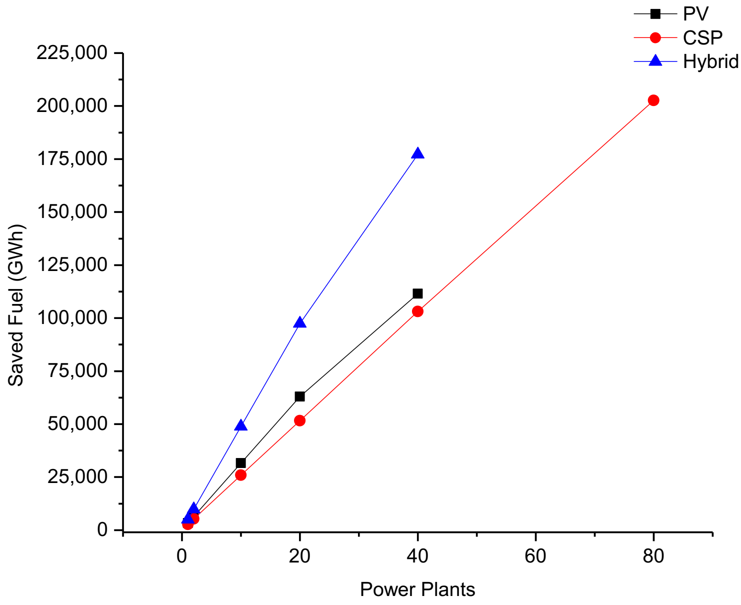
The impact of each solar technology with different solar power integration is shown in Figure 6.16 (c). When 56 GW of PV was supplied to the system, about 111,475 GWh of fuel was saved. CSP has almost the same impact on fuel by supplying 32 GW, saving 103,047 GWh. This is due to the curtailment that takes place in the PV during the day: the diurnal effect. The hybrid power plants show a better performance in saving more fuel because this is utilising the most received solar power. The efficiency of hybrid power plants is evident when comparing adding two hybrid power plants compared to other technologies.


PV
CSP
Hybrid
SMP ($/MWh)
Power Plants

(a)


PV
CSP
Hybrid
System Operating Cost (MUSD)
Power Plants

(b)



(c)

Figure 6.16 Impact of solar technologies on power system

6.10 Discussion

The economic dispatch approach provides a better understanding of the Saudi system operation in terms of fuel prices and solar technology integration. The analysis in this work is designed to look at different aspects that illustrate the advantages and disadvantages of changes to the traditional way of running the system. The issue of fuel prices is a very important aspect to consider as this will have a direct impact on the system, the customers and the government. System operating costs have been presented through different 'what if' analyses of any potential changes in fuel prices. The average SMP is more than doubled if all fuel prices are doubled. This also happens if the crude fuel price only is doubled. Any increase in crude fuel prices will significantly affect the system.

Integrating different solar technologies into the system was investigated in order to evaluate each technology independently. This analysis noted the impact of each technology on the system operating cost, including the curtailment cost, solar addition to the system, and fuel saved. Every technology has its own pros and cons, especially when considering capital cost and related investments. When comparing PV and CSP power plants, the operating cost of PV is cheaper in general. However, when 40 CSP plants were added to each area, it was found to be much cheaper than having PV power plants. This is related to the solar curtailment cost in PV. Overall, the integration of hybrid solar power plants provides better results for the system. It outperforms the other two technologies on all indicators, especially when there are more plants. It combines the advantages of both technologies to provide a robust performance. Considering the seasonal variation, the performance of each technology has been investigated over a short horizon for each technology in winter and summer in order to evaluate the impact and value each technology adds to the system.

Hybrid solar power plants provide best fit integration for the system; significant thermal reduction is observed and replaced with cleaner energy. In this analysis, unserved load penalties were not encountered because there was sufficient generation supply and no power flow constraints on the system.

6.11 Summary

This chapter presented the construction of a complete test network to be used for simulations of the Saudi power system. This included input data, such as generation data, lines, branches and time series for demand. Three different types of solar technologies were optimised through integrating them into the Saudi power system. These different solar power plants were developed in Chapter 4 and employed in this chapter to study and analyse their impact on the system. The analysis showed that the system operating cost benefits from solar technologies in the Saudi power system while using the system actual operating cost.

Chapter 7 **Conclusion**

7.1 Thesis Summary

This study aims to develop a better understanding of the electricity system in the KSA and the available solar resources by evaluating their impact on the system when solar power plants are integrated.

Chapter 1 provides an introduction to the research, its scope and the objectives. It presents the contribution to knowledge and outlines the thesis.

Chapter 2 reviews the KSA and its electricity system, as well as considering aspects that impact electricity, such as geography, climate and the social system. It introduces renewable energy resources alongside some renewable generation types, specifically solar and wind power in the KSA. A general review is provided of key solar concepts and the solar technologies PV and CSP. It identifies that very limited analysis of grid integration of solar power in KSA has been conducted.

Chapter 3 presents a detailed investigation of power generation and demand in the KSA. This includes a study of energy consumption, available capacity, fuel, type of technology and producers in relation to how much energy is being produced. This shows indicators of supply and demand while measuring the average annual growth rate for multiple aspects, such as consumption, fuel and generation etc. The system demand over a one-year period is modelled using hourly time series data. Finally, three different models are used to generate an electric demand forecast for KSA, which is compared to data from SEC.

Chapter 4 provides an analysis of solar energy resources in the KSA to find the best locations with the greatest potential. High resolution data is obtained for this purpose, which is the most recent, with more parameters included to investigate solar resources in depth. Solar resources are compared using satellite-based and ground-based measurements. Spatial and temporal variabilities for the resources are examined, including spatial maps for different models. Several sites are then nominated best locations for deploying solar technologies.

Chapter 5 provides a two-stage multi-objective optimisation which is used with multiple variables and indicators to evaluate different systems. Hybrid and CSP-alone solar power plants are tested in four different sites. An optimisation model generates a non-dominated set of solutions, each of which is a possible power plant, and in this process one point is carefully investigated, considering technical and economic trade-offs.

Chapter 6 presents the integration of different solar technologies using an economic dispatch model. Modelling a Saudi test power network is undertaken and this is used to assess the value of renewables integration. This illustrates the operating cost of the system without any renewables and then shows the impact of solar operating cost using PV, CSP and hybrid energy systems. Several scenarios are used and applied uniformly in all technologies to compare and find best performance. An increase in fuel price for the system is tested and its impact on the system operating cost is shown.

7.2 Contribution

This thesis is the first study to consider large scale solar power integration within the power system of the KSA. This work provides an approach of integrating solar power investigating solar resources, grid, and different solar technologies. It is believed that this work offers a useful insight for solar resources assessment and best locations for the deployment of solar technologies. The representative test network created and used in this research will help those who are interested in the Saudi electricity sector to further study and examine the Saudi power system in different aspects.

It is believed that the evaluation of solar technologies in this work will give realistic technical and financial indicators that help to estimate and compare the financial return from deploying such technologies. At the same time, the results of investigating these technologies will be useful to identify the technologies most suitable for Saudi Arabia. Finally, applying the time series results from the solar technologies in the economic dispatch provides a key contribution of better understanding their impact on the system especially in terms of the fuel and operational cost savings.

7.3 Implications of Research

The thesis ultimately set out to examine the role that solar generation could play in Saudi Arabia. It was clear that the solar resources are plentiful, widespread and their patterns are well aligned with seasonal electricity demand patterns. It was shown that PV, CSP and hybrid PV-CSP were able to deliver substantial volumes of energy that displaced fossil fuel generation resulting in significant reductions in system operating costs. However, the daily availability of solar energy means that without storage, solar cannot deliver all electricity needs. The analysis with CSP and particularly the hybrid PV-CSP, shows that inclusion of storage at plant level assisted considerably in terms of ensuring greater reliability of supply and significant reductions in fossil fuel use. However, as the analysis was conducted using moderate amounts of plant level storage it should be noted that there may be other 'system level' storage solutions available. These outcomes concur with analyses for other renewable resources and locations and demonstrate the universal challenge of integrating renewable energy.

7.4 Limitations and Future Work

Different solar resource approaches were used in this work: satellite-based and ground-based measurements. Satellite-based sources can be employed to find better temporal and spatial resolution for the KSA, perhaps by using MERRA or the satellite application facility for climate monitoring (CM SAF). These sources provide long-term measurements to be used for inter-annual variability, which will help to better understand the characteristics of solar irradiation in the KSA since inter-annual variability affects solar power plant output.

The analysis only included solar resources, but it is worth noting that the future energy mix is set to accept different types of resources. Wind resources have a high potential in the KSA and investigations into this resource will provide more options to balance the energy mix. Nuclear technology is important to include in the model and this can be studied with the energy mix as it can provide a cheap stable baseload dispatch while abating carbon emissions.

The optimisation model used in this work for solar power plants can be expanded and developed to include more scenarios. This can include technical or economic aspects. These scenarios can include PV storage, fossil fuels, and more objectives such as carbon emissions. Moreover, PV and CSP are treated as must run generators in this study while in future study the storage can be used as a part of the dispatch when applying a system level modelling.

This study focused on the value of renewable integration, solar power in particular. It examined the opportunities renewables offer through delivering a more sustainable energy supply whilst maximising hard currency earnings from the sale of oil. This was done by investigating the cost related aspects of the system and the fuel savings, which found it could lower system operating costs and save more fuel. However, it is worth including other renewable resources in the model and studying their effects on the system as well. Power flow constraints should be applied in future to give more insights into the system operations. Applying more dynamic parameters provides the unit commitment of the system, which is another important study area that should be considered in the future. This leads to a more detailed and realistic study of the flexibility of the system, especially the greater capacity of the system, which will affect multiple parameters, such as minimum load level, generation scheduling, uncertainty associated with renewables variability, reserve etc. CSP with storage in this context can be examined when used to supply reserve. Lowering carbon emissions is an important objective that can be included in the model by employing carbon taxes on thermal power plants. This will impose some changes on system operation and consequently on the system operating cost.

Finally, while there are analyses of the cost of solar generation plant and implications of their operation on electricity system operating cost, there is no wider analysis of electricity system capital and operating costs over time. This would be a substantial exercise in its own right but is one that this work could provide a strong foundation.

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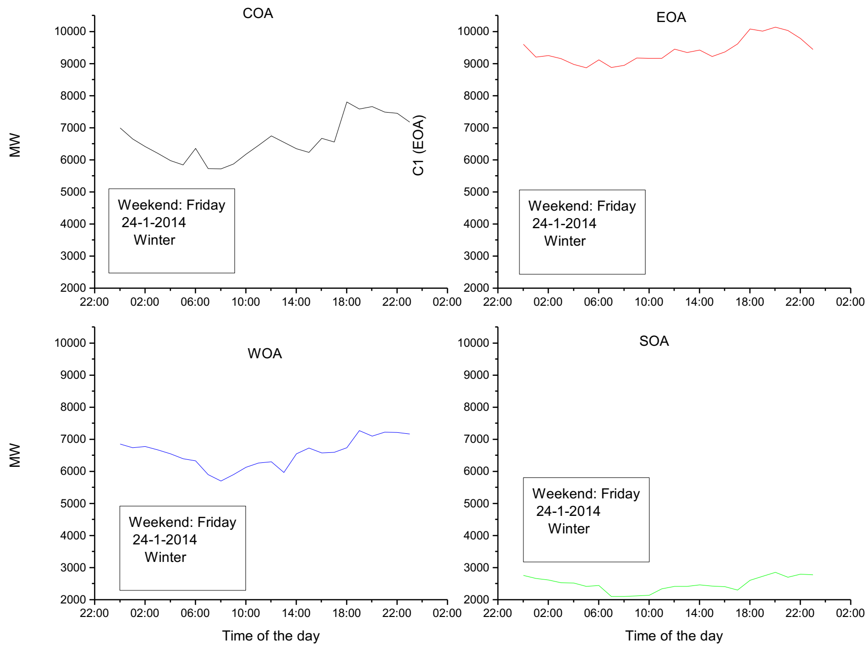
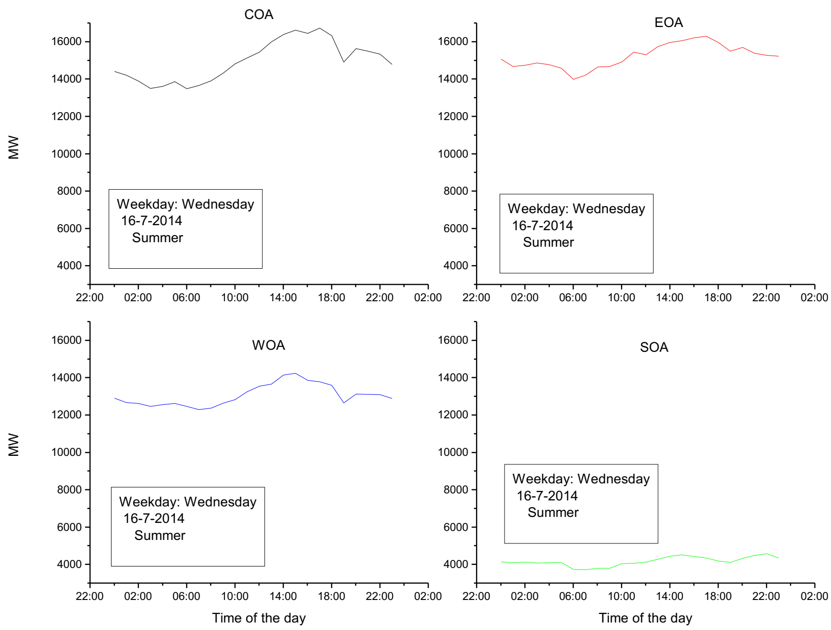
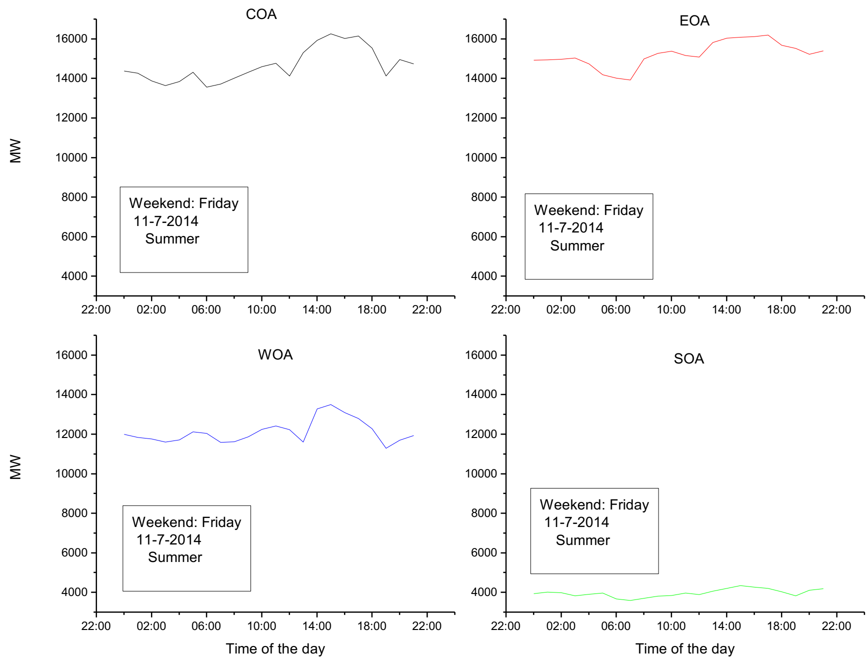
Appendix A



A.1 Weekend load profile during winter 2014 for each region

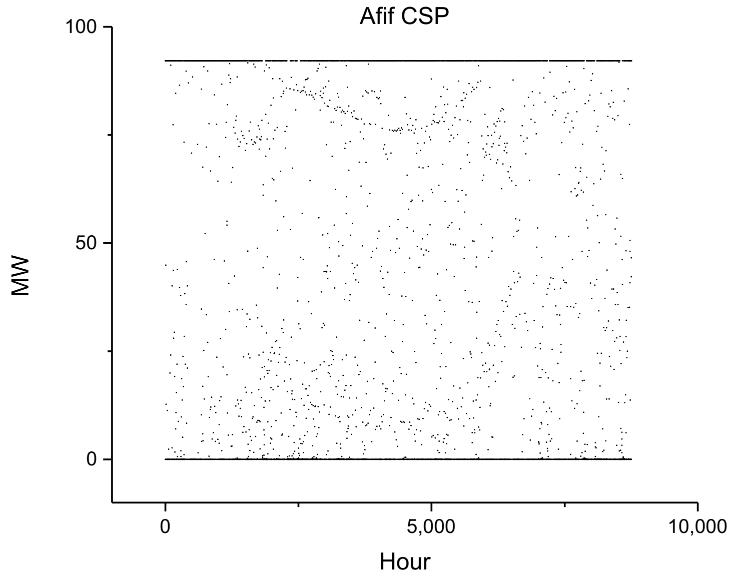


A.2 Weekday load profile during summer 2014 for each region

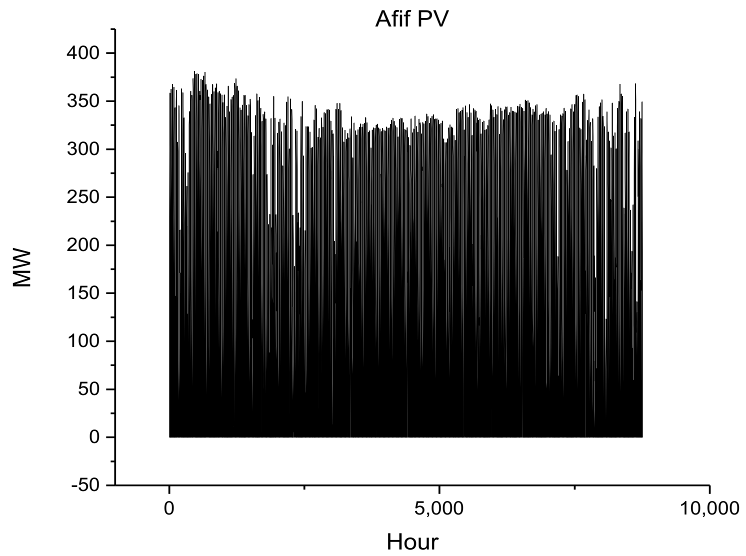


A.3 Weekend load profile during summer 2014 for each region

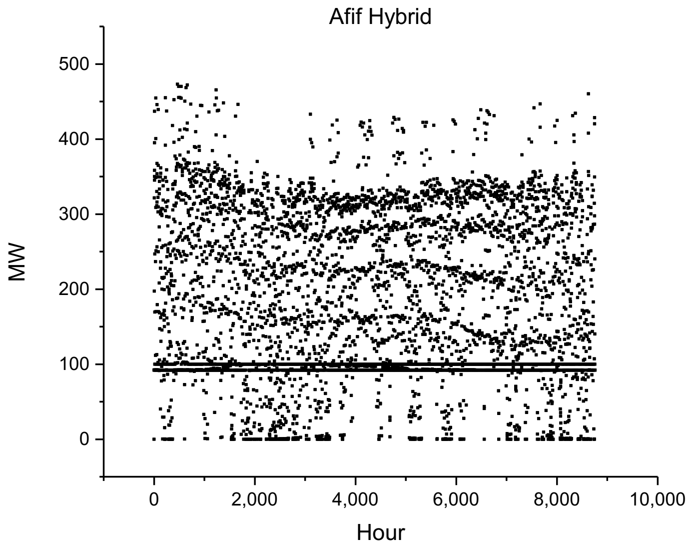
Appendix B



(a)

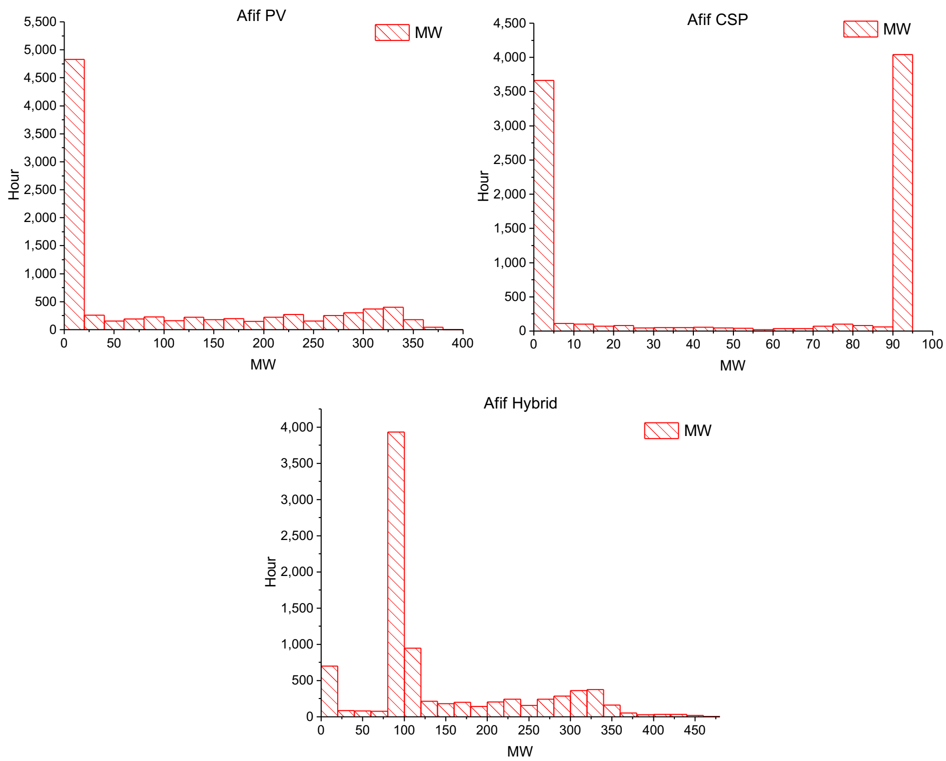


(b)

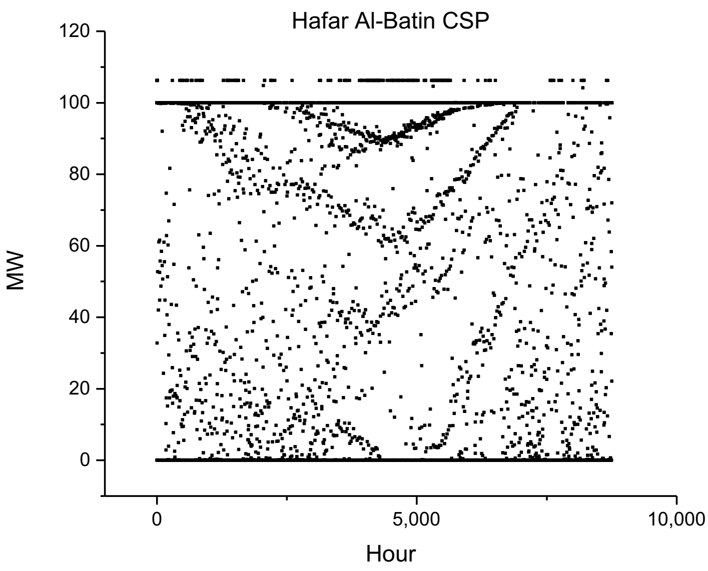


(c)

B.1 Full year hourly profile of hybrid system with contribution of each plant PV+CSP (Afif)

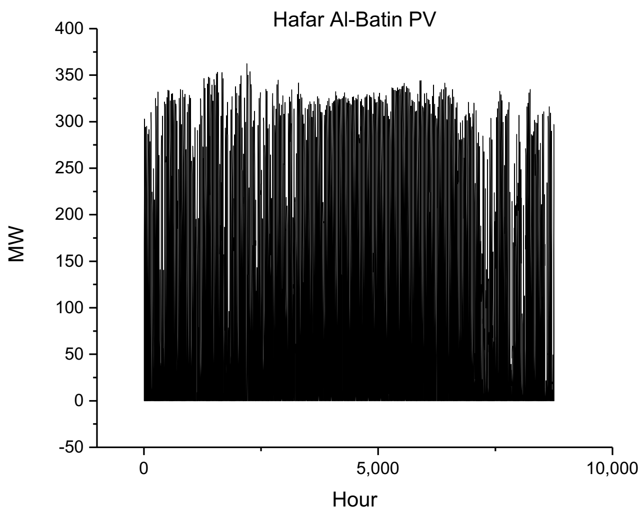


B.2Full year hourly distribution for different technologies in Afif site to show capacity distribution in MW



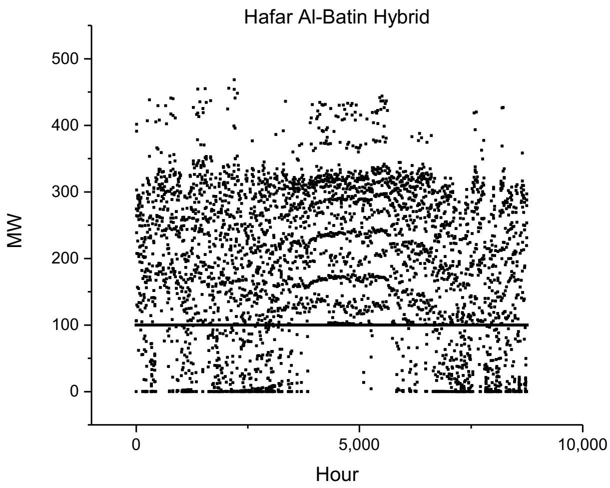
Hafar Al-Batin CSP
120
100
80
60
40
20
0
MW
0
5,000
10,000
Hour

(a)



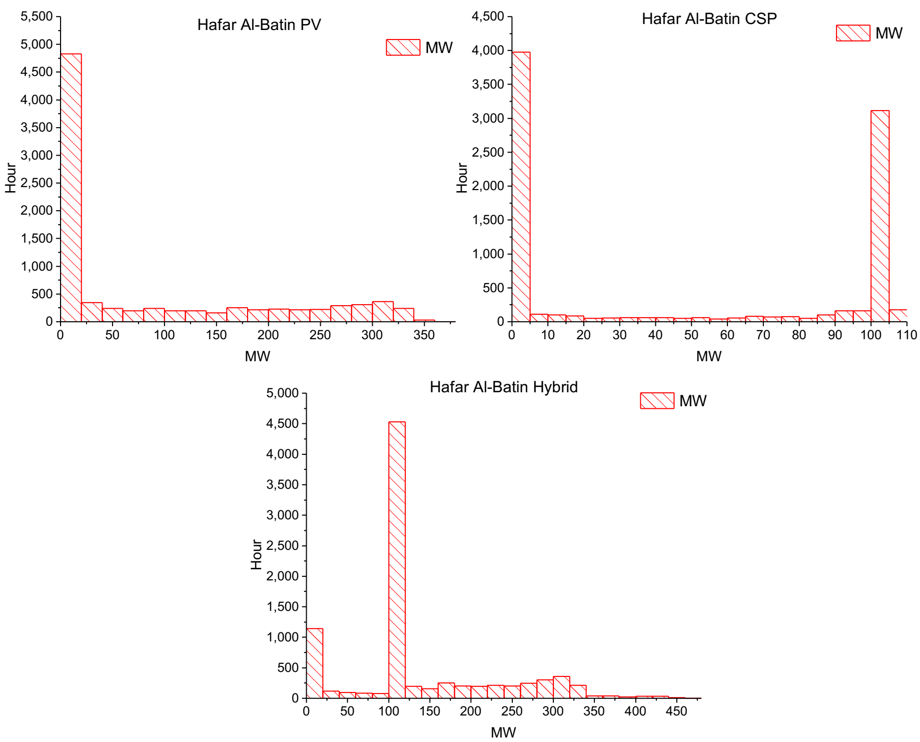
Hafar Al-Batin PV
400
350
300
250
200
150
100
50
0
-50
MW
0
5,000
10,000
Hour

(b)

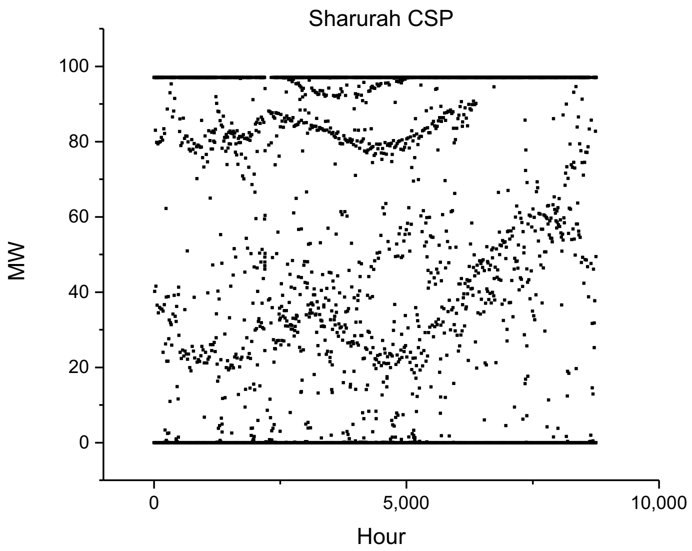


(c)

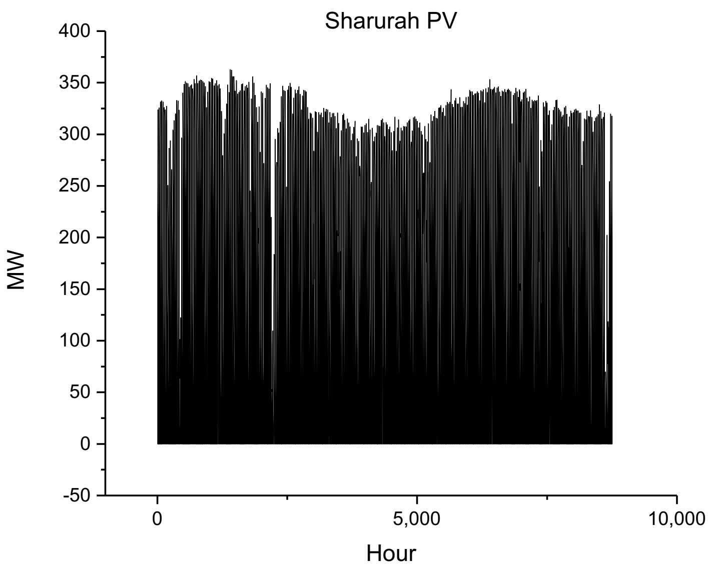
B.3 Full year hourly profile of hybrid system with contribution of each plant PV+CSP (Hafar Al-Batin)



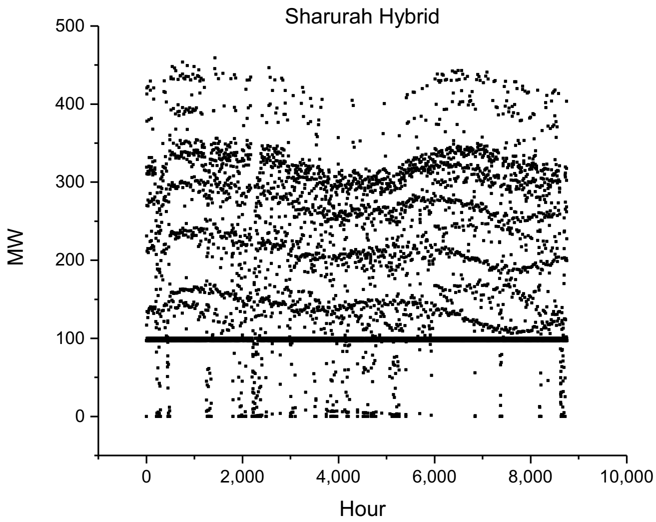
B.4 Full year hourly distribution for different technologies in Hafar Al-Batin site to show capacity distribution in MW


Sharurah CSP
MW
100
80
60
40
20
0
0
5,000
10,000
Hour

(a)

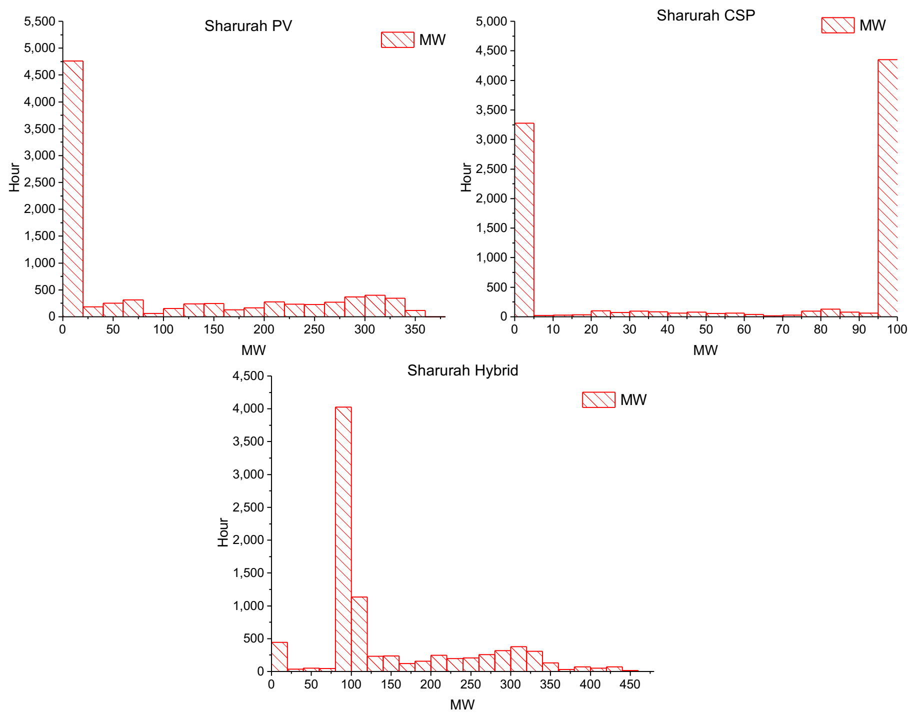

Sharurah PV
MW
400
350
300
250
200
150
100
50
0
-50
0
5,000
10,000
Hour

(b)

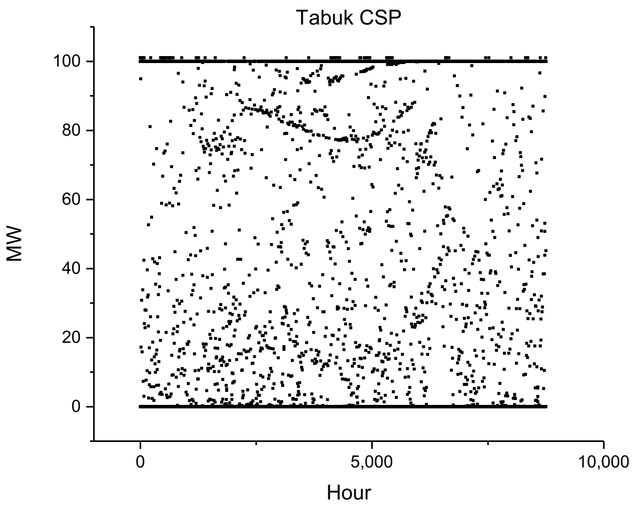


(c)

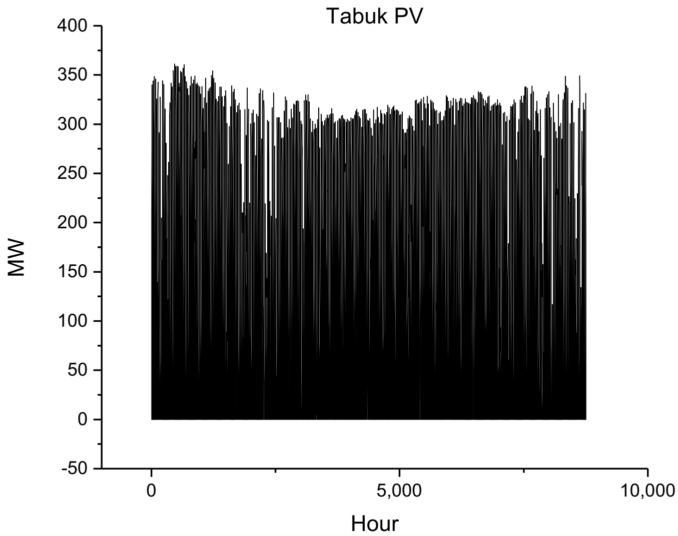
B.5 Full year hourly profile of hybrid system with contribution of each plant PV+CSP (Sharurah)



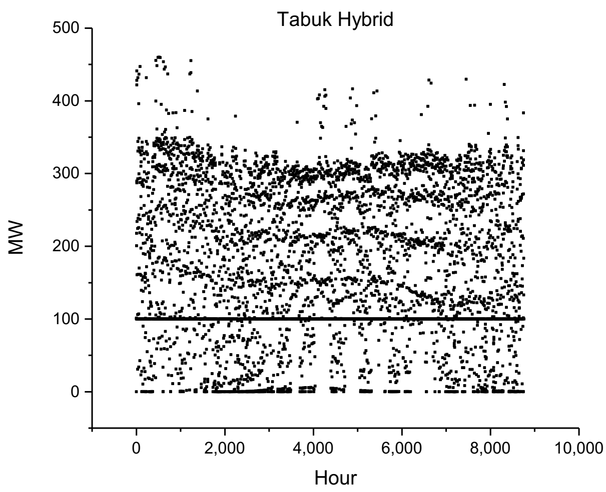
B.6 Full year hourly distribution for different technologies in Sharurah site to show capacity distribution in MW


Tabuk CSP
MW
Hour
0
20
40
60
80
100
0
5,000
10,000

(a)

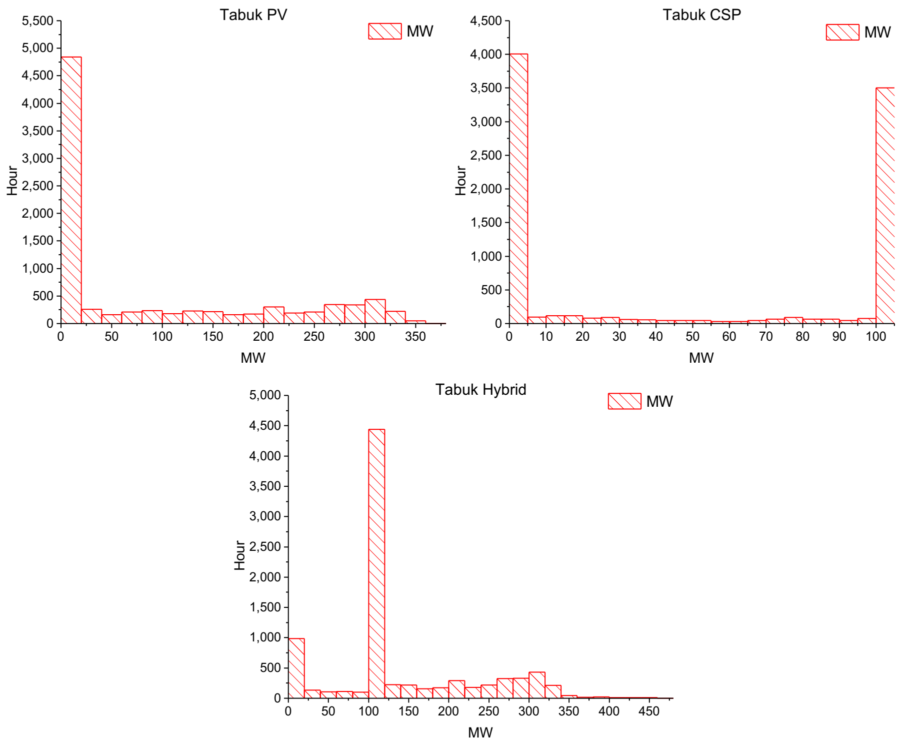

Tabuk PV
MW
Hour
-50
0
50
100
150
200
250
300
350
400
0
5,000
10,000

(b)



(c)

B.7 Full year hourly profile of hybrid system with contribution of each plant PV+CSP (Sharurah)



B.8 Full year hourly distribution for different technologies in Tabuk site to show capacity distribution in MW

Appendix C

Line ID	Line Name	Capacity (From-To)	Capacity (To-From)
1	EOA to COA	1,000	1,000
2	EOA to COA	1,650	1,650
3	EOA to COA	1,650	1,650
4	EOA to COA	1,650	1,650
5	EOA to COA	1,650	1,650
6	EOA to COA	1,650	1,650
7	COA to WOA	1,650	1,650
8	COA to WOA	1,650	1,650
9	SOA to WOA	1,650	1,650
10	SOA to WOA	1,650	1,650
11	EOA to COA	1,650	1,650
12	EOA to COA	1,650	1,650
13	COA to Qassim	1,800	1,800
14	COA to Qassim	1,800	1,800
15	Qassim to Hail	1,800	1,800
16	Hail to Jouf	800	800
17	Jouf to Arar	800	800

Table C.1: The KSA 380kV test network lines

Demand ID	Demand Name	Demand	Demand Ratio
1	COA Riyadh	6,839	0.209
2	COA Qassim	1,239	0.038
3	COA Hail	612	0.019
4	COA NEA	484	0.015
5	EOA Dammam	2,386	0.073
6	EOA Qaisuma	311	0.010
7	EOA rest	9,177	0.281
8	SOA Asir	923	0.028
9	SOA Baha	239	0.007
10	SOA Bisha	340	0.010
11	SOA Jazan	1,259	0.039
12	SOA Najran	305	0.009
13	SOA rest	223	0.007
14	SOA Tihama	557	0.017
15	WOA Jeddah	3,785	0.116
16	WOA Madinah	901	0.028
17	WOA Makkah	1,572	0.048
18	WOA rest	906	0.028
19	WOA Taif	471	0.014
20	WOA Yanbu	157	0.005

Table C.2: The KSA 380kV test network demand nodes