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Solar Energy Potential in the Kingdom of Saudi Arabia: A Comparative Analysis, Assessment and Exploitation for Power Generation

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Abstract

This research investigates the potential for employing solar energy as a sustainable power generation source in the Kingdom of Saudi Arabia (KSA). The work maps the availability of solar energy throughout the country, and investigates the feasibility of implementing the technology at two case study locations. These are the existing power generation grid sites of Wadi Aldawasir (located 20° 23′ 22.00″ N 45° 12′ 32.00″ E), and Shuaibah (located 20° 37′ 22.84″ N 39° 33′ 44.02″ E). The first case study site, Wadi Aldawasir, covers an area of 48,900 m^2, where parabolic trough solar thermal technology is proposed for power generation. The second case study site, Shuaibah power plant is one of the largest desalination and fossil fuel plants in the world with a 1,030,000 m^3/ day capacity. Both case studies were assessed in terms of site specifications with selection based on Direct Normal Irradiation (DNI). A feasibility study examining Concentrated Solar Power (CSP) potential was conducted for both locations, with analysis of weather data, particularly monthly and annual, global horizontal and beam normal irradiation data. From these data, a reasonable estimate of CSP potential, and viability of the technology was determined. Simulation was then performed using Solar Advisor Model (SAM) and Renewable Energy Technology Screen (RETScreen) software, taking into account the location weather data, (DNI, dry-bulb and dew-point temperatures, relative humidity, barometric pressure, and wind speed), technical specification, (solar field, Solar Multiple (SM) Solar collector Assemblies (SCAs), power cycle and thermal storage) and economic parameters (energy unit cost, maintenance, etc.). Simulation evaluated annual energy performance (solar radiation resource of the solar field, electrical energy delivered by solar thermal plant, system losses, required solar field area), levelised cost of unit of power generated, CO_2 emissions savings, and other financial feasibility indicators. The work shows that the energy yield of the new solar power plants using proposed CSP technology in both case studies is feasible.

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List of Abbreviations

BOE	Barrels of Oil Equivalent
Btu	British Thermal Units
CF	Capacity Factor
CPV	Concentrated Photovoltaic Cell
CSP	Concentrated Solar Power
CSPP	Concentrating Solar Power Plant
CTEG	Concentrating Thermoelectric Generator
DIF	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiation
DSSC	Dye Sensitised Solar Cell
ERI	Energy Research Institute
EPW	Energyplus Weather
FIT	Feed in Tariffs
GHI	Global Horizontal Irradiation
GHG	Greenhouse Gas
GDP	Gross Domestic Product
HCE	Heat Collection Element
HTF	Heat Transfer Fluid
ITD	Initial Temperature Difference
ISCC	Integrated Solar Combined Cycle
IRR	Internal Rate of Return
IRENA	International Solar Energy Society and International Renewable Energy Agency
KACST	King Abdul Aziz City for Science and Technology
KACARE	King Abdullah City for Atomic and Renewable Energy
KAUST	King Abdullah University for Science and Technology

KFUPM	King Fahd University of Petroleum and Minerals
KSA	Kingdom of Saudi Arabia
LCOE	Levelised Cost of Energy
Mboe/d	Million Barrels of Oil-Equivalent Per Day
NREL	National Renewable Energy Laboratory
NPV	Net Present Value
PTC	Parabolic Trough Collectors
PV	Photovoltaic
PP	Power Plant
PPA	Power Purchase Agreement
RETs	Renewable Energy Technologies
RETScreen	Renewable Energy Technologies Screen
RPS	Renewable Portfolio Standards
SSC	Sam Simulation Core
SEC	Saudi Electricity Company
SAM	Solar Advisor Model
SCA	Solar Collector Assembly
SETP	Solar Energy Technologies Program
SM	Solar Multiple
SSG	Solar Steam Generator
STS	Solar Thermoelectricity Systems
SDA	Systems-Driven Approach
GCC	The Gulf Cooperation Council
TES	Thermal Energy Storage

CHAPTER 1

INTRODUCTION

1.1. Background

Recently, increased interest in alternative energy resources arose from concerns over fossil fuel depletion and continuous and sustained environmental degradation. Renewable energy sources are key alternative energy resources (Chen et al., 2010). Solar energy represents the most plentiful of the different renewable energy resources, which are distinguished by being non-polluting, freely available, and quite friendly to the environment. While solar energy is not readily exploitable everywhere, regions that enjoy 3-6 kWh/m^2 of monthly average daily solar radiation have the most potential for harnessing it economically. The direct advantage of employing solar energy is the decreased reliance on fossil fuel, and other non-renewable energy sources (Shaahid and El-Amin, 2009).

There is notable diversity in energy resources worldwide, and a discernible and growing trend in the exploitation of renewable energy. This is driven by various considerations, such as the environment, economics, and energy security. As such, the world is undergoing a gradual transition from hydrocarbon-based economies to more sustainable forms. There is also increased interest in renewable energy in the main oil producing countries, and countries characterised by oil-dependent economies (Al-Saleh, 2007). The need for renewable energy resources in these countries should not only be aimed to strengthen economies, but help achieve and provide a healthier environment for future generations. In this context, it is very important to consider the representative case of a major oil producing power, such as the Kingdom of Saudi Arabia (KSA), which possesses at least a quarter of the proven world oil reserves. The country is also characterised by an expanding urban and industrial sector. At the same time, it is endowed with an abundant solar resource. Although several pilot projects in the domain have been implemented since 1970, exploitation of renewable energy remains inadequate (Al-Saleh et al., 2008).

Electricity demand in KSA is growing continuously, and additional power generation capacity is required to meet this demand. Conventional power generation plants not only increase greenhouse gas (GHG) emissions, but are also the main source of environmental pollution and associated human health problems. Thus, there is greater need to find new alternatives for conventional power plants (Almasoud and Gandayh, 2015). Although KSA is the world's premier oil producer, alternative resources have considerable potential (Steel and Gordon, 2012). Renewable energy resources are of high level in KSA, since the country receives substantial amounts of solar irradiation, and has large deserts, representing freely usable space.

In KSA, solar energy is the renewable resource with the greatest potential for full exploitation, given its abundance. The Arabian Peninsula receives an average annual solar irradiation of around 2200 kWh/m^2. Since 1960, implementations of solar energy in KSA have been rising. For example, the Solar Village in Riyadh hosts the "Solar Hydrogen Production Plant". Despite the great promise in solar energy exploitation, development over the years has been relatively slow in KSA, because of different challenges (Hepbasli and Alsuhaibani, 2011).

Energy use in the Saudi electricity sector and impact on carbon dioxide emissions for the 2010-2025 period was examined by Mansouri et al. (2013). It considered conventional and new technology use, concluding that use of new technologies will produce reductions in CO_2 emissions. The highest CO_2 reduction level was predicted to be obtained in 2025. These savings range from 136 up to 235 $MtCO_2$, which reveals great opportunity for using clean technologies. In this context, various research projects in KSA have economically and technically assessed some of these options (Alawaji, 2001).

Wind and solar energy resources were examined using recorded data to obtain annual wind power and solar potentials (IBP, 2015). Results show that annual wind power potential lies in the range of 31.7-94.6 W/m^2, while annual solar potential is almost 2200 kWh/m^2. Two methods for exploiting the incident solar irradiation in KSA were investigated by Baras et al. (2012), namely Concentrated solar power (CSP) and Photovoltaic (PV) technologies. The study reveals that due to extreme ambient temperatures during the summer, PV technology is not practical due to significant performance deterioration. However, CSP technology was found to be favourable at these extremes of temperature. Two major applications of CSP technology are considered in KSA, namely electricity generation and industrial thermal processes, such as water desalination.

Electricity demand growth in KSA is driven by the country's development, and economic and population growth (Al Ammar and Hammach, 2010). Various studies show that the country's oil consumption increased by 50% in the period 2000 to 2008, of which nearly three-quarters corresponds to electricity generation to meet an annual 8% increase in demand.

Alternative energy resources are seen as an attractive solution to meet growing electricity demand. Furthermore, installation and operation of renewable energy resources can offer new employment opportunities and may be considered a solution to economic and social problems. The high unemployment rate of 11.7 % can be partially solved with emerging renewable projects and industries (CDSI, 2015). Reports suggest that using solar resources for generating 5 GW of electricity by the year 2020 could create 15,000 job opportunities in the country's solar industry (Alriyadh, 2012).

Renewable energy resources development would also reduce unwanted emissions, especially GHGs. This would help the country meet various international commitments, including the Kyoto Protocol. Electricity produced from renewable energy sources could meet national demand and surpluses could be exported, eventually improving the country's economy (IEA, 2011).

KSA is considered the Middle East's largest petroleum consumer either directly burning crude oil or used in the transportation sector. Consumption was driven by economic growth, which was caused by historically large fuel subsidies. The Statistical Review of World Energy by BP (2014) ranked KSA 12th in the list of largest total primary energy consumers worldwide for 2013. In that year, KSA consumed 9×10^{15} British thermal units (BTU), of which 60% was from oil, and the remaining 40% from natural gas. In contrast, renewable sources are needed to meet 50% of the country's electricity demand at a target date of 2032, as required of the King Abdullah City for Atomic and Renewable Energy (KACARE) programme. However, electricity demand is also increasing in this period, and it is necessary to increase power generation capacity up to 120 GW. Moreover, in order to minimise the peak-power periods in Gulf Cooperation Council (GCC) member countries, KSA participates in linking to these countries' power grids (EIA, 2014a).

KSA has experienced rapid economic growth, and consequently, energy consumption in recent years has risen in parallel (Alyousef and Abu-Ebid, 2012). Per capita energy consumption increase of more than 30% was observed. This was mainly associated with the decline in oil exports. Total energy consumption reached almost 800 million Barrels of oil equivalent (BOE) in 2008. It is expected that this energy consumption will have doubled by 2030, resulting in reduced oil exports.

1.2. Problem Statement

A study of CSP projects in KSA is performed in this research. Two CSP plants are proposed at two locations in the country. The first utilises parabolic trough technology, and the other solar tower technology.

KSA covers an area of over 2 million km^2, occupying the largest portion of the Arabian Peninsula. It receives almost 2200 kWh/m^2 from solar irradiation annually, with large tracts of unused land and desert. The quantity of solar irradiation received, and available land make it attractive for the implementation of CSP projects. The rise in electricity demand has spurred the search for alternative power and electricity generation technologies. The fact that petroleum resources are non-sustainable and fluctuating world price trends has increased the potential for new energy resources that are independent of fossil fuels.

Figure.1.1 indicates the UK trends in oil prices from 1987 to 2014. It represents the Retail Price Index (RPI) of selected fuel components. The graph illustrates how the real price of each component has varied over 27 years period, and helps compare these components (Dempsey et al., 2014).

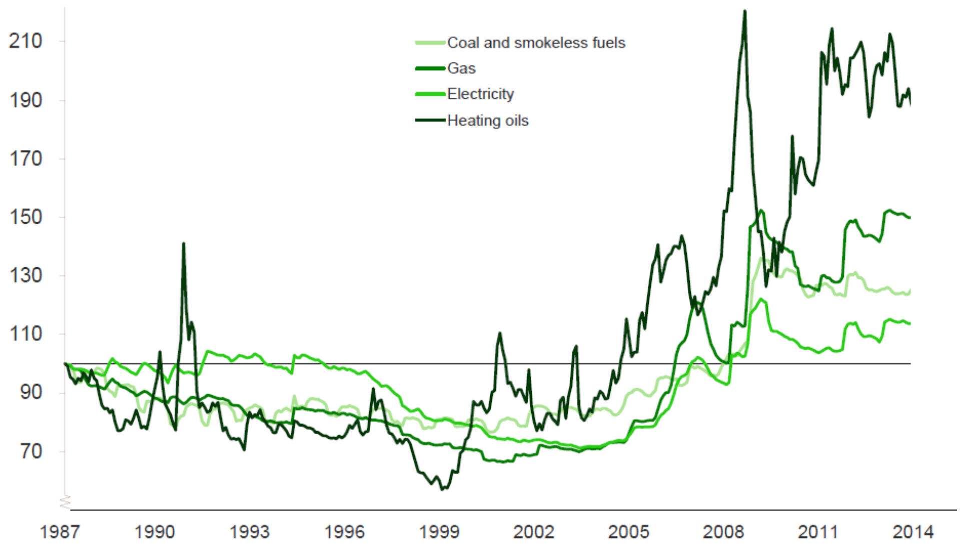


Figure 1.1 Index Prices of selected fuel components of the RPI (Dempsey et al., 2014)

The need for new, alternative power generation resources has been accentuated by rising oil prices, fossil fuel resource depletion, and negative environmental impact. CSP plants are an alternative examined in this research.

1.3. Research Importance

There are several underlying reasons in searching for new power generation and electricity technologies, as stated in section 1.1. These include environmental impact and high worldwide prices of fossil fuels and oil products.

This research explores environmentally-friendly electricity generation plant with relatively low emissions compared to conventional technology. In addition, the implementation of solar energy for electricity generation would improve the country's economy, since generated electricity can cover domestic demand. This would also allow more oil products for export, and hence, further revenues for the country.

A feasibility study for solar energy in KSA is presented in this work by studying implementation of CSP plants at two different locations. This task is accomplished by reviewing and understanding the country's energy generation and consumption. Also existing solar energy projects and recent developments are highlighted. Modelling and simulation of solar energy technologies was performed to assess the contribution of such technologies to two existing fossil fuel plants. This study provides information on the effectiveness and contribution of two solar energy technologies to the country's domestic electricity generation.

1.4. Aims and Objectives

1.4.1. Research Aim

The overall aim of this research programme is to assess, quantify, and outline technological solutions to exploit renewable energy resources in the KSA, particularly solar energy. Design and feasibility assessment of CSP plants integrated into existing fossil-fuelled plants in KSA are addressed by this work. Large-scale solar technologies would be used as an alternative for generating electricity, due to the abundant solar resource in KSA. This work focuses on investigating and simulating the technical and economic feasibility of CSP plants using parabolic trough and solar tower technologies at two different locations in KSA. The ultimate objective of this project is to expand knowledge in the area of renewable energy, and inform decision makers in KSA, considering large-scale power generation using solar energy.

1.4.2. Research Objectives

The main objectives of this study are:

- Review energy generation and consumption in KSA, and completed solar energy projects.
- Highlight recent developments in solar energy technologies, particularly CSP trough and tower technologies.
- Investigate and explore solar energy technology, and computer modelling tools for design purposes.
- Perform design and simulations of two selected power plants in KSA with different characteristics.
- Assess and evaluate solar power technologies' contributions in simulation results for the two case studies.
- Understanding the concepts and principle of work of the CSP techniques.

1.5. Novelty and Added Value

This research investigates the technical design and feasibility assessment for two key solar thermal power technologies, which are parabolic trough and tower, at two different locations in the KSA used for power generation. This area of research has not been explored in previous academic studies, and therefore this research is unique and sets new findings to the power generation from CSPs in the KSA context, as it fills the gaps associated to this area of research.

The following aspects demonstrate the gap in the available studies, and efforts concerning the application of renewable energy in KSA.

- **Location**

KSA is located in a dry arid region having high daily solar radiation, with remote areas receiving even greater amounts. In fact, remote areas do not require large amounts of electrical energy compared to urban centres. Moreover, these areas are far from vital cities that require large amounts of energy, so there is difficulty in transporting energy over distances. Similarly, all GCC countries and other Middle Eastern countries, like Iraq, and some North African countries, like Egypt, lie in this region of high insolation. This research investigates the technical design and feasibility assessment for two key solar thermal power technologies, which are parabolic trough and tower, at two different locations in the KSA used for power generation. This area of research has not been explored in previous academic studies, and therefore this research is unique and sets new findings to the power generation from CSPs in the KSA context, as it fills the gaps associated to this area of research.

- **Limited projects**

The studies reviewed suggest that completed projects in KSA harness limited solar energy compared to the large amount available. Consequently, every day large amounts of solar radiation are lost, and not exploited effectively. Furthermore, implementation of CSP plants is lacking. In terms of renewable energy projects, the country has established some solar energy projects in recent years. The aim being to advantageously exploit the high solar irradiation, long daylight hours and vast rainless area. Examples of key solar projects in KSA are:

- **Solar Village Project**: The project was established in 1981 with the purpose of supplying electricity generated from solar energy to three remote, off-grid villages near Riyadh. The project included a PV system composed of solar radiation lenses on modular flat panels, 160 PV sun tracking arrays producing around 350 kW of power, a 300 kVA inverter for voltage conditioning, a 100 kWh lead-acid battery bank, and a weather monitoring station. The project supplies 1.0 to 1.5 MWh of electrical power daily to the villages. The problem encountered in this project relates to degraded PV cell performance. The failure was traced to short circuits in the cells due to ceramic material fatigue. This was caused by continuous thermal cycling and water condensation (Obaid and Mufti, 2008).
- **Solar PV power plant**: This was established in Farasan Island, and uses Solar Frontier CI (G) S thin-film module technology. The PV power plant produces 864 MWh per year for local citizens and small businesses (Cheyney, 2011).
- **King Abdullah University**: The project established in Thuwal employs polycrystalline PV panels, supplying 3,300 MWh of electrical power per year to campus buildings (Al-Mureeh, 2012).
- **Solar Frontier installation in Saudi Aramco**: The site is in Dhahran and uses PV technology to cover car parking spaces using CIS modules offered by Solar Frontier. It has an installed capacity to supply up to 10 MWh of electricity annually (Raed, 2012).
- **Solar desalination plant**: This was established in Al Khafji with the use of the Ultra-high concentrator photovoltaic (UHCPV) technique to offer around 30,000 m^3 drinking water per day. However, this amount is not sufficient, where further improvements must be introduced (Rodríguez, 2011).

However, these current solar power installations may still be considered research and development efforts on renewable energy sources. In addition, they are PV-based systems, with high energy production costs. This increases the need for further effort to develop PV systems with low costs, equivalent to those of conventional energy systems. Despite the efforts exerted in recent years to implement solar projects in KSA, these remain quite limited, relative to the substantial amount of solar radiation received daily. This means that the opportunity to capture significant amounts of solar energy every day is being lost. In contrast, KSA is heavily dependent on fossil fuel power plants to meet domestic energy demand. This dependence on conventional power generation plants is a critical problem, as the extraction costs of oil are expected to continue rising rapidly where this is a fundamental factor behind oil price rises, and the appearance of 'fracking' and shale oil extraction starting to become 'economic' in comparison. This represents strong competition in the world energy field besides crude oil and natural gas. Also, regional political instability is also a major factor in supply security concerns. Consequently, the cost of generating electricity from conventional plants will rapidly increase (Bryden et al., 2013, Pazheri et al., 2012).

This review of some solar power projects in KSA established that these are PV-based, and that there are no solar thermal projects in the whole country. This defines the contribution of this current study, which tackles non-PV solar power systems. PV-based solar systems convert sunlight directly into electricity using semi-conductors. However, the efficiency of PV-based solar systems decreases with higher temperature, and some energy is lost from these systems to the surrounding environment. In contrast, solar thermal systems may use mirrors to concentrate sunlight and generate heat, which is then used to run heat engines and generate electricity. This means that such systems function during daylight hours only, and require energy storage. However, thermal-based solar systems are more efficient for large scale power generation. In addition, they are cheaper than PV-based systems (Danowitz, 2010).

- **Slowdown in investment**

Data provided in the literature review suggests a slowdown in renewable energy project implementation. The wide use of oil as a source of energy is not the only reason behind the limited use of solar energy in KSA. Other reasons are sand impact or blasting, which reduces the reliability of systems as it causes rapid aging and degradation all through the setup lifetime. In addition, dust accumulation blocks some of the light and reduces the solar energy captured by 8-12% per month. The lack of availability of government subsidies for solar energy generation programmes, where these subsidies can improve the prospects of solar energy competing with the incentives given to commercial energy sources. Other current problems concerning the use of solar energy in KSA are that established solar projects in the country are clustered in limited areas in the country. In addition, the techniques used in storing solar energy have not reached their complete potential. A further point is that some solar projects were actually established by foreign countries, which import their energy from KSA (Koot, 2013).

- **High dependence on oil**

KSA should quickly exploit solar energy for different applications as oil is a finite energy resource that will finally become depleted. Oil costs will increase as a result of this depletion. KSA is required to cover costs of oil price spikes. When this happens, it provides a chance for the solar industry to compete with the oil industry on price basis. According to Schwartz (2011), KSA currently has a domestic consumption of 2.4 million barrels per day (b/d) of oil, which is projected to rise to 8.3 million in 2028. Furthermore, prices of electricity generated from crude oil resources are subsidised by the government, which makes it hard for alternative energy projects to compete.

- **Requirement for a new energy strategy and regulations**

Since solar power is a rapidly growing field in the in KSA, policies and standards are in the early stages of development. But there are no clear or separate regulations or policies regarding renewable energy and sustainability for buildings and large scale projects in KSA.

- **Gaps in the available researches**

There are few studies that analyse solar energy projects and planning actions taken by KSA. Most of the data collected in this research are from international organisations and websites like IEA, World Nuclear Association, National Renewable Energy Laboratory (NREL), and United Nations (UN) …etc. There is a notable shortage of official governmental studies and publications in this area. Only recently, some serious effort was made to study the renewable energy situation and start developing an energy strategy. There is a trend in the future to establish regulations concerning renewable energy. This is totally justified, because alternative energy still cannot compete with non-renewable resources in KSA. Indeed, energy from fossil-fuels is subsidised by the government, and energy prices in KSA are among the lowest in the world.

1.6. Contribution

This work proves the need, importance and potential of using alternative energy in KSA by presenting data collected on this topic, as well as researches and projects that aimed to reduce the dependence on non-renewable resources, and comparing these with the worldwide trend. It also highlights the importance and contribution of the research conducted.

- **Energy Consumption Investigation in KSA**

Research starts by investigating and discussing the growth of energy consumption in KSA. It helps bring understanding of the current situation in the country, and the expected trend in coming years.

The investigation focused mainly on the energy produced or consumed, disaggregated by sector, type of energy (thermal, electricity), source of energy, trends …etc.

- **Investigation of renewable energy potential in KSA**

The next step was to investigate and discuss the potential of using alternative energy sources to meet the increasing demand on the energy sector, and reduce the dependence on non-renewable energy sources. These alternative energy sources include sustainable sources, such as wind energy and solar energy as the main source of renewable energy. Indeed, the availability of these resources is introduced in this work, where KSA is considered one of the rich countries in solar energy and wind energy. This research also included those studies and data collected on this subject, as well as implemented and planned future projects, within the national energy strategy. The discussion also includes other sources of renewable energy that have potential in the country like geothermal, waste to energy …etc.

- **Beneficial projects**

This research proposes an environmentally-friendly electricity generation plant with relatively low emission compared to conventional ones. This is done in order to improve on the conventional methods and technologies used in KSA through modelling and feasibility of CSP plants as mature solar technology systems.

- **Economy improvement**

New technologies will contribute to covering the country’s electricity demand, and consequently, improve the country’s economy. This releases more oil products for export, and hence, more revenue for the country. It will also enhance employment and technology transfer.

- **Solar energy in the Kingdom of Saudi Arabia (KSA)**

This project provides ideas for implementation of two CSP plants in different locations in the country. Modelling and feasibility studies were performed as part of this project. In addition, the study provided deep analysis and results to assist decision makers in the energy sector enhance implementation of the new strategic plan by 2032, aimed at producing 25 GW of electricity from CSP systems.

- **Additional trends**

The project also investigates and explores solar energy technologies and computer modelling tools for design and modelling purposes. These tools were used for the design and simulation of two CSP plants in KSA. These plants have different characteristics, and the study assessed the contributions of individual solar power technologies.

Also, awareness of renewable energy sources has to be increased in addition to proper training and education programmes.

The main contribution of this work is to enhance the investigations conducted in the field of solar power in KSA, especially investigations concerning the design and feasibility of CSP systems. In addition, this work enhances the investigation of detailed parts of CSP subsystems to improve efficiency, performance, accuracy and financial records.

1.7. Thesis Structure

This thesis consists of seven chapters, namely Introduction, Literature Review, Modelling of Renewable Energy Systems in KSA, Risk Assessment, Results and Analysis, Conclusions, and Recommendations.

The first chapter discusses solar energy, giving a general background, and also a description in the context of KSA. This is followed by the problem statement and an illustration of the research's importance. Once the main aim and objectives are clarified, the research structure is previewed in detail, and finally, the chapter concludes with a summary.

The second chapter describes various solar energy projects in KSA, and is divided into eleven sections. It begins with a General Introduction, followed by presentation of

Energy Consumption, Potential of Renewable Energies, and Review of Solar Energy, both worldwide and in KSA. Subsequently, Solar Energy Technologies, SWOT Analysis, Gap Analysis, Research Contribution and a Summary are given.

The third chapter consists of five sections. An Introduction to KSA renewable systems in general is provided. This is followed by a description and discussion of the two power generation grid site locations, Wadi Aldawasir and Shuaibah. Then, the energy consumption of KSA is profiled. The assessment and selection of software for large scale solar power generation feasibility study is described. The two key software programs used were Solar Advisor Model (SAM) and Renewable Energy Technologies Screen (RETScreen). Also presented and discussed are the main methods used to collect data. Finally, a chapter summary is provided.

In the fourth and fifth chapter, the results and analysis are presented, along with a detailed discussion of the feasibility of CSP integration into the mini-grid and grid at the two locations. The simulation of the proposed CSP plant using SAM and RETScreen software for both locations is also presented. An evaluation and discussion of the simulation results is given, and finally, a summary of the whole chapter.

In the sixth chapter, titled Risk Assessment, an assessment concerning uncertainties and risks that can occur during the course of certain activities is presented to identify particular threats, risks responsibilities and liabilities faced during the research work, and understand how these may impact the implementation of the two case studies. In addition, an evaluation concerning how these risks arise, and the necessary action to mitigate them is proposed.

Chapter Seven covers main conclusions and proposes avenues of future work, along with recommendations. The references, as well as appendices, are provided at the thesis end.

1.8. Summary

In this first chapter, an introduction to the whole thesis was presented by providing a brief background on solar energy, its importance, implementation and studies that focus on the projects conducted in KSA. It is obvious that there is significant potential for utilising abundant solar radiation in KSA for generating electricity. This trend is driven by various reasons including an increase in the country's electricity demand, fluctuating oil prices and negative environmental impact.

The second part of this chapter has clarified and discussed the problem statement, research importance, aims and objectives, as well as the research structure. Gap analysis and thesis' contribution were explained and outlined. From these sections, it was found that there was a large need for utilising solar energy for electricity generation in the KSA. The country has potential, given large portions of unused land receiving substantial amounts of solar radiation. It was found that before installing CSP projects, it is important to create models of these projects so that their contribution and effectiveness can be assessed. In this way, project time and cost can be minimised.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

An expansion in renewable energy choices is occurring worldwide, driven by various economic, environmental, and energy security motives. Indeed, the world is transforming from hydrocarbon-based to sustainable energy economies. Yet, limited attention has been paid to evaluating the use of renewable energy in the main oil producing countries. Specifically, those whose economies are heavily reliant on oil, and where only few researches on this topic exist.

Many countries, including KSA, seek a sustainable and healthier future. Consequently, there is a need to investigate the use of renewable energy in KSA, which is a key oil producing country. The country possesses sensible wind and substantial solar energy resources. However, since the 1970s, these abundant renewable energy sources have not been exploited appropriately (Al-Saleh, 2007).

The main goal of this chapter is to present past efforts in exploiting renewable energy sources, especially solar energy, in KSA. The chapter starts with an overview of energy consumption, globally, and in KSA. It estimates the level of electricity consumption in KSA and around the world. Consumption trends are compared, identifying where efficient solutions must be found to secure reductions. Next, sections discuss the potential for using renewable energy sources as the best solution for meeting a large part of expanding energy demand. Results show that the most commonly used renewable energy source is solar energy. Therefore, the last section presents an overview of solar energy in KSA and worldwide.

In addition, a SWOT analysis is presented evaluating the strengths, weaknesses, opportunities and threats relating to the literature review, based on determining its objectives and recognising those factors, both favourable and unfavourable, that contribute to achieving these objectives.

2.2. Energy Consumption

The following subsections investigate and discuss the energy consumption trends, worldwide and in KSA.

2.2.1. Worldwide Energy Consumption

A detailed account of the trends and energy consumption analytics is necessary to establish the premise for the study. Energy production and consumption from various renewable and non-renewable sources is controlled by many factors. These factors are unique to each country, and include economic performance, geopolitical uncertainty, governance, and market structure. In a statistical review report, BP (2014) presented the overall growth in global consumption relating to primary energy sources of 2.3% in 2013. Fossil fuels (oil, natural gas and coal) reached record global consumption levels that were higher than production. Other energy sources like nuclear power, hydroelectricity and renewable energy expanded at rates lower than the 10-year average. It may be noted that emerging economies contributed up to 80% of total world energy consumption growth, with China at the forefront. The rise in 2013 was 0.5%, but remained below the 10-year average of 2.5%. This has been the case among emerging economies like the Brazil, Russia, India, China and South Africa (BRICS) bloc, while Organisation for Economic Co-operation and Development (OECD) countries saw a 1.2% increase. It may be noted that energy consumption in the EU countries reduced by 0.3%, where Spain led by a 5% drop, while in Asia, Japan's consumption dropped by 0.6%.

BP (2014) addressed the change in energy consumption levels for all fuel-types. Oil saw a 1.4% net increase or 1.4 million barrels per day (b/d). Non-OECD countries accounted for 51% of global oil consumption, driven by overall development. The consumption levels of OECD countries dropped by 0.4%. The US led in oil consumption levels, with a growth of 400,000 b/d, beating China for the first time by almost 10,000 b/d. The most popular product from oil refinement in terms of volume in this case were the light distillates. The report also discussed production information relating to different energy sources, along with prices, processing and trade. Energy consumption is more focused on the present context and does not consider other details, beyond global energy production. The United Arab Emirates became one of the few OECD countries, in which oil production increased by 250,000 b/d.

After oil, the most widely used energy source was natural gas with a share of 23.7% in global energy consumption. Primary energy consumption growth for natural gas was 1.4%, even though it was below the 10-year average of 2.6%. The primary energy consumption growth was above 1.8% average in OECD countries, and below 1.1% average in non-OECD countries, except for North America. The major growth rise of 10.8% was in China compared to 2.4% in the USA, where overall consumption growth was 81% altogether. The highest natural gas consumption of 12.2% was recorded in India, followed by the EU countries. Coal is the third most prominent fossil fuel accounting for a record high value of 30.1% of the overall share in 2013. Its consumption grew by 3%. It contributed mostly (89%) in the consumption outside the OECD, with a growth of 3.7%. However it was still below the 10-year average of 3.9%. Within OECD countries, coal consumption rose by 1.4%. Other alternative, non-renewable fuels included nuclear power, which accounted for 4.4% of global energy consumption. It was the only fuel whose global consumption levels did not rise in 2013. The global output grew by 0.9%, contributed mostly by the increase from the US, China and Canada. The other alternative energy source was hydro-power, which accounted for 6.7% of global energy consumption. A below-average increase of 2.9 % was recorded in China’s and India’s hydroelectric energy consumption. These countries lead the Asia-Pacific region and account for 78% of world growth (BP, 2014).

It was reported that mainly wind and solar energy sources increased energy consumption by 2.7% in 2013. This is significant increase of 0.8% (BP, 2014). In terms of power generation, renewable energy consumption increased by 16.3%, and accounted for 5.3% of overall utilisation. Wind energy accounted for over 50% of all renewable energy sources and increased by 20.7%. It was followed by solar energy at 33%. Alternative fuels also accounted for the renewable energy consumption growth of 6.1%; mostly contributed by Brazil (16.8% growth) and the US (4.6% growth). Total energy consumption growth can be attributed to the BRICS bloc countries, which increased energy demand by 3.5%. This was reported in the Enerdata (2014b) yearbook. China experienced a slowdown, but still topped the charts with total energy consumption increase of 0 % for the first time in 17 years. Figure. 2.1 shows overall energy consumption by various countries across in the world.

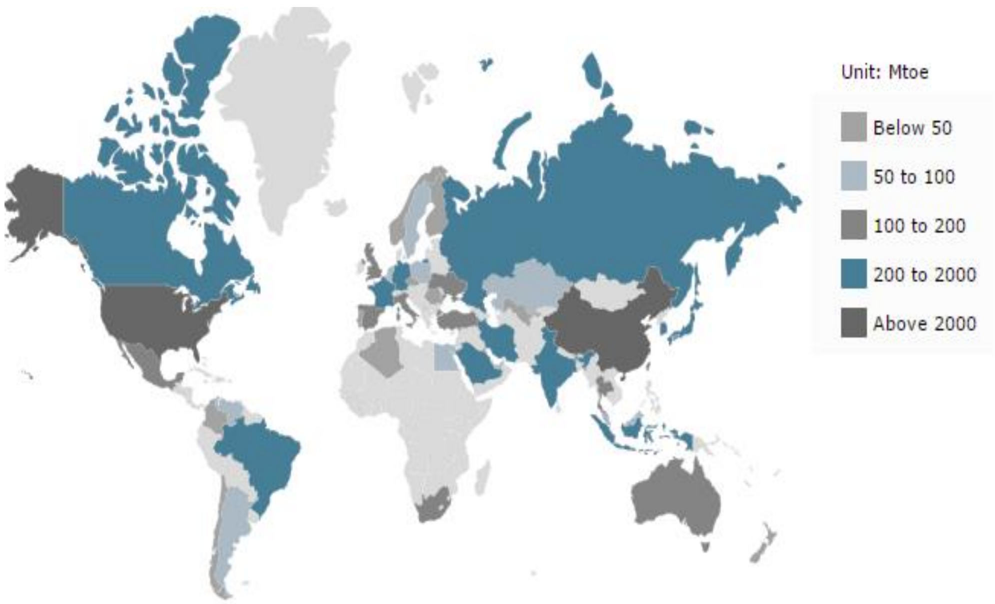


Figure 2.1: Overall energy consumption (Enerdata, 2014b)

Energy consumption is expressed in Mtoe units, which stands for million tons of oil equivalent (1 kWh = 0.0859845 Mtoe) (Unit, 2015). Figure 2.1 shows that China and the US are the largest consumers of energy. Data shows that China leads the top ten consumer countries with 3,034 Mtoe of energy, followed by the US with 2,224 Mtoe (Enerdata, 2014b); India is third (872 Mtoe), Russia is fourth (751 Mtoe), Japan is fifth (437 Mtoe), Germany is sixth (307 Mtoe), Brazil is seventh (306 Mtoe), South Korea is eighth (277 Mtoe), Canada is ninth (251 Mtoe) and France is tenth (243 Mtoe).

Additional analysis of the global energy developments conducted by IEA (2014) provided an outlook on energy system and security concerns. The abundant source of inexpensive oil has been the Middle East. However, this region has recently gone through turmoil that seems to surpass the 1970 oil shocks. In addition, the Russia-Ukraine conflict, which represents the dispute among oil and gas companies in these countries, has been a major problem for natural gas supplies.

GHG emissions and air pollution are not properly regulated within a global legal framework, which adds uncertainties to future global energy consumption, where energy demand will increase by 37% by 2040. The rate has reduced compared to the last two decades (2% per year) and it is predicted that it will increase by 1% after 2025. Suppressing energy demand can be attributed to controlling oil demand by as much as 23 million b/d in 2040. An energy crisis may occur, but solutions were discussed by

IEA to meet these requirements. These solutions involve improving energy efficiency and adopting better oil prices and rules. Renewable energy technologies (RETs) rely on improved regulation of the power sector, strengthening commitments between all concerned parties in order to face different challenges. Similar issues were raised by the World Energy Council based on their work programme on the World Energy Congress in Montreal (WEC, 2013). They produced a survey of energy reports covering different fuel resources, including coal, oil, natural gas, nuclear and uranium, hydro-power, waste and bioenergy, wind, solar PVs, geothermal, peat, and marine energies, and energy efficiency. Key indicators that help understand global energy consumption scenarios in terms of what has changed in the last 20 years are presented in Table 2.1.

Table 2.1: Key indicators for the energy scenario from WEC (2013) report

	1993	**2011**	**2020**	**Growth (1993-2011) – (%)**
Population (billion)	5.5	7	8.1	27
GDP (Trillon USD)	25	70	65	180
TPES (Mtoe)	9.532	14092	17208	48
Coal (Mt)	4474	7520	10108	68
Natural Gas(bcm)	2176	3518	4049	62
Nuclear (TWh)	2016	2386	3761	13
Hydro Power (TWh)	2286	2767	3826	21
Biomass (Mtoe)	1036	1277	1323	23
Other renewables (except hydro) (TWh)	44	515	1999	n/a
Electricity Production/year Total (TWh)	12607	22202	23000	76
Per capita (MWh)	2	3	3	52
CO_2 emissions/year				
Total CO_2 Gt	21	30	42	44
Per capita tonne CO_2	4	4	n/a	11
Energy intensity koe, 2005 (USD)	0.24	0.19	n/a	-21

Energy consumption scenario in developed countries is more predictable than for the rest of the world, especially for emerging economies such as BRICS countries. Fritz (1981) had presented an article based on his research at the Max Plank Institute for Physics in Munich. Potential from the developing countries has been seen mostly in terms of increasing nuclear energy resources. This had been reinforced by International Atomic Energy Agency (IAEA) studies, the 10th World Energy Conference and applied systems analysis by the International Institute etc. The author accessed relevant energy organisations from 156 different countries in the developing world, including those in Asia, Africa and Latin America. Many global models for developing world energy demand were presented by Fritz (1981). His work encouraged several future studies focusing on the developing world, in terms of nuclear energy consumption/conversion statistics, as well as other alternative sources.

After reviewing the energy consumption in various countries in the world, the following section investigates more specifically the energy consumption in KSA over several years, and demonstrates how it increased with time.

2.2.2. Energy Consumption in KSA

Domestic energy demand has rapidly increased in KSA. Electricity demand growth in KSA is very strong and depends on season, since air conditioning systems are used heavily during hot summer months (Woertz, 2013). The main reasons behind the electricity demand rise are industrial development in the country, population growth and government subsidies that encourage wasteful energy consumption. KSA recently experienced shortages in natural gas, and is seeking alternative energy resources to reduce oil and diesel consumption. These energy alternatives include nuclear power plants and renewable energy resources. Figure 2.2 shows the energy consumption per sector in KSA in 2011. One of the main problems associated with uncontrolled energy demand is the threat of oil export, and thus the threat to KSA's role as a main oil produce (ECRA, 2014b).

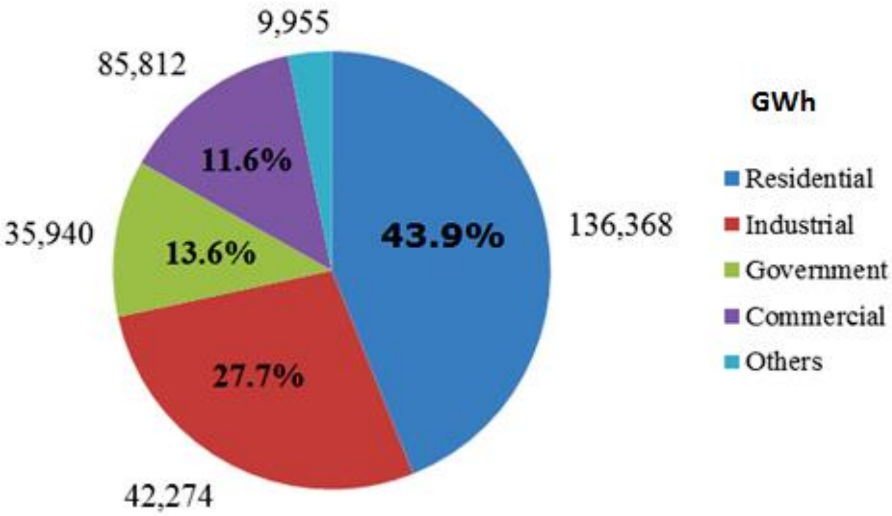


Figure 2.2 Energy consumption in GWh per sector in KSA in 2014 (ECRA, 2014)

Reform of financial subsidy programmes is politically very sensitive, since citizens consider such support an entitlement. Thus, the Saudi government has enacted reluctant decisions about financial aid and subsidies. The main and only sources for energy consumption in KSA are oil and natural gas. The oil resource contributed almost 130 Mtoe in 2012, while natural gas has contributed by 93 million Mtoe (BP, 2013). On the other hand, other Gulf states, including Qatar, United Arab Emirates (UAE) and Iran are dependent on natural gas for their energy production.

Electricity demand increases in KSA and its growth of 8% is above Gross domestic product (GDP) increase. Electricity demand during summer is higher by 40% than in winter. This is caused by air conditioning systems. For example, in 2010, the country burned 0.9 million barrels of crude oil /day in July. The figure below shows the percentages of oil used to generate energy per month from 2009 to 2014 (EIA, 2014b).

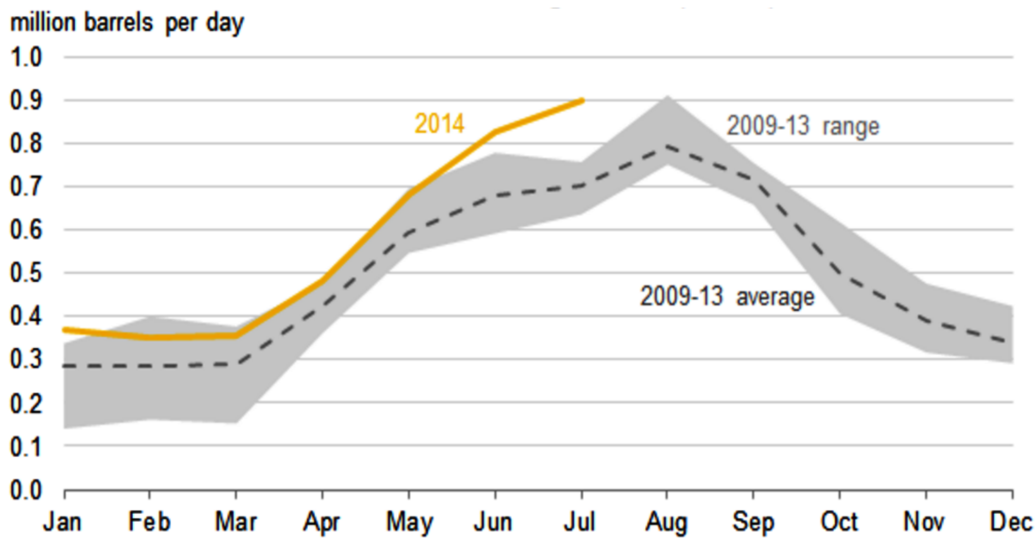


Figure 2.3: Percentages of oil use to generate electrical energy per month from 2009 to 2014 (EIA, 2014b)

The economic boom has encouraged growth in domestic energy consumption. In fact it was caused by large fuel subsidies and high oil prices. KSA was placed 12th in the list of largest total primary energy consumers worldwide for 2013 by the “BP Statistical Review of World Energy 2014”, consuming 9×10^{15} BTU, split between 60% from oil, and 40% from natural gas. In contrast, renewable sources must meet 50% of the country’s electricity demand at a target date of 2032, within the remit of the KACARE programme (EIA, 2014a). It may be noted that generation capacity will need to be increased from 65 GW to up to 120 GW. Another advantage of increased renewable energy production will be oil and natural gas surplus that can be exported. KSA as a member of the GCC participates in the efforts to connect member countries' power grids to renewable plants in order to balance loads and supply during any peak periods.

According to UN (2015), energy demand in KSA is driven mainly by the growing population, varied consumption pattern and increasing per capita energy demand. The average annual rate of population increase from 2010-2015 in KSA was 2.32%. Indeed, the population in KSA increased by more than 200% from 1980-2015. However, it is expected that the population increase from 2015-2050 will be from (10-50) %, where estimates suggest that the average annual rate of population increase for 2015- 2020 in KSA would be 1.55 %. With the estimated growth rate, GDP growth in Saudi is very high, and is higher than GDP rates in developed countries. Additionally, the KSA economy has the characteristics of the highest input/output model. Comparing the energy intensity per GDP unit for KSA and OECD's European members, this was found to be more than double for KSA. It is expected that this gap will continue to grow until 2030. According to the UN, KSA's population will grow from 28 million in 2010 to 45 million in 2050, with a peak reached in 2065. Recently, a demographic transition was experienced by the Saudi community. This was caused by urbanisation and increased female education, which in turn led to reduced birth rates.

Car fuel demand in KSA is relatively high due to various reasons, such as the lack of a public transportation system, the geographical extent of the country and substantial financial subsidies. The annual oil consumption growth rate is 7.3 %., where KSA is considered one of the largest oil consumers worldwide. Actually, it is the "sixth-largest oil consumer" and from the total Saudi crude oil and natural gas production almost one fourth is consumed in the country itself (Dudley, 2015). In 2010, KSA spent over $42 billion on subsidies to the oil and electricity sectors, $30 billion for oil and $12 billion for electricity. In total spending on fossil fuel financial subsidies, KSA holds second place worldwide, preceded by Iran and followed by Russia, India and China (IEA, 2011).

In 2010, the estimated total domestic energy demand for crude oil, gasoline, diesel, natural gas and fuel oil combined, in KSA was 3.4 million barrels of oil-equivalent per day (mboe/d). Assuming current rates of growth are maintained, then by 2028 this energy demand will likely rise to 8.3 mboe/d.

On the other hand, the electricity generation sector operates within a highly favourable pricing regime on fuel inputs, which are only a fraction of international market prices. This disparity in price is revealed in Table 2.2. This low price regime is a significant obstacle to sector improvement in adopting greater efficiency initiatives, or seeking alternative primary energy sources, whether nuclear or renewables, given the lack of pricing pressure. Furthermore, the actual average price in 2012 paid by consumers to the Saudi Electricity Company (SEC) and cost of production were 3.79 cents per kWh and 4.00 cents per kWh, respectively. Indeed, consumers on average were paying below electricity production unit cost. Even worst, if producers were forced to pay the market price on fuel inputs, the unit cost of electricity would rise by over five-fold to 21.30 cents per kWh (ECRA, 2014a).

Table 2.2: Prices paid by power producers in KSA compared to international prices (ECRA, 2014a)

Fuel	Price Paid by Power Producers $/MMBTU	International Price $/MMBTU
Heavy Fuel Oil	0.43	15.43
Natural Gas	0.75	9.04
Diesel	0.67	21.76
Crude Oil	0.73	19.26

In 2013, the total energy consumption per capita in KSA was greater than 3 times the world average, around 6.5 toe per capita compared to the world average of 1.9 toe. The following figure illustrates the consumption of energy per sector from 1990 to 2011 (Enerdata, 2013).

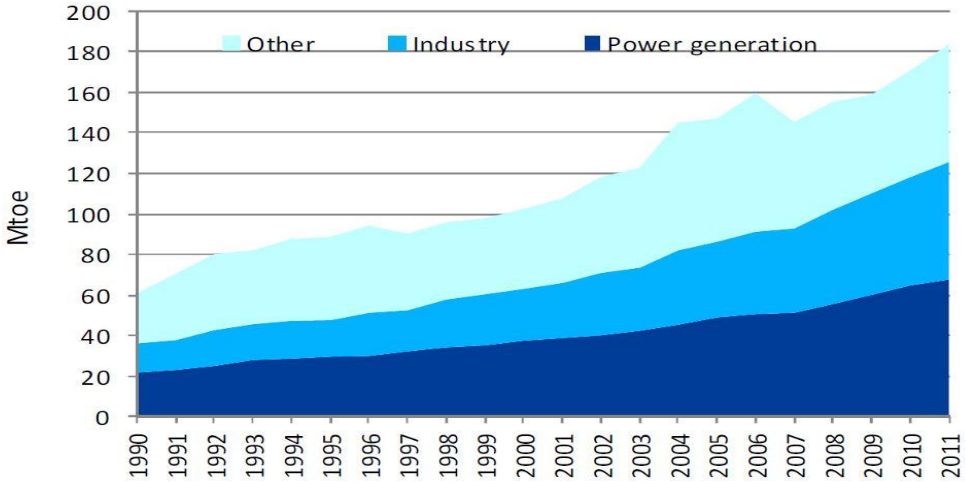


Figure 2.4: Energy consumption trends by sector

The power generation sector is the largest consumer accounting for 37% of energy consumption in 2011, followed by the industrial sector at 32%. In addition, the non-energy uses of the petrochemical sector witnessed elevated energy consumption of 19% in 2011. As shown, there is a rapid growth in the consumed energy per capita over the years.

In addition, the consumption of electricity has grown rapidly since 1990, where the electricity share in the final energy consumption rose from 13% in 1990 to 16% in 2011. This rise was led by increasing non-industrial consumer (residential, governmental, commercial …etc.) demand reaching a share of 82% of total electricity consumption in 2011, compared to 73% in 1990. This in turn caused a related erosion in the share of industry in consuming electricity, where it was 18% in 2011 compared with 27% in 1990. The figure below shows the consumption trends of electricity by sectors from 1990 to 2011 (Enerdata, 2013).

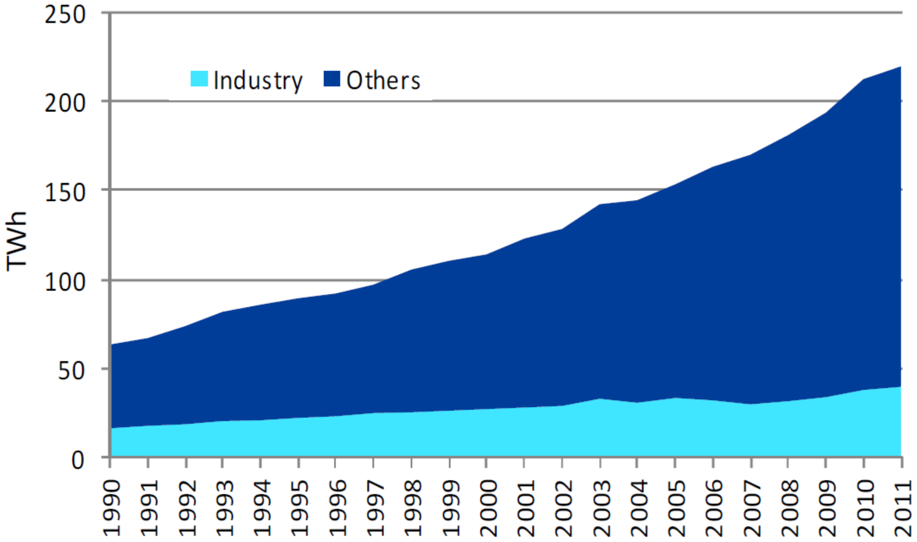


Figure 2.5: Consumption trends of electricity by sector from 1990 to 2011

In practice, the consumption of energy is growing faster than production, where this results in an increase in total energy intensity of 1.8%/year from 2000 to 2011. This is opposite to the trend observed in various countries, since development in KSA involved energy-intensive industries and high consumption lifestyles in both transport and buildings due to the low electricity costs. 61% of the rise in the period from 2000 to 2011 resulted from the industrial sector, while 38% from power generation. The following figure shows the trend of energy efficiency (Enerdata, 2013).

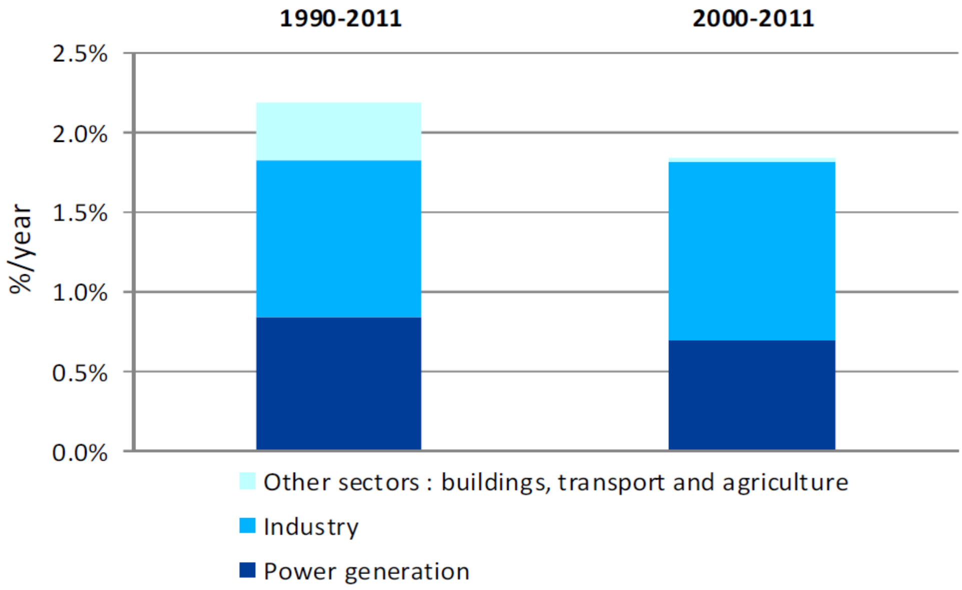


Figure 2.6: Trend in energy efficiency

The power sector efficiency, which represents the thermal power plants increase over time, where it was 27% in 1990, increasing to 37% in 2010. This is due to the increasing gas-fired capacity share since 2000. Figure 2.7 shows thermal power plants efficiency from 1990 to 2011 (Enerdata, 2013).

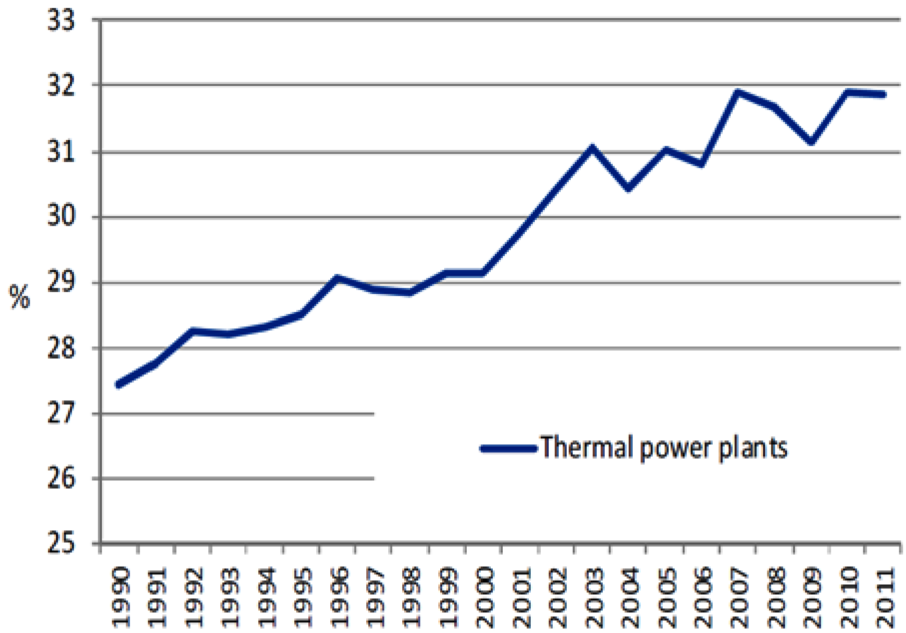


Figure 2.7: Power generation and thermal power plants efficiency from 1990 to 2011

The figure below illustrates the thermal electricity capacity per technology.

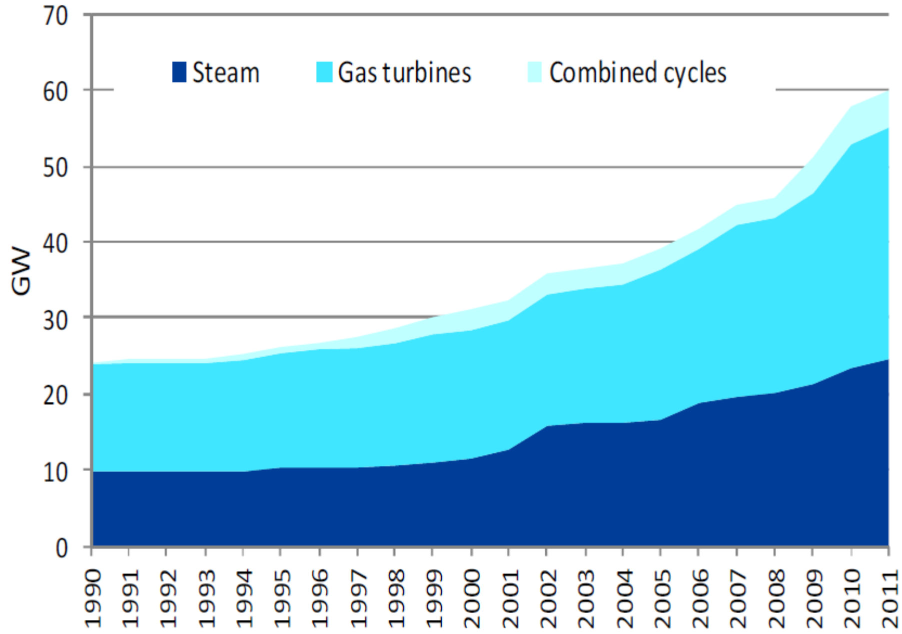


Figure 2.8: Thermal electricity capacity per technology (Enerdata, 2013)

The main challenges facing the electricity sector in KSA are not only technical, but also socio-economic and financial (Al-Ajlan et al., 2006). The table below illustrates the reported challenges.

Table 2.3: Challenges facing the Saudi Electrical Energy Sector

Technical	Socio-economic	Financial
• Huge variations in load distribution and electricity consumption as a result of weather changes; seasonal variations. • Highly skilled managers' shortage. • Low reserve margins of generation capacity. • Lack of legislation, building codes and standards.	• Need for social education and awareness about energy conservation. • Population growth (3.7%). • Rapid economic and social developments. • Need to link economic and social welfare to subsidised electricity tariff structure.	• High capital investments required to meet the demand. • Project funding should promote energy efficiency or employing new technology. • Large loans (current total $1667 million) to SEC to install further generating capacity. • Environmental costs not reflected.

The most significant and important challenges in this category are seasonal and daily electricity consumption variations that result from weather changes. Al-Ajlan et al. (2006) points out that:

> "… the load distribution is worst where most loads are residential and commercial as it forces utilities to have unused capacity: their generators run at part load, and they are forced to use costly, yet inefficient, gas turbines to serve the peak loads. This situation is exacerbated during daylight hours in summer as the peak load demand coincides with the highest temperatures, causing a drop out in output power and efficiency."

Such facilities suffer from the lack of thermal insulation and energy efficiency standards in residential, commercial, and public buildings that lead to high amount of energy wasted due to high cooling load requirements in summer. Moreover, existing generation reserve margin is low within the peak period (months). During peak periods, the peak load nearly reaches the "maximum installed capacity". This was the case in 2003. The electrical daily consummation that is resulted from weather change is shown if Figures 2.9 and figure 2.10.

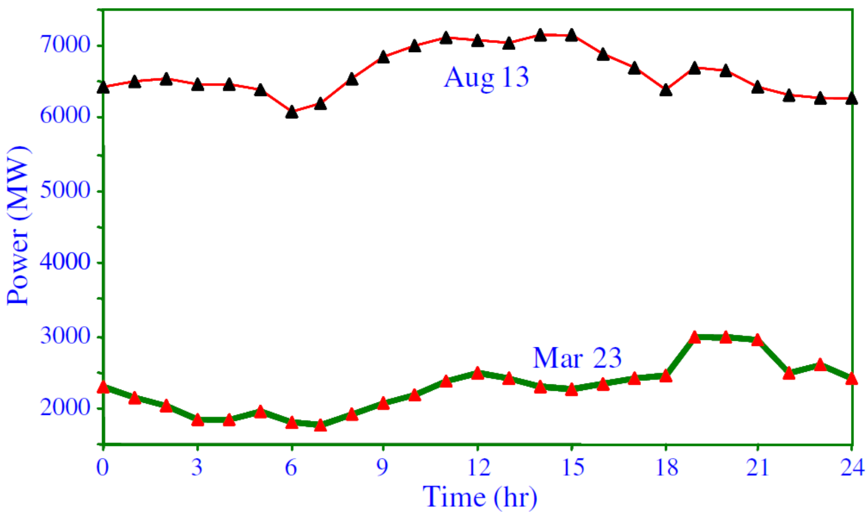


Figure 2.9: Daily Load Profile in the Riyadh Region for different seasons in 2001 (Al-Ajlan, et al., 2006)

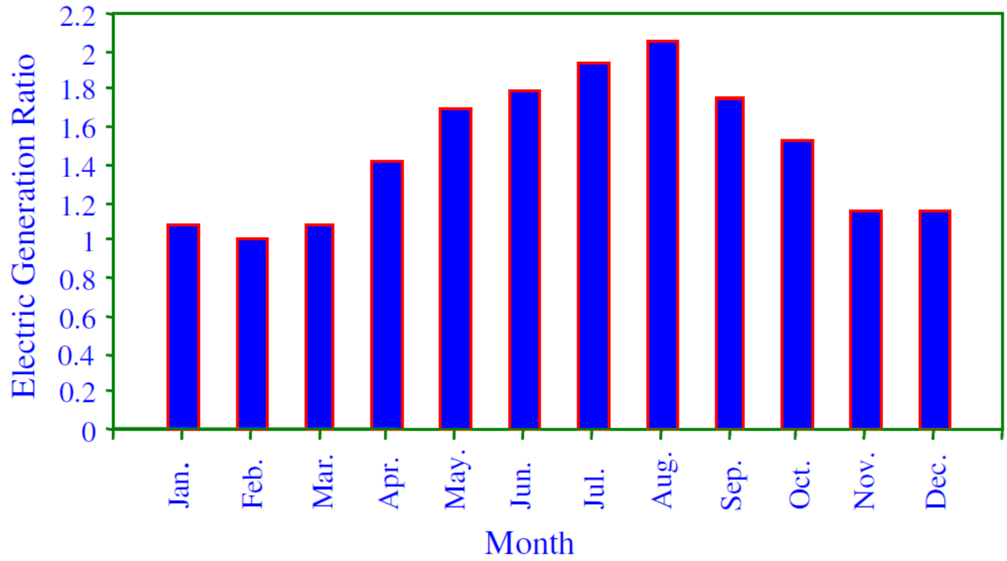


Figure 2.10: Normalised Monthly Electricity Consumption (Al-Ajlan, et al., 2006)

In practice, KSA is the largest oil exporter worldwide, yet recent studies predict that KSA may become a net oil importer by 2030 or 2038. Recent efforts to control domestic energy consumption provide an optimal test to compare consumption with other oil and gas exporting countries. The energy demand in KSA has risen by 7.5% annually in the last five years. On the other hand, KSA has not utilised energy efficiently, and the ratio of energy consumption to GDP, i.e. energy intensity, is four times that of some energy effective countries, as illustrated in the following two figures (Hino, 2015).

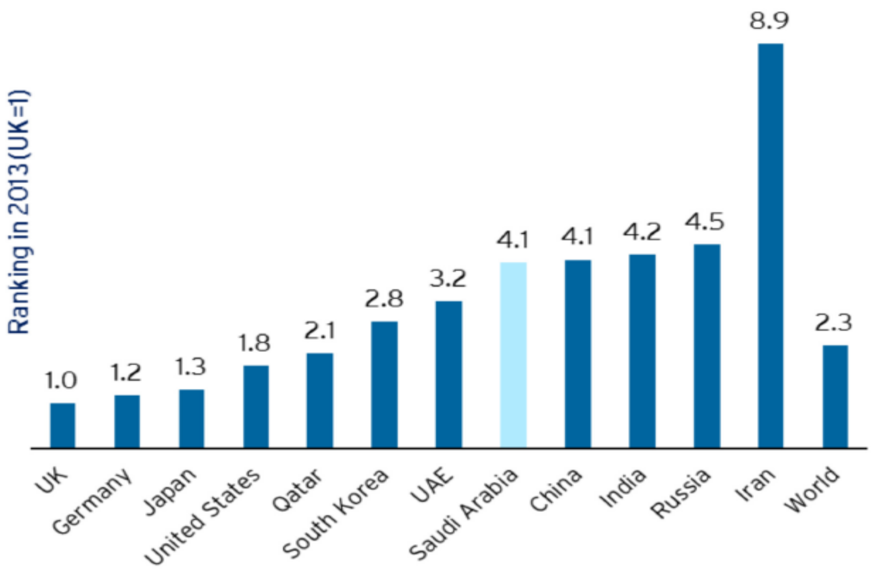


Figure 2.11: Intensity of energy in KSA compared to other energy effective countries in 2013 (Hino, 2015)

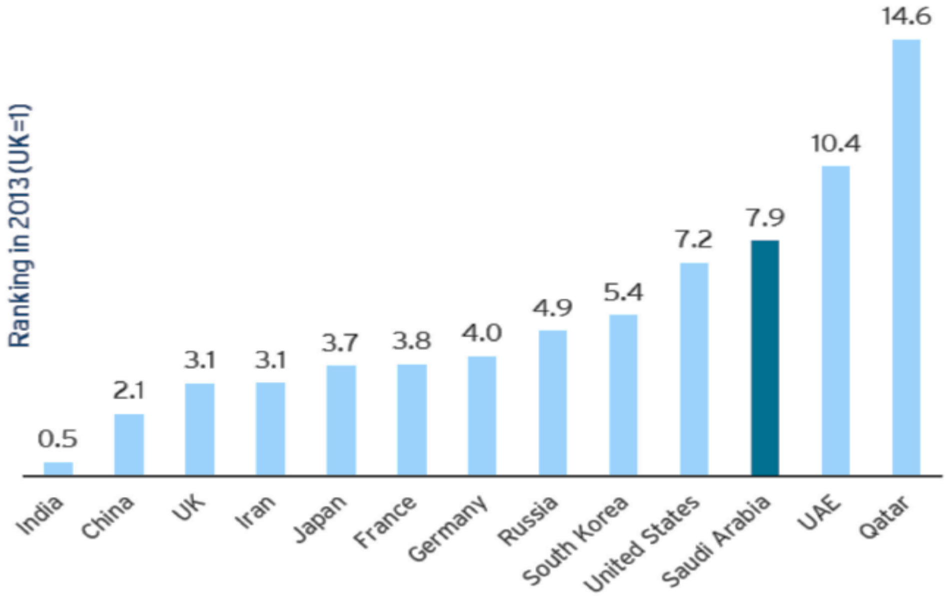


Figure 2.12: Consumption of energy per capita in KSA compared to other energy effective countries in 2013 (Hino, 2015)

In practice, KSA consumes the highest oil volume worldwide to generate electricity. In 2013, around 58% of electricity was generated from oil, and 42% from gas. The following two figures show oil production and consumption in KSA (Hino, 2015).

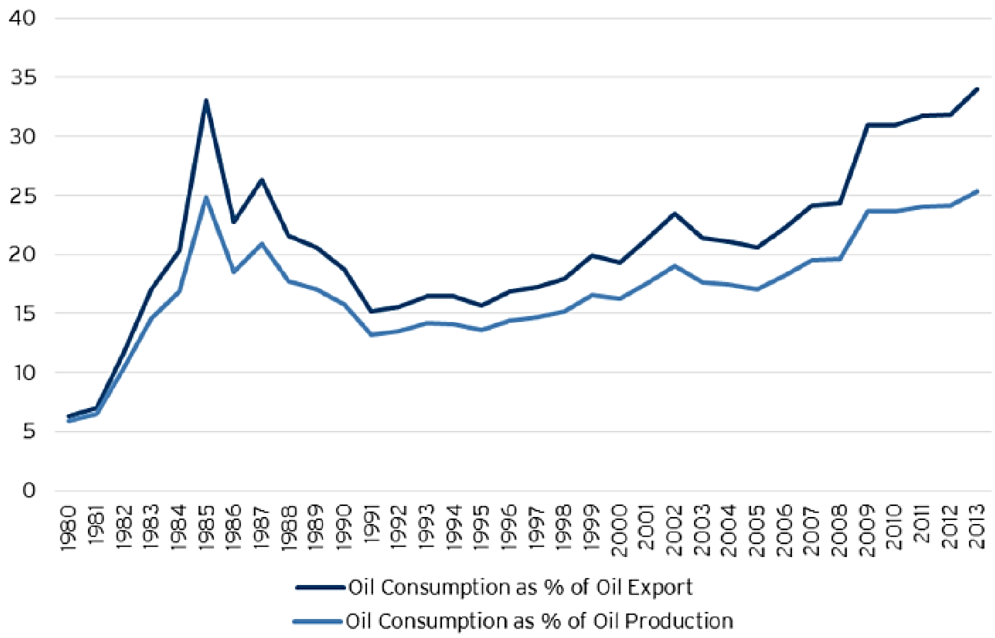


Figure 2.13: Oil consumption in KSA (Hino, 2015)

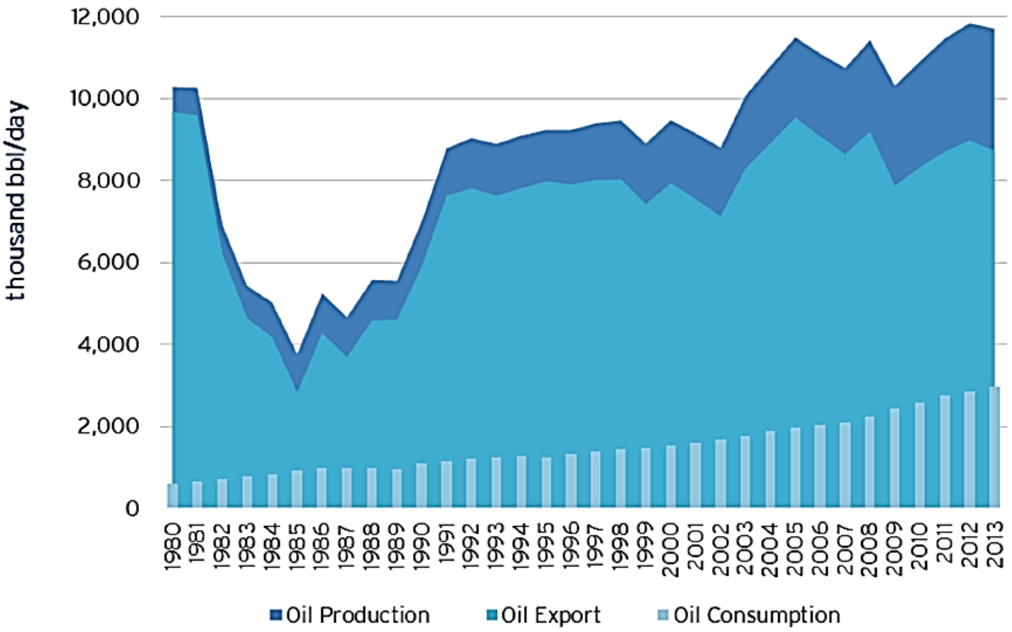


Figure 2.14: Oil generation, export and consumption in KSA (Hino, 2015)

In response to this problem, in 2010, the government established the Saudi Energy Efficiency Centre (SEEC). This new body published a Minimum energy performance standard (MEPS) to control lighting and cooling consumption, fuel economy standards for cars, and an energy efficient construction code (Hino, 2015).

Another study conducted by Statista (2015) shows the main consumption of energy in KSA in the period from 1998 to 2014 in million metric tons of oil equivalent, as illustrated below. The figure (2.15) clearly shows a consistent annual rise in energy consumption in KSA.

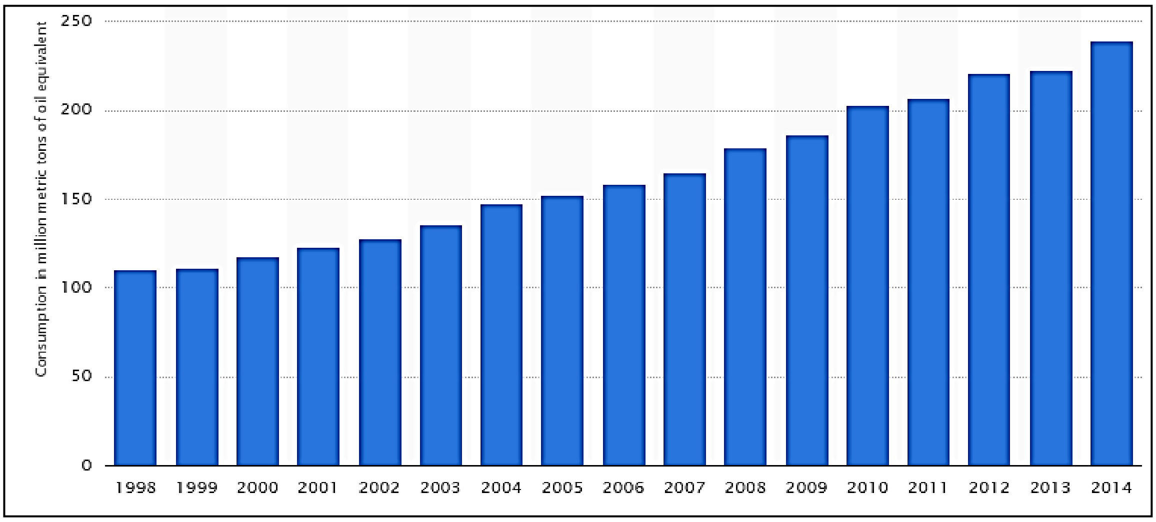


Figure 2.15: Consumption of energy in KSA in the period from 1998 to 2014

Reports published by the SEC in 2014 presented the amount of generated energy in the period from 2000 to 2013 from steam, gas, and combined cycle turbines, as well as diesel, rented diesel units, solar plants, desalination plants, water and Electricity Company and large producers as shown in the following table. It can be clearly seen that the highest average annual growth rate during this period is for large producers. However, it can be noticed that there is no growth in generation in this period for the solar (PV) plants (SEC, 2015).

Table 2.4: Amount of generated energy in the period from 2000 to 2013

Details \ Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Growth Rate during period(%)	Average annual growth rate (%)
Steam	5,672	6,748	8,747	10,165	10,293	10,293	11,472	12,651	12,795	12,795	12,795	13,986	13,986	14,686	16,782	195.9	8.1
Gas	13,229	13,318	13,486	13,684	14,013	15,273	15,843	16,984	18,915	22,389	24,495	25,281	26,327	24,416	24,527	85.4	4.5
Combined Cycle	2,387	2,390	2,484	2,484	2,445	2,444	2,385	2,385	2,371	2,369	2,300	2,299	2,331	6,342	6,899	189.0	7.9
Diesel	772	774	740	685	672	630	608	583	389	360	383	358	439	464	415	-46.2	-4.3
Total Power Plants Capacity at the end of year	22,060	23,230	25,457	27,018	27,423	28,640	30,308	32,603	34,470	37,913	39,973	41,924	43,083	45,908	48,624	120	6.8
Rented Diesel Units	-	-	-	-	288	411	358	354	488	767	724	1,057	1,289	1,506	1,495	419.2	17.9
Solar (PV)	-	-	-	-	-	-	-	-	-	-	-	1	1	1	0.3	-40.0	-15.7
Desalination Plants	3,436	3,096	2,946	2,866	2,445	2,539	2,905	2,395	2,444	1,954	2,059	1,811	1,570	1,717	2,676	-22.1	-1.8
Water & Electricity Company	-	-	-	-	-	-	-	-	-	945	1,739	1,753	1,755	1,771	1,750	85.2	13.1
Big Producers	294	187	256	207	370	711	1,429	1,597	1,840	2,906	4,643	4,602	5,891	7,559	10,961	3628.2	29.5
Total Available Capacity	25,790	26,513	28,659	30,091	30,526	32,301	35,000	36,949	39,242	44,485	49,138	51,147	53,588	58,462	65,506	154	6.9

The figure below shows the development of real generation capacity of energy for the SEC in terms of unit types in the period from 2000 to 2013. It can be seen from the figure 2.16 that there is a continuous increase in the generation of energy, especially gas-fired units (SEC, 2015).

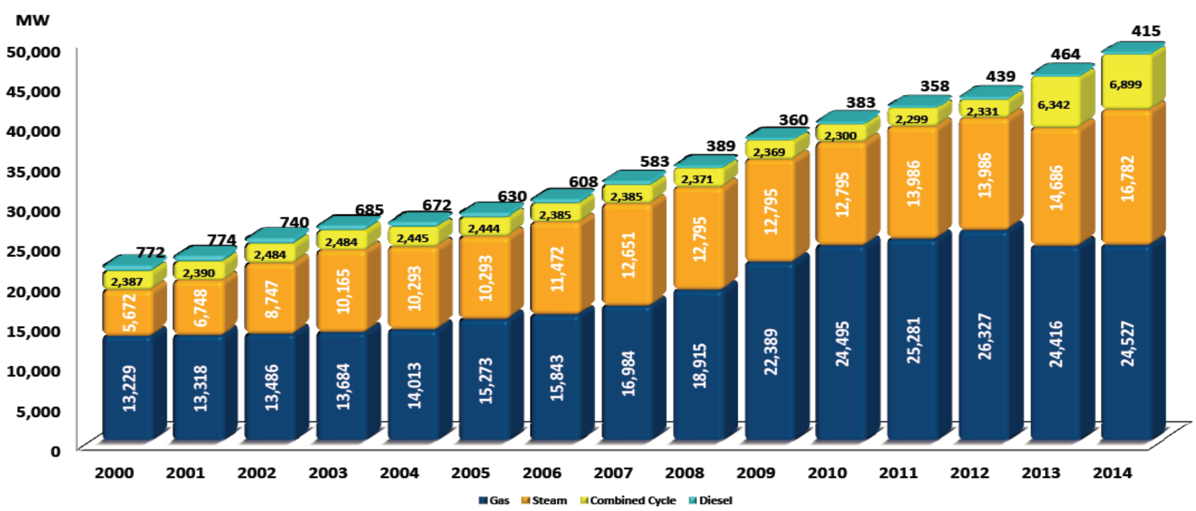


Figure 2.16: Development of real generation capacity for the SEC (2015)

However, the contribution of solar (PV) plants was too limited during 2012-2013 compared to other producers, as shown below.

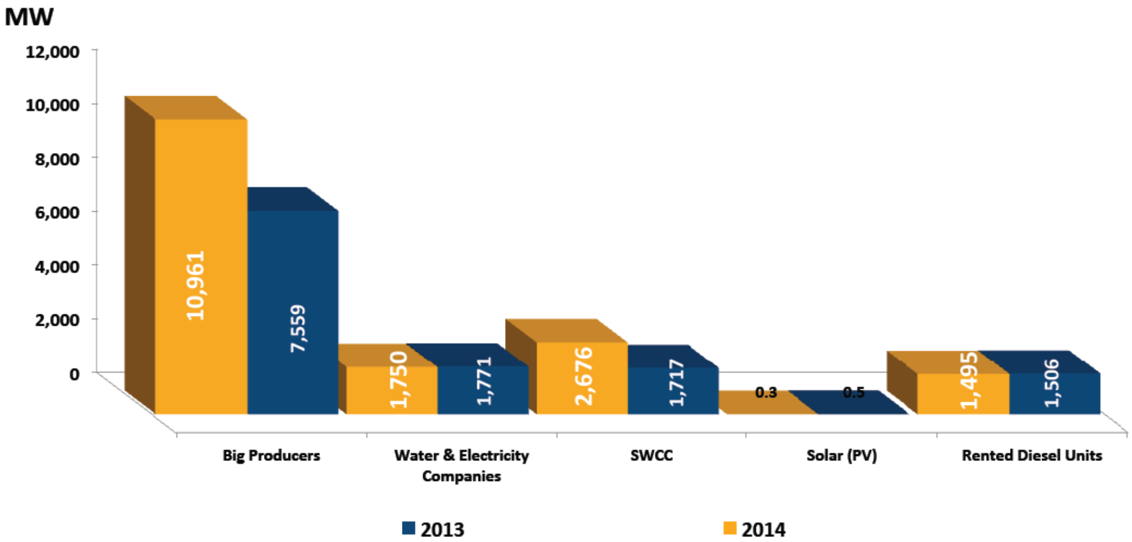


Figure 2.17: Contribution of solar (PV) plants compared to other producers in 2012-2013

Furthermore, there was negligible relative distribution in transmitted energy by solar (PV) plants compared to other sources in 2014 as shown in the figure below (SEC, 2015).

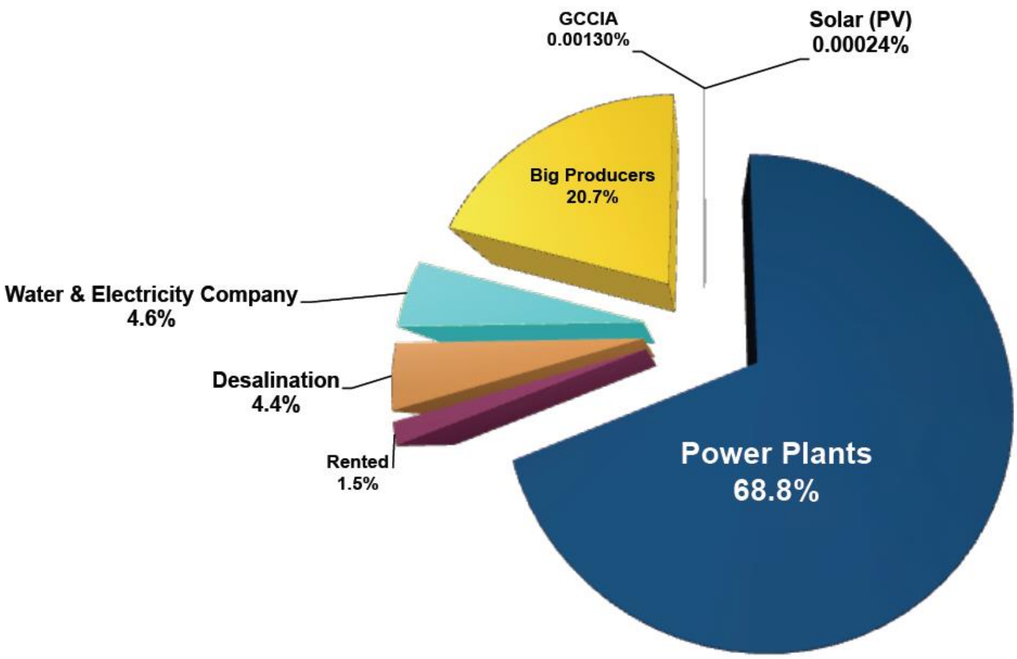


Figure 2.18: Relative distribution of transmitted energy

Reports published by SEC in 2015 concerning fuel consumption in 2014 demonstrated that the highest percentage of consumed fuel in KSA was for gas as shown below (SEC, 2015).

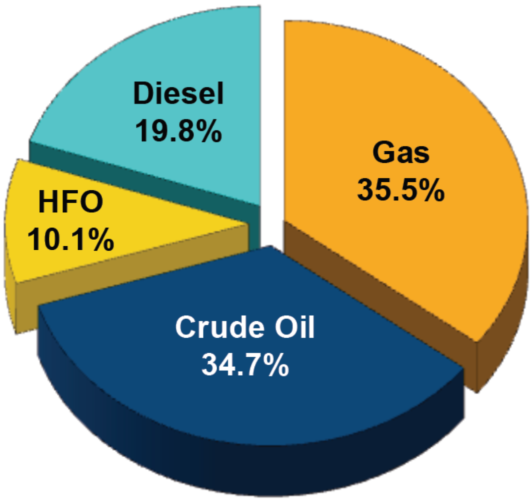


Figure 2.19: Fuel consumption in 2014

In summary, there appears to be wide worldwide dependence on fossil fuels to generate energy and offer electricity to citizens. The rapid increase in the costs of these fuels and their rising pollution led to increased emphasis on alternative environmentally friendly sources of energy that have low costs. The alternatives are the renewable sources, especially solar energy. The following section discusses these types of energy sources.

2.3. Renewable Energies

The following subsections offer a discussion concerning the main renewable energy sources worldwide, and in KSA, as the focus of this study.

2.3.1. Potential of Renewable Energies Worldwide

Energy is a necessity for life and is the engine of economic development. Many studies on renewable energy sources have done. Pimentel et al. (2002) argued that the US could meet 50% of its energy needs, while utilising 17% of land resources. Their study highlighted how fossil fuels consumption in the US accounted for 22% of the total global CO_2 emissions, despite constituting 4% of the world population. The potential for a number of RETs relevant the US consumption was assessed, including hydroelectric, solar thermal, biomass, wind power, geothermal, PV, and passive energy systems as well as alternative fuels, such as biogas, vegetable oil, methanol, and ethanol.

The potential for these renewable energy sources is recognised in terms of the associated constraints like increasing population, and thus the demand for liquid fuels, and electricity, availability of land resources (categorised into urban land, highways and farmed for the purpose), manpower labour for operating these technologies and relationship between production location and population centres. The study emphasised the need of around 200 quads (quads is a unit of energy equal to 1 quadrillion BTU where 1 quad (short for quadrillion BTU) is 10^{15} BTU, which is about 1.055×10^{18} J)) of renewable energy globally at the expense of 20% of the world land area. The US energy programme suggests a consumption reduction of overall energy, while using more renewable resources. It targets individuals, communities and industries. It is estimated that $40 billion from fossil fuels subsidies will be cut, which could be directed towards developing and implementing RETs. Processed RETs in this study are supposed to allow the US to acquire 45 quads of the energy by 2050, without any adverse effects on suitable reforestation and food production.

It was noted the energy system has developed dramatically and is characterised by two main transitions. Grübler et al. (1995) and Grübler (1998) define them as:

i. Transition from wood to coal in the industrialised countries commenced around late 18th century. Marker: invention of the stream engine.
ii. Diversification of end-use technologies and supply sources for electricity production converting it to end-use form in terms of light, heat and work. Oil gradually succeeded coal – which is still in sufficient application – as the dominant fuel source, later adding natural gas. Marker: discovery of the internal combustion engine.

Turkenburg et al. (2000) highlighted requirements for the future with a sustainable energy system that essentially enables switching systematically towards renewable energy sources. Turkenburg et al. (2000) provided a list of reasons on why they are viable alternatives. Firstly, an increase in the renewables helps to bring more diverse range energy sources, thereby leading to a more secure energy system. Wider abundance of renewables compared to fossil fuels also cuts down geopolitical constraints for a country including its added investment of fuel imports. The usage of fossil fuels (also to a degree for bioenergy) comes with health risks, which can be minimised with renewables due to lower air pollution levels.

Access to energy services is considerably improved in rural regions since RETs are quite applicable to small-scale off-grid applications, where more developments, efforts and investigations must be performed to apply them in large scale applications, since the renewable energy sector is still limited in KSA. Increased renewable energy share should also bring additional balance in fossil fuels use. More renewable energy projects increase local employment opportunities and economic development. Finally, renewable energy usage alleviates the GHG emission issue, even for biomass applications. Hoogwijk (2004) presented different potential categories in order to address future viability of renewable energy sources. They are as follows:

i. The theoretical/available potential
ii. The geographical potential
iii. The technical potential
iv. The economic potential, and
v. The implementation potential

Hoogwijk (2004) discussed each of these aspects based on how they were defined, modelled and assessed, focussing mainly on biomass energy sources. All of these aspects were reviewed under four different scenarios, A1, A2, B1 and B2 by considering available areas for energy crop. Figure. 2.20 presents the spatial area distribution that is potentially available. This includes sites of energy crop, which is a plant that grows as cheap and low-maintenance harvest to be used in making bio-fuels to generate electricity or heat, in the year 2050 for all four scenarios (Hoogwijk, 2004). The study also covers other renewables in a similar analytical survey. Findings focus on increased reliance on renewable energy sources, including biomass, wind and solar energy.

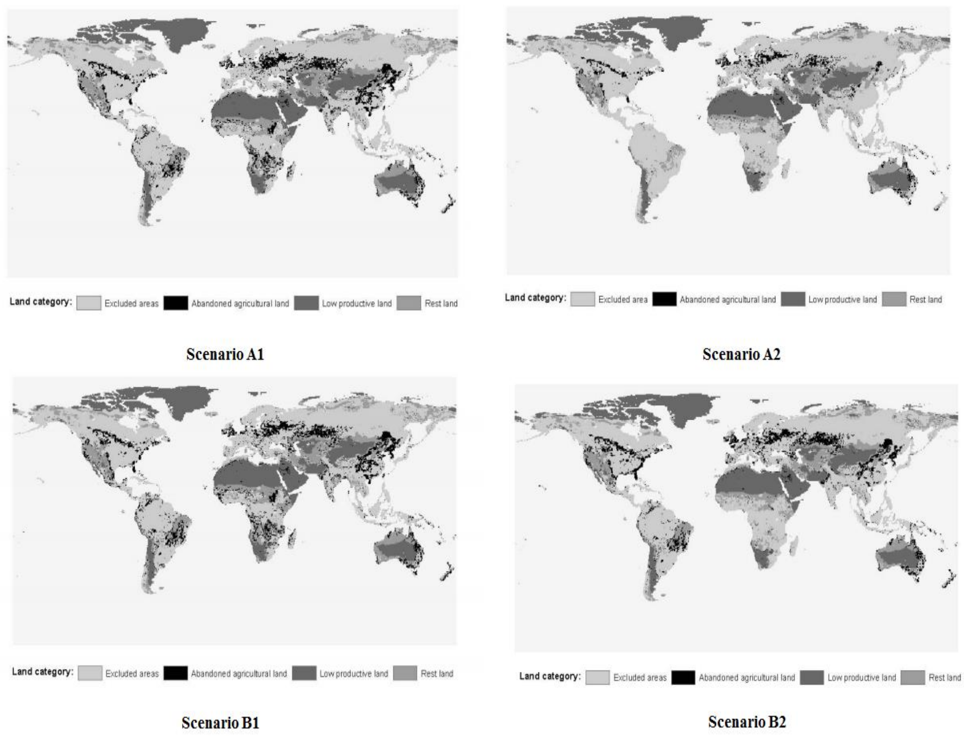


Figure 2.20: Global land availability and energy crop productivity for bioenergy

On a positive note, Weischer (2011) stated that Intergovernmental Panel on Climate Change (IPCC) measures needed to accomplish renewable energy penetration, by as much as 80% – by the year 2050. Weischer's study was review of the IPCC reports in the given context, which involved 164 energy scenarios that were peer-reviewed. One of the barriers to large-scale renewable implementation was price, since fossil fuels are often cheaper. This is mostly due to large subsidies offered by many countries for fossil fuels. The IPCC measures are used to improve the performance of renewables and reduce their costs. Renewable energy is characterised as an active and cost-competent power source in various regions and areas. To further encourage the development and implementation of renewables, IPCC has contributed a Smart renewable energy policy concerning the regulatory structure of target countries and encouraging the community to participate in energy decisions through suitable incentives. Investments in renewable energy projects were made with the help of banks and other companies. Developing countries with renewable energy production potential were favoured places. The latter can be justified by preference for more energy access, energy security, opportunities for economic development and better health prospects due to the clean energy features.

It should be clear that shifting energy consumption and production trends towards renewable sources is the most viable solution to prevent an energy crisis in the near future. Heavy dependence on most energy requirements on non-renewable sources like fossil fuels makes the transition towards renewables a difficult task. However, it is still achievable through proper policies and technologies. The figure below shows the shares in renewable energy sources of total energy consumption (Mtoe) worldwide in 2014 (Enerdata, 2014a).

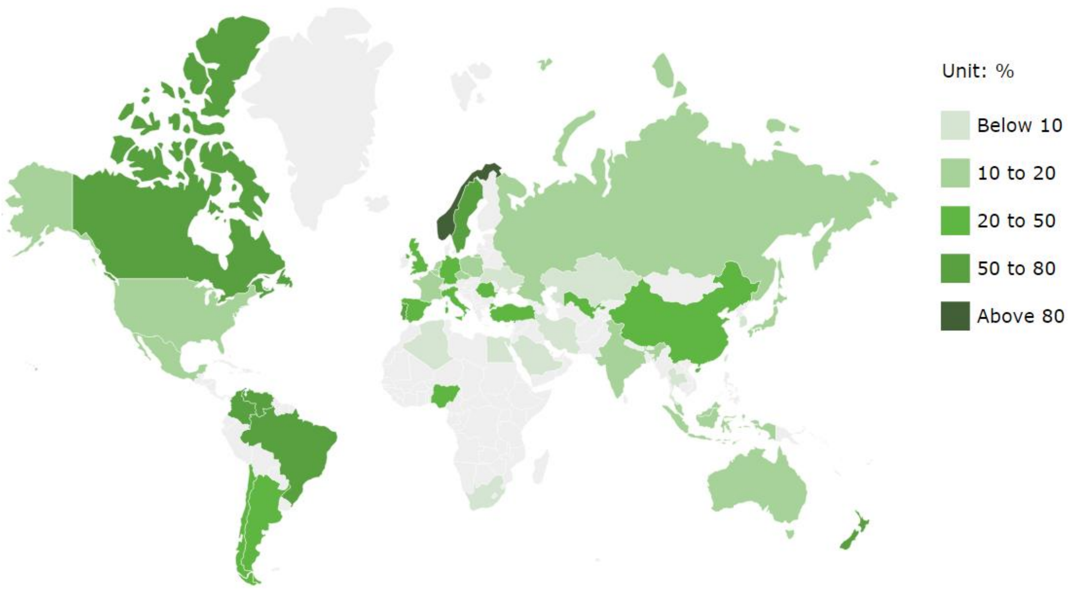


Figure 2.21: Shares of renewables in electricity production

The values above are summarised in the following figure for the top ten countries.

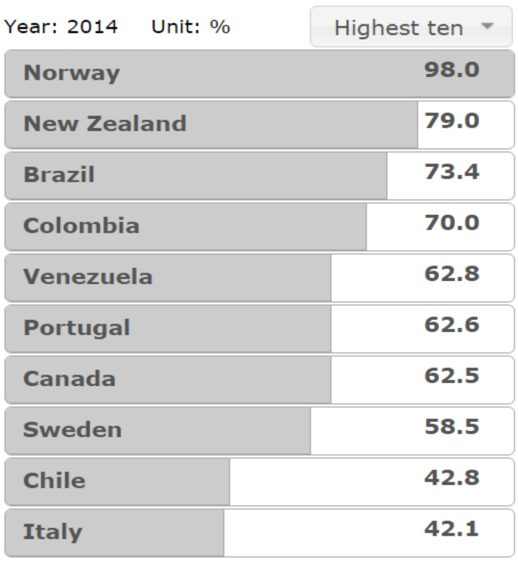


Figure 2.22: Renewables share into electricity production at the highest 10 countries around the world in 2014

The unit in the above graph 2.22 used is in “%”, expressing the percentage share of renewables in the primary energy consumption. The country with the highest renewable energy contribution is Norway with an impressive 98%, followed by New Zealand at 79%. Third in line is Brazil (73.4%) and Colombia at fourth (70%). Overall share of renewables in Europe – including hydroelectricity – in terms of consumption is 30% (Enerdata, 2014a). In terms of energy consumption, EIA (2015a) provided data on energy consumption for the electricity sector from different resources, as shown in Table 2.4 below. The unit used is trillions.

Table 2.5: Recent data on energy consumption for electricity (EIA, 2014)

January to August	2014	2013	2012
Coal	11,351	11,083	10,473
Natural Gas	5,545	5,632	6,584
Petroleum	225	178	151
Nuclear Electric Power	5,540	5,489	5,447
Hydroelectric Power	1,741	1,841	1,892
Geothermal	103	105	97
Solar/PV	115	53	25
Wind	1,160	1,068	887
Biomass	336	303	300
Electricity Net Imports	104	122	110

The table above includes renewables like geothermal, solar PV, wind and biomass. Their consumption trends reveal their active utilisation and hence, potential. Hydroelectric power is often regarded as renewable, and together with wind have the highest overall usage among renewable energy sources. While hydroelectricity consumption showed a steady decline between 2012 and 2014, wind energy has shown a steady growth. Solar energy consumption had started from a lower baseline, but has shown significant increments, as seen in the data. With the right policy and regulation, IPCC predicts that the global energy supply will boom for renewable sources to up to 80% by 2050. The drive towards renewable energy resources has not been only because of impending energy crisis, but also from rising environmental threats, including GHG emissions, which are to be contained up to almost one-third of the present levels at 450 ppm (Nutall and Aidara, 2011). In this report, researchers reviewed various renewable energy sources, bioenergy, solar energy (direct), geothermal energy, hydropower, ocean energy and wind energy. Environmental and social implications were considered, while reviewing more than 160 (with 4 analysed in-depth) scientific scenarios on how renewable sources could play a greater part in energy supply by 2050. The best case from the 4 analysed scenarios involved a 77% contribution from renewable energy sources by 2050, which amounts to 314 of 407 Exajoules/year. These scenarios had been defined in terms of functioning variables like energy efficiency, per capita consumption and population growth. The report predicts an inevitable increase in renewable share of energy despite possible enabling of policies.

The largest part of renewable energy can be assigned to hydropower, which is accessed by operational dam projects with reservoirs, in-stream and run-of-river projects of different scales. Share of energy contribution from this source has been 16% since 2008. A fall of 10-14% has been predicted, probably in the context of greater share of other renewable energy sources. Wind energy is the most prominent renewable source after hydroelectricity, where it contributed up to 2% to global energy (electricity) demand by the end of 2009. Wind energy is predicted to grow by 20% by 2050 with rapid expansion of off-shore and on-shore wind power farms in the EU, North America, China and India. The next most promising renewable energy source is direct solar energy, which is applied as either PV or CSP systems. Despite its meagre share in the total energy supply across the world, it is predicted that solar energy will grow into one of the major energy supply sources. Its growth still depends on the current solar energy scenario, and is governed by continuous innovation, reduction in cost, and public support.

Annual growth of 130 Exajoules/year for solar energy is expected by 2050, consequently, appearing third in line among renewable energy sources. Other energy sources include geothermal, ocean and biomass. At present, the consumption rate of electricity from geothermal energy is around 0.7 Exajoule/year, which should expand to contribute up to 3% and 5% to meet global electricity and global heat demands respectively by 2050. Energy from biomass is the most sustainable and clean source of electricity production, as it allows 80–90% reductions in emissions compared to fossil fuel sources. This energy source should reduce its share in electricity production with 100–300 Exajoules, by 2050. Ocean energy on the other hand is in the early development stage. It is not expected to have a larger contribution to the mix until 2020. It will deliver energy up to 7 Exajoules by 2050 (Nutall and Aidara, 2011).

Moriarty and Honnery (2012) demonstrated that the major forces driving the shift from fossil fuels to alternative sources as primary energy sources are the depletion of energy reserves and GHG emissions. Renewable energy sources are major providers of all energy requirements in the future. This is mainly due to the possibility that nuclear power will not show increments as an energy source. Considering production costs and energy efficiency contribution of these sources may not reach up to 1000 Exajoules by 2050. The technical ability for renewable sources is appreciated at the end. The solution for maintaining (if not increasing) the future potential of renewable energy ultimately depends on significantly reducing overall energy consumption levels, thereby ensuring environmental sustainability.

Mostafaeipour and Mostafaeipour (2009) presented a comparative study of renewable energy in the Middle East region, including geothermal, biofuel, tidal, wind and solar energies, with the last two being more available and accessible. The estimates show that about 10 to 20% of solar energy reaching the Earth is in the Middle East region. This is enough to generate all energy required from solar and wind energy. Large scale wind energy utilisation will enable many countries to produce electric power and reduce the cost of energy import. The Middle East is abundant in energy resources, whether in the form of fossil fuels or renewables such as solar energy. However, the power demand is rising rapidly with huge economic and social challenges for the region.

Adoption of renewables in Middle East countries varies widely from country to country with about 10% of power generation from renewable sources, mainly solar, wind and hydro. Algeria produces 500 kW power with solar systems, representing 0.3% energy in total country power growth. Egypt, Iraq, and Jordan are the most active centres in RE energy. Egypt plays an important role in the renewable energy sector, generating 2010 MW power from renewable energy, representing 11% of power demand. In Jordan, there is a widespread use of solar hot water systems that are mounted on building roofs. KSA also increased its R&D projects in renewable energy through the American-Saudi cooperation program (SOLERAS) as it will be more investigated in the forthcoming section. Other Middle East countries are gradually initiating their own renewable energy programmes. Morocco is one of the fastest growing countries in renewable energy in the Middle East. It generates 1324 MW power from renewable energy, reaching 30% of the total energy production with future plans to improve hydro energy systems. It also installed 16,000 solar PV systems for electricity generation and 111,332 solar water heaters in houses in rural areas. In Palestine and Oman, solar renewable energy is used for water pumping, lighting, communications, etc. In Syria, hydro power is the main renewable energy system, generating 2000 GWh to 4000 GWh in per year.

The Middle East is well-placed in terms of renewable energy, which can potentially provide a sustainable supply of pollution-free electricity. Consequently, energy price stability will result due to the non-depleting nature of renewables. Oil consumption in this region has increased by 5.6%, which is higher than in other countries. If fossil fuels are replaced by more future-adept technologies like renewable energy, it is possible to mitigate rising demand for energy and reduce environmental impact in the MENA region. The wind and solar energy resources are equally huge. Every year, 3500 hours of sunshine reach Middle East countries, potentially producing 5 kW/m^2 daily. In Iran, average solar radiation is 19.23 MJ/m^2. It is estimated that the wind and solar energy potential in MENA region is more than 6500 MW/m^2.

Significant renewable energy sources that may meet future potential energy demands have been established. Solar energy is seen as one of the key solutions for this purpose, as the Sun is the Earth’s source of energy. The pressing issue has been to identify factors that delimit large scale growth and deployment of solar energy technologies, which has been a topic of increasing research and market interest. In a similar work by Margolis and Zuboy (2006), the non-technical barriers to use of solar energy were identified and assessed. The most commonly encountered barriers are listed as follows:

i. Shortage of government policies that effectively support energy and renewable energy;
ii. Insufficient data dissemination and consumer awareness of energy efficiency and renewable energy;
iii. Higher prices of RETs – particularly for solar energy – compared to conventional non-renewable energy;
iv. Rigid energy systems, which are not easily accommodating;
v. Financing options for renewable energy projects are limited and constrained;
vi. Costs and benefit assessments on energy choices are unaccounted for;

vii. Lack of adequate skillsets and training in the available workforce;
viii. No proper standards, codes, or guidelines for net-metering and interconnection;
ix. The general public's perceptions on the aesthetics of renewable energy systems is not based on good information; and
x. Inadequate community and stakeholder participation in renewable energy projects.

An extensive literature database was accessed in this study, while adopting two strategies related to solar/PV or renewables. They were respectively linked with barriers and institutional policy making. The study mostly marked the political and financial scenarios of the UK, the US, Australia, OECD countries, and the Netherlands. The growth of solar energy technology deployments was measured, listing solar technology test cases. Different methods were applied in reviewing the literature, including energy policy analysis, financial analysis, PV stakeholder focus groups, observations for a predetermined period (2 years, for instance in Florida, USA), analysis of relevant technologies, interviews with stakeholders, through questionnaires, architectural design analysis, and suitable workshops and reports (Margolis and Zuboy, 2006).

Among the different renewable energy sources, solar energy has the largest potential. It can be noted from the rate at which solar energy falls on the Earth's surface – 120 petawatts. That rate easily suffices for an energy supply equivalent to 20 years of the whole world's energy demand (Chu, 2011). Figure. 2.23 presents a graph for the global energy demand comparing the potential of different renewable energy sources with data collected from the 2009 Worldwatch Institute study. It validates higher solar energy potential at the technology level in the period.

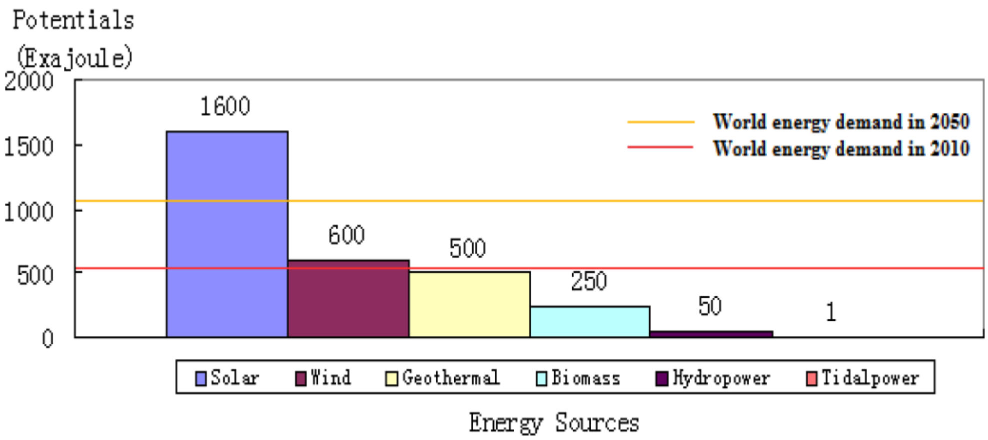


Figure 2.23: Potential of Renewable energy sources as per present technology level

Global energy demand is supposed to increase annually by 5%, which necessitates the need for advances in relevant technology for increasing every energy source's potential. Chu (2011) addresses various applications that can use solar energy, including generating electricity, photochemical application, solar propulsion, solar desalination, and controlling room temperature. Solar energy does not involve any CO_2 emission, and is a clean renewable source. Timilsina et al. (2011) submitted a review on implementing and developing solar energy in terms of policies, economies and technical aspects. Research states that the solar energy theoretical potential will significantly exceed global energy demand. Its contribution towards global energy supply has however been minimal. Main problems that limit large-scale solar energy utilisation are recognised by various studies on the topic.

One reason could be higher costs associated with existing solar energy technologies compared to fossil fuels for electricity production. This problem has not been remedied, even after reduced capital costs for many solar energy technologies and rising fossil fuel price. This main economic problem is accompanied by other technological, financial, and institutional barriers. These obstacles have greatly limited large-scale solar energy implementation. Relevant policies to lessen these constraints include tax credits, Feed in tariffs (FIT), subsidies and grants on the capital costs, public investment, and relevant financial incentives. Renewable portfolio standards (RPS) are also involved and contain standards specific to solar energy (Arvizu et al., 2011). A combination of policy portfolios were deployed in the US, featuring RPS, net metering, Renewable energy certificates (REC), federal tax credits, rebates and subsidies for enhancing the solar energy market. In countries like Spain and Germany on the other hand, FIT was used for a similar purpose. The Kyoto Protocol was addressed owing to its clean development mechanism (CDM) in encouraging solar energy projects, since it also covers cost competitive criteria.

Limited contribution was possible in comparison to other renewable energy sources. Relevant studies reviewed in the work of (Timilsina et al., 2011) suggest that total solar energy source on international level can cross 10% in 2050. This still cannot be considered a fair share, even within the renewable energy supply considering the requirement of bringing the intensity of carbon (CO_2 emissions) the energy system worldwide down by about 75%. Solar energy's technical potential on an annual basis is shown in Table 2.5 (in terms of Mtoe). Presented data involve minimum technical potential as per assumptions for annual sky irradiance and annual average sky clearance and available land area, as of the year 2007.

Table 2.6: Solar energy's annual technical potential and energy demand

Region	**Minimum technical potential (Mtoe)**	**Maximum technical potential (Mtoe)**	**Primary energy demand (2008) (Mtoe)**	**Electricity demand (2008) (Mtoe)**
North America	4322	176951	2731	390
Latin America and Caribbean	2675	80834	575	74
Western Europe	597	21826	1822	266
Central and Eastern Europe	96	3678	114	14
Former Soviet Union	4752	206681	1038	92
Middle East and North Africa	9839	264113	744	70
Sub-Saharan Africa	8860	227529	505	27
Pacific Asia	979	23737	702	76
South Asia	907	31975	750	61
Centrally Planned Asia	2746	98744	2213	255
Total	37492	1190108	1226	1446

The study also compares different renewable energy sources in terms of their technical feasibility potential according to efficiencies of existing conversion technologies. For solar energy, the technical potential is around 80,000 Mtoe, which exceeds current primary energy consumption levels at 39,000 Mtoe. This means that technical potential is double consumption. This is evident in the abundant solar irradiance that is received by the Earth's surface, varying by latitudes as 0.06 W/m^2 at the highest and 0.25 W/m^2 at the lowest.

Solangi et al. (2011) addressed solar energy policies across the world. Their study referred to the BP 2010 Statistical Energy Survey, which states that total solar energy global installed capacity by 2009 was 22928.9 MW, which is an increase of 46.9% on the previous year. The most effective policies adopted in different countries for successful solar energy market expansion were FIT, RPSs and others. The study set energy policies for solar power deployment in Malaysia as a qualitative benchmark to assess relevant policy-making in other countries across the world, which have been successful in solar energy investments.

2.3.2. Potential of Renewable Energy in KSA

KSA is one of the largest countries in the world, covering an area of 2.3 million km2. The country is rich and developed quickly, and its electricity requirements are increasing annually by around 5%. KSA plans to invest about US$117 billion over the next 25 years in power generation systems (Geni, 2013). In practice, around 80% of people living in Saudi state capitals and industrial centres are supplied by electricity by the state power grid system. However, it is not financially-viable to expand this system to lightly populated areas in the country. Therefore, several remote communities require independent electrical energy sources. Such regions represent important potential for the application of renewable energy. The main benefit of using renewable energy in the country is to meet remote sites' demands and enhance the national grid to assist in satisfying peak load demand in summer (Geni, 2013).

Despite ranking among the world's largest producers of fossil fuels and the largest exporter of oil, KSA needs to consider its position in the future energy market. Future energy demands calls for renewable sources of energy. It has thus been a major country goal to compete in the global renewable energy market. This is acknowledged in KSA's active investments, which amount to US$109 billion (ARAB-NEWS, 2013). With such an aggressive drive, KSA aims to use renewable energy of about 54 GW to meet up to one-third of its energy demands by 2032. The country's primary organisations behind this drive, include KACARE. KACARE presented its revised National Energy Plan, which involves different renewables as detailed in Table 2.6.

Table 2.7: KACARE's revised National Energy Plan for energy supply

Renewable source		Energy generation
Solar power	CSP	25 GW
	PV	16 GW
Nuclear power		18 GW
Waste-to-Energy		3 GW
Geothermal		1 GW
Wind power		9 GW
Hydrocarbons		60 GW

KSA's power demand will be met by these sources. They are largely aimed at water desalination plants. The International Energy Agency (IEA) recommended that long-term policies are expected in the KSA, as in other countries. These should compose a reliable framework that supports deployment of renewables (ARAB-NEWS, 2013). By 2032, electricity demand in KSA is expected to rise to over 120 GW. This means an increase of overall fossil fuel demand from 3.4 million b/d in 2010 to 8.3 million b/d in 2028– given there is no implementation of any alternative energy measures (KACARE, 2014). KACARE is involved in building a comprehensive sustainable energy programme, which is the first of its kind in any country, in order to secure KSA's future as a major energy supplier. This energy programme includes activities that examine a number of basic scenarios, such as dropping peak demand by optimising energy efficiency and energy conservation, derived benefits for conserving fossil fuels, issues related to power generation (such as load factors, management, and technologies and their limitations), human resource potential, establishing KSA's role in the alternative energy market, setting product chains internationally, and deriving benefits for the local value chain as much as possible. Introducing alternative and renewable energy sources should reduce fossil fuels consumption for power generation and water desalination.

The former purpose has been to reduce utilisation of non-renewables down to 50% by 2032. Forming partnership roles between local and international stakeholders is a main aspect of KACARE energy programme. It also seeks to establish local sourcing inputs for energy activities as 60% for nuclear energy and 80% for solar energy developments. A minimum of 70 stations had been planned by KACARE. They should be installed around KSA for measuring electricity generating capacities from the different renewable sources, such as solar, wind, geothermal and waste. Ten stations had already been installed by 2013 (Mahdi, 2013). Figure. 2.24 shows a timeline of alternative energy source deployment up to 2032.

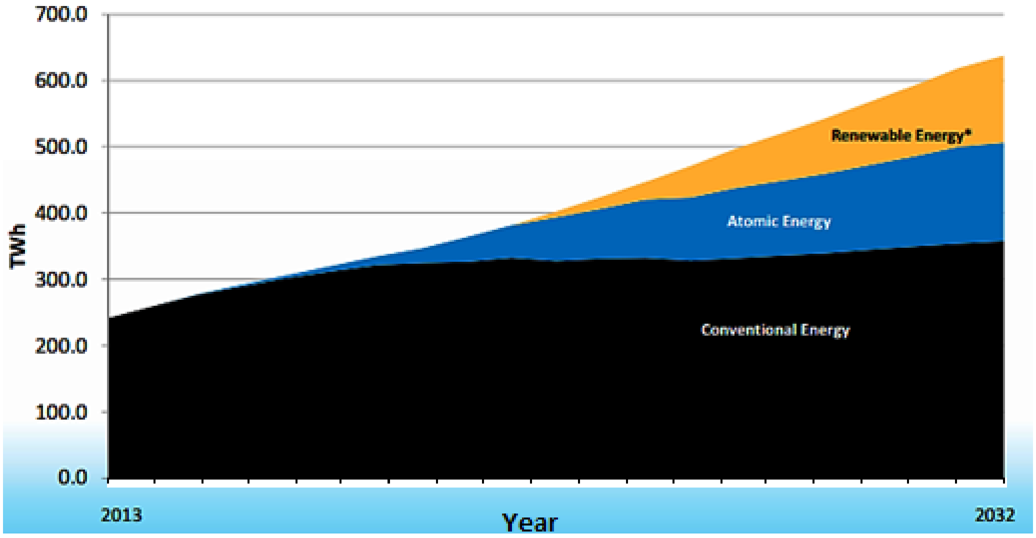


Figure 2.24: Timeline of deploying alternative energy in KSA

The above figure includes load factors for each renewable as follows: 0.2 for PV, 0.34 for CSP, 0.2 for wind, 0.9 for geothermal and 0.85 for waste-to-energy (Babelli, 2014). The following sections present available renewable sources in KSA.

The increasing demands of electricity and various financial and social issues can be addressed and met based on developing renewable energy resources. A study report was published in Alriyadh (2012), demonstrating that the generation of 5 GW of solar power in the year 2020 can result in around 15,000 job opportunities in the country's solar sector. In addition, the development of this energy to produce electricity can reduce GHG emissions and assist in meeting the country's commitments. Measurements demonstrated that KSA receives solar energy on an average of 2,200 thermal kWh per square meter daily, where this is considered an optimal amount of solar energy that must be used.

Alswaha (2015) presented that various actions have been taken to establish a foundation for developing renewable programmes in KSA to meet its target renewable energy by 2032. Some of these involved constructing a nationwide renewable energy resource and carrying out investigations concerning grid connection and control to cope with the irregular nature of wind and solar power based on the level of penetration. In practice, KSA had started using solar energy with PV systems, around thirty years ago to offer electricity to a specific municipality in the north of Riyadh. After that, King Abdullah University for Science and Technology (KAUST), Saudi Aramco, SEC and many universities began evaluating and constructing pilot systems on the use of renewable energy, mainly solar energy. However, the field of renewable energy is still restricted in KSA, and there is a need to collaborate with experienced lenders, manufacturers, contractors and developers to improve the renewable energy industry and establish effective renewable energy projects.

The main types of renewable energy in KSA are waste-to-energy, wind, geothermal, and solar energies. The following subsections discuss the use of these energies in KSA.

2.3.2.1. Wind Energy

Wind energy is considered one of the main promising renewable energy choices. In practice, wind is an eco-friendly renewable energy source, where it is broadly used as a main solution to counter weather changes. Based on a report published by KACARE (2013), in KSA, various efforts will be made to construct wind turbines taking into account choice of appropriate locations. The probability in KSA is that these turbines will be constructed along the beaches of both Arabian Gulf and Red Sea to offer 9GW in 2032. This energy can be used them to desalinate seawater and convert brackish into potable water. Nevertheless, the availability of wind cannot be predicted, and this indicates that the wind energy is useful when it is combined with other sources of renewable energy. Various growing technological developments of wind turbines are in progress to improve their effectiveness, thus, KACARE (2013) stated that they plan to work with stakeholders to carry out various researches, investigations and developments, create inter-associated nationwide industries and train Saudi citizens nationwide on skills and techniques of wind turbines and energies in KSA.

Throughout the 1980s, many developed countries were seeking a way to harness wind energy due to the common energy crises and continuous environmental pollution issues (Habali et al., 2001). Lately, wind energy has attracted attention as one of the potential renewable energy options. Before 1999, internationally, wind turbine installed capacity was 10000 MW and global annual installation rates were 30%-40%. In the period between 1991 and 1997, wind energy associated costs fell by 30% (Andersen et al., 2000). This was caused by the success of wind turbines and well-defined future wind energy potentials. Additionally, according to both the American Wind Energy Association (AWEA) (1999), and Global Wind Energy Council (GWEC), the global cumulative installed wind capacity increased from 7,600 MW in 1997 to 369,553 MW in 2014. In the 1990s, installed wind energy capacity grew annually by 25.7%. Subsequently, allied to consistently falling production cost, the rate of capacity expansion has doubled in each three year period. Consequently, the unit cost of wind-derived electricity has fallen to around a sixth compared to the cost in the early 1980s, and as such further reductions may be predicted in coming years. Industry analysts note that the cost reduced further by 20-40% in 2005.

Recently, the main challenge is to utilise wind to produce required electrical power. Some obstacles that impede implementation are resource intermittency, need for energy storage, most sites that have higher amounts of daily winds are usually found in remote regions, which are very far from the regions of consumption (Said et al., 2004).

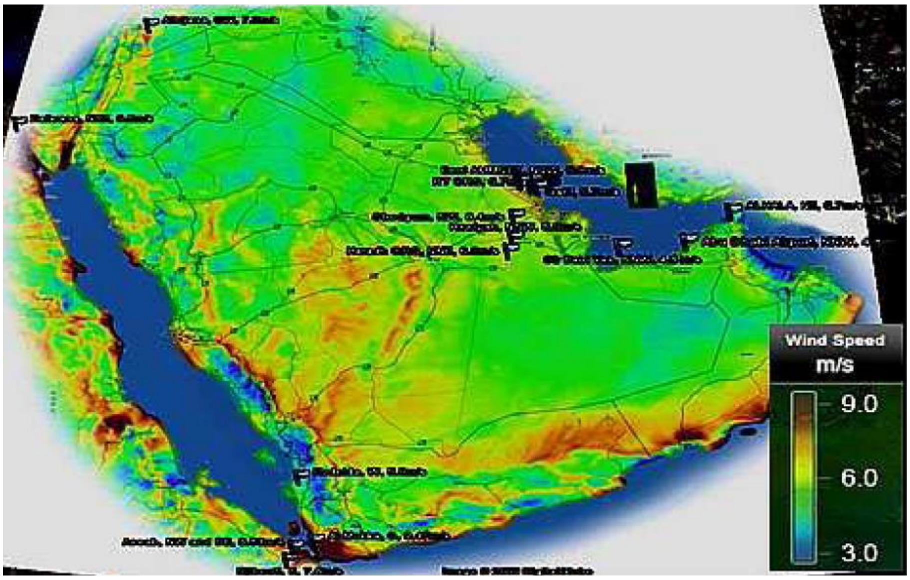


Figure 2.25: Wind map of KSA

The KSA wind resources map (Figure. 2.25) highlights two areas with large wind potential, located along the Red Sea and the Arabian Gulf regions (Al-Ammar and Al-Yousef, 2010). As shown in the figure, there are large numbers of regions that include useful average wind speeds like Alwajh, Yanbu, Turaif, Jouf and Dhahran. In the two principal wind resource areas highlighted, wind speed ranges from 14-22 km/h on the Arabian Gulf, and 16-19 km/h on the Red Sea. As such, the average wind speed over the year for both areas is over 16.7 km/h, while average energy density over the year varies from 250 to 500 kWh/m² on the Red Sea coast, dropping to 50 kWh/m² inland.

Numerous studies and publications on wind energy potential in KSA were conducted by Alaidroos et al. (2012), Rehman (2004), and Al-Abbadi (2005). It was found that the lowest cost required for electricity production from wind resources is \$0.0234/kWh. Alaidroos et al. (2012) presented a detailed analysis of wind energy availability in Yanbu and wind data. Prevailing wind direction at this location is mainly from the south with average speed of 8 m/s as shown in Figure 2.26.

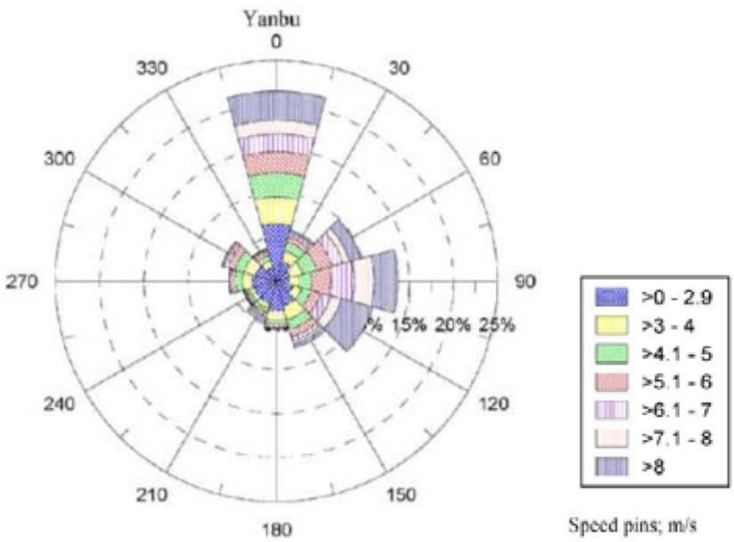


Figure 2.26: Wind rose chart at 40m above ground at Yanbu (Alabbadi, 2004)

Figure 2.27 presents 14 year mean monthly wind speed data. The key important inference is that higher wind speeds occur in May to September, which coincides with high seasonal demand for power for air conditioning in buildings.

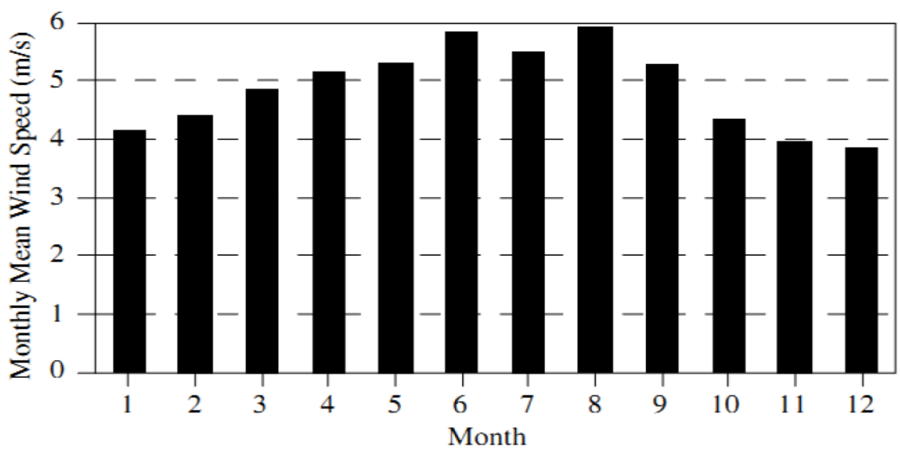


Figure 2.27: Monthly Mean Wind Speed in Yanbu (Rehman, 2003)

2.3.2.2. Solar Energy

The sun is notably a major and quite abundant natural resource in KSA, providing large scope in meeting the country's energy needs. KSA receives abundant sunlight daily, and has high insolation rates compared to other countries around the world. Thus, KACARE (2014) plans to develop clean, cheap solar energy techniques to assist in meeting various peak demands, particularly in the summer season with the purpose of securing around 41GW of solar energy in 2032.

Pazheri et al. (2012) in their study demonstrated that KSA can lead other countries in the region in harvesting valuable solar energy. The Gulf Cooperation Council (GCC) countries have an annual solar radiation rate of about 250 W/m^2, while in Europe this reduces to 100-200 W/m^2. From a technical perspective, converting sunlight into electricity can be conveniently done in any place in the region, with cost varying inversely with the amount of received sunlight. Areas that receive a large amount of solar power therefore incur less cost. The growing oil price and predicted shortage in the near future may attract European investors to import solar power from KSA to cover energy demands in their own countries.

Focus of this work is mainly on reviewing the effort done by KSA to harvest solar energy. The programme of using solar energy technologies started back in 1980s through the "solar village" scheme to provide power to villages in remote areas. Another research programme related to solar energy was conducted by The Energy Research Institute, KACST (King Abdul Aziz City for Science and Technology) as reported by Said et al. (2004). An important area for use of solar energy is water desalination. At the moment, around 1.5 million barrels of oil per day is consumed in desalination plants.

Hepbasli and Alsuhaibani (2011) reported on many R&D demonstration projects constructed in partnership between KSA and American Saudi (SOLERAS) throughout previous decades in the fields of PV, solar thermal electricity, solar desalination and solar cooling. These include the following:

- 1981-1987: three projects: AC/DC electricity for remote regions, Solar Village and 350kW PV System (2155MWh).
- 1987 -1993: three projects: the solar hydrogen production demonstration plant, Solar Village and 350 kW PV system used to produce hydrogen (1.6MWh).
- 1981-1987: solar cooling laboratory was developed.
- 1989-1993: hydrogen measurement and production testing (laboratory scale), Solar Village and 1kW solar hydrogen generator.
- 1986-1991: 2 kW solar hydrogen (50kWh) project was conducted in KAU, Jeddah.
- 1987-1991: 3kW PV test system and Solar Village project were implemented.
- 1996: 4kW PV system was established in southern areas of KSA.

- 1996-1998: 6kW PV system solar seawater desalination was constructed in the Solar Village.
- 1994-1999: PV water desalination was constructed, which is (0.6m^3 per hour), Sadous Village, PV/RO interface.
- 1996-1997: a Solar-thermal desalination project in Solar Village was constructed with Solar desalination of brackish water.
- 1996: PV in agriculture (4kW) was constructed in Muzahmia, AC/DC grid-connected.
- 1990: Long-term performance of PV (3kW) in Solar Village was constructed; performance evaluation.
- 1993-2000: Developed fuel cell (100-1000W) was constructed in solar village with hydrogen utilisation.
- 1993-1995: Internal combustion engine (ICE) in solar village, hydrogen utilisation.
- 1994-2000: Solar radiation measurement in 12 stations, Saudi solar atlas.
- 1994-2000: Wind energy measurement in 5 stations, Saudi solar atlas.
- 1988-1993: Solar dryers in Al-Hassa/Qatif, food dryers (dates, vegetables, etc.).
- 1986-1994: Two solar-thermal dishes (50kW) in the Solar Village, (Advanced solar Stirling engine).
- 1993-1997: Development of solar collectors in the Solar Village, domestic, industrial, agricultural.
- 1999-2000: solar refrigeration in Solar Village (desert application).

Recently commissioned solar projects in KSA as published by SOLARPLAZA (2014) are:

- 2010: KAUST solar park: a roof-mounted solar array project commissioned by Saudi Aramco company in Riyadh to generate 3,332 GWh of energy per year.
- 2011: a pilot ground mounted system commissioned by SECO & Showa Shell Sekiyu company in Farasan Island, Jazan, to generate 864 MWh of energy per year.
- 2012: Saudi Aramco Solar Car Park: a car park mounted array commissioned by the Saudi Aramco company in Dhahran, Ash Sharqiyah, to generate 17.5 GWh of energy per year.
- 2012: Princess Noura Bint Abul Rahman University commissioned a solar thermal plant with 900,000 litres storage.

- 2013: King Abdulaziz International Airport Development Project: a ground mounted system commissioned by GACA company in Jeddah to generate 9,3 GWh of energy per year.
- 2013: KAPSARC project: a ground mounted system commissioned by Saudi Aramco company in Riyadh to generate 5,8 GWh of energy per year.
- 2012: King Abdullah Financial District project: a rooftop mounted array commissioned by KAUST company to generate 330 MWh of energy per year.

On the other hand, the main solar project under-construction in KSA is Al Khafji seawater desalination project to be commissioned in Al Khafji (SOLARPLAZA, 2014).

Developing renewable sources energy meets growing energy demand, increases employment chances, and also minimises GHG emissions. That would assist KSA to honour its commitments under the Kyoto Protocol and other international conventions. It would also provide additional power for export, mainly solar-produced electricity (IEA, 2011).

KSA location is within the equatorial sunbelt. When compared to other locations on the globe, this location receives the largest amount of solar radiation. Measurements show that the average solar radiation arriving at KSA every day on every square meter amounts to 2,200 kilowatt-hours (kWh). This is considered an abundant quantity of solar energy that is freely available, and is open to being used effectively (Andrew, 2012). Solar energy in KSA is considered the major renewable energy source, and the most suitable alternative to fossil fuels.

The article, “Saudis Could Export Solar for the Next Twenty Centuries” by Kraemer (2012) was published in April 12, 2012. It noted that:

> *“Every square meter of KSA produces an extraordinary 7 kilowatts of energy daily in each 12 hours of sun power. If the Saudis were to use up each days solar energy supply, or 12,425 TWh of electricity, it would be a 72 year supply.”*

With the launch of the online Renewable Resource Atlas, KSA took an essential step to bring concrete plans for renewable energy closer to reality. The establishment of the atlas offered comprehensive renewable energy data to interested developers on which to base their project designs. The Renewable Resource Atlas was launched at an event with a large audience, including various utility companies, industry players, policy makers and academic entities, and the Saudi Minister of Water and Electricity. The represented companies included Siemens, Alstom, ACWA Power, International Solar Energy Society and International Renewable Energy Agency (IRENA). In practice, the atlas project can assist developers in evaluating project sites in the country in order to decide the optimal places, plan operations and maintenance. When financiers have precise data, they can make financial decisions, where these data can help technology developers to implement the correct technologies for the country (Hashem, 2013).

Since 1960, different solar energy applications in KSA have grown (Huraib et al., 1996). Research activities started at universities with small scale projects throughout 1969, in addition to major research and development work. This resulted in the growth of solar energy technologies, and in 1977, KACST was founded. For the previous two decades, key RD&D (research, development and demonstration) work had been conducted by the Energy Research Institute (ERI), and KACST continued this work. In the solar energy field, ERI established international cooperation programmes, namely HYSOLAR with the Federal Republic of Germany and SOLERAS with the USA. These joint projects focused on areas of shared interest to the partner country agencies, leading to large demonstration systems like cooling systems, agricultural applications, water desalination, and electricity generation Alawaji (2001) and Huraib et al. (1996) presented a brief illustration of these projects, in addition to the technical accomplishments of these projects.

The figure below shows the R&D activities in solar technologies at KAUST. These revolve around five solar technologies. The first solar technology is crystalline silicon PV, in which reducing the costs of this mature PV technology is being pursued. The second solar technology is Copper Indium Gallium Selenide (CIGS) thin film PV, which has essential effect on improving the efficiency and offering effective fields for applications in the future. The third solar technology is concentrated PV, which has high potential to reduce the costs of producing energy in regions of high solar irradiation. The fourth solar technology is the third generation PV, which cover a solar technologies array that is more exciting for future because of its potential to offer low generation costs. The fifth solar technology is the solar thermal heat and power, which has significant potential for application in KSA (KAUST, 2009).

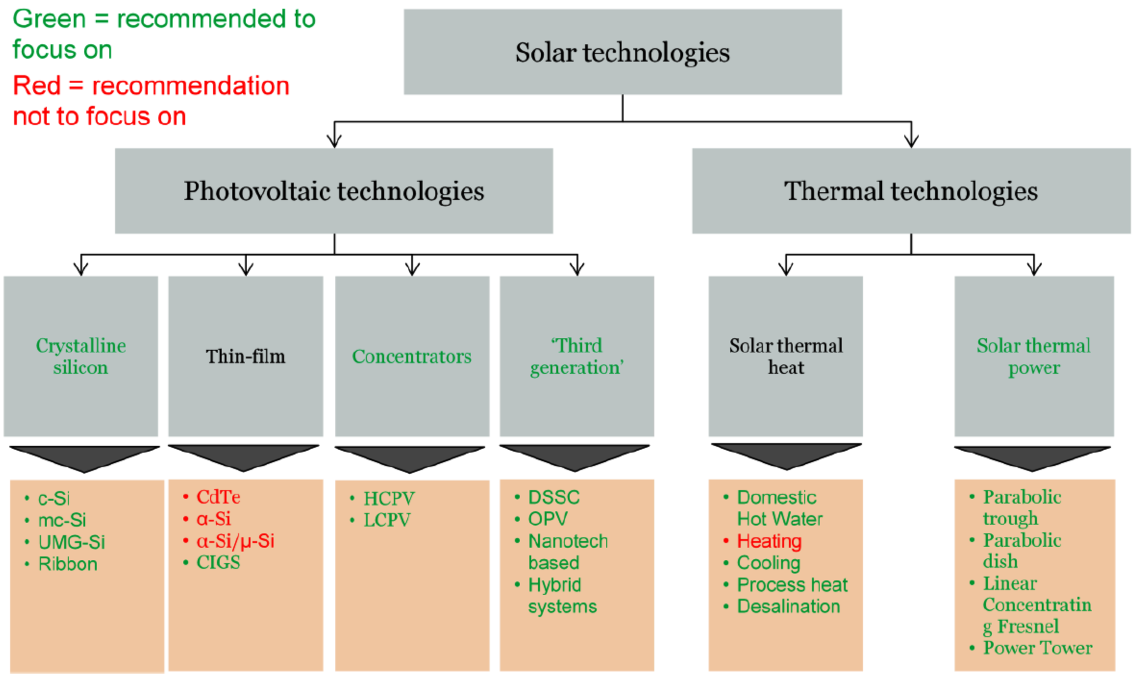


Figure 2.28: Solar technologies for R&D activities in KSA at KAUST (KAUST, 2009)

The area located between 40° North and 40° South is known as the Sunbelt. KSA is located between 31° North and 17.5° North, and hence, is located in the Sunbelt. This location allows KSA to take advantage of solar energy. When anyone wants to build a solar power plant they must identify a suitable location considering insolation. The figure below shows the annual average of solar irradiations in the country in the period from 1999 to 2011 (Koot, 2013). As studies investigated the solar radiation over Saudi, the average solar radiation differs from the 7.004 kWh/m^2 at Bisha representing a maximum value to 4.479 kWh/m^2 at Tabuk representing a minimum. High solar radiation values are observed in most southern areas, like Sulayyil, Nejran and Bisha, which are close to the case study location of Wadi Al Dawasir as shown in figure 2.29. This will be discussed in *Chapter 4* in due course.

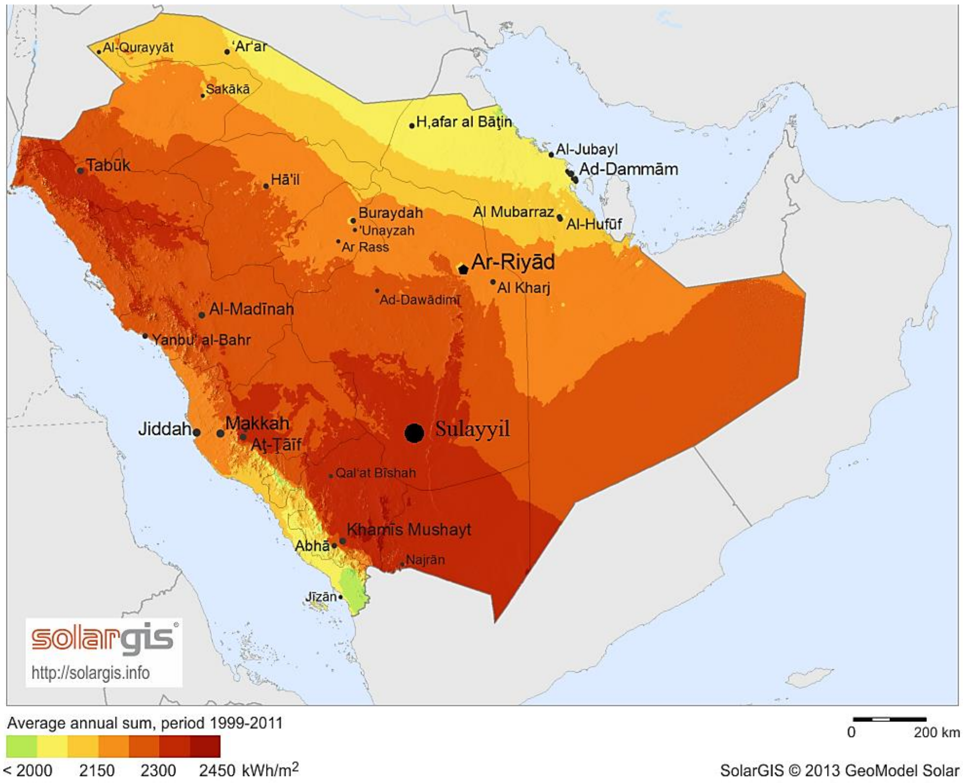


Figure 2.29: Annual average of solar irradiations in the country in the period from 1999 to 2011 (SolarGIS, 2015)

Figure 2.30 presents a map of KSA that describes the top-ten cities ranked by solar radiation intensity (Almasoud and Gandayh, 2015).

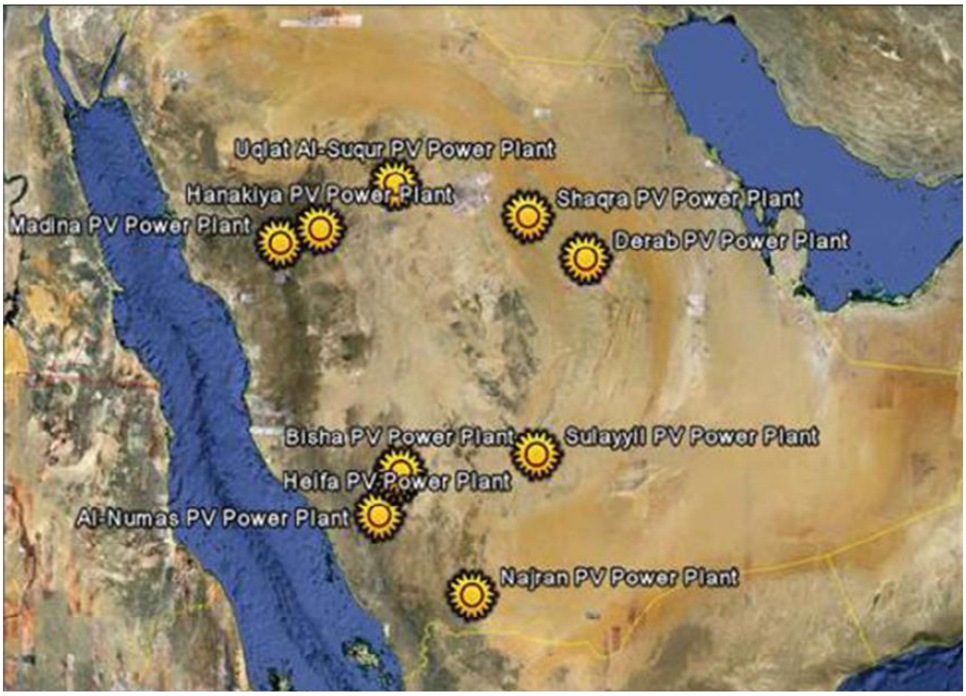


Figure 2.30: Top-ten positions of PV PPs according to solar irradiation level

In order to estimate average global solar radiation value, meteorological data must be provided, such as amount of cloud cover, relative humidity, ambient temperature, sunshine hours and solar radiation. According to (Almasoud and Gandayh, 2015), sunshine duration differs between 9.4 hours per day as maximum and 7.4 hours per day as minimum, with an average duration of daily sunshine of around 8.89 hours/day. Hence, solar energy is significant source of renewable energy. Several countries and organisations have made efforts in investment and research terms in solar energy field in KSA. One of these efforts is the previously-mentioned Renewable Energy Atlas project, providing renewable energy-related data and weather data from ground measurement devices.

2.3.2.3. Waste to Energy

Recently, a significant amount of generated solid waste in KSA is gathered in landfill sites to be reused to generate energy. Thus, KACARE (2014) considers various waste-to-energy plants to decrease landfill and associated challenges of air and ground pollution, where the techniques used are clean and mature. These techniques may be selected based primarily on the financial feasibility of the process of converting waste into energy, where opportunities are present for various developments in KSA to enhance the techniques used. KACARE plans to generate 3GW of electricity using waste by 2032.

2.3.2.4. Geothermal Energy

In practice, the generation of geothermal energy depends on the normal underground heat. This source of energy is safe and clean, and does not suffer any fluctuation in use. The main benefit of this type of energy source is that it can be used throughout the year at any time. It is considered a main energy production source in various countries. However, this type of energy is limited in KSA, but can be used in combination with other energy sources. Three main methods can be used to extract geothermal energy, namely flash steam, dry steam and binary cycle. KACARE has proposed to drive pipes into the ground to produce steam in order to drive turbines, which produce electricity. In addition, reports demonstrate that KACARE aims to work with stakeholders in KSA to develop geothermal technologies. This will result in other opportunities that can enhance the economic wellbeing of the sector. KACARE plans to extract 1GW of geothermal energy in 2032 (KACARE, 2014).

2.4. Solar Energy Potential and Technologies

2.4.1. Overview

Solar energy is a clean and safe form of energy that can be converted to electricity through PV and CSP systems. The most commonly used material for making these panels is silicon, which is incidentally the most abundant element found on the earth's crust (comprising 27.7%), second to oxygen (Britannica, 2014). Silicon is also environmentally safe, promoting sustainability of solar technology. The major disadvantage of silicon solar panels is associated with operational safety under several conditions, mostly owing to unwanted leakage of cadmium telluride (CdTe) or gallium arsenide (GaAs) from the silicon cells. These can be poisonous and harm the environment (Chu, 2011). Solar energy potential has been rising with more innovative technologies. Chu (2011) presents an overview of solar technologies, including photovoltaic solar panels (most commonly used), concentrated photovoltaic systems (maximum efficiency recorded), dye sensitised solar cell (based on cheap organic materials), solar thermoelectricity system (based on thermoelectric effect) and CSP (based on matured heat engine). Figure. 2.31 illustrates different types of existing solar technologies and their basic operating principles.

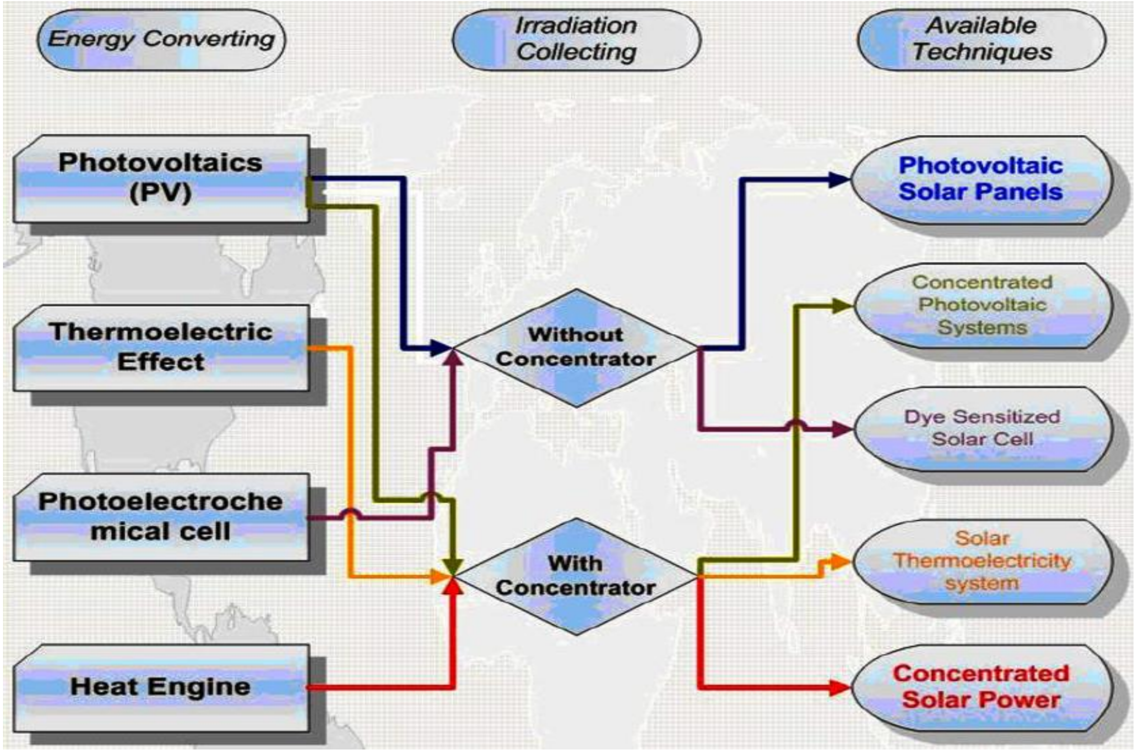


Figure 2.31: Overview of solar technologies (Chu, 2011)

The most mature technologies among the solar technologies are CSP, and non-concentrated photovoltaic solar panels (PV), which are currently fully commercialised. The ones at experimental stage are upcoming solar technologies like solar thermoelectricity systems (STA), concentrated photovoltaic systems and dye sensitised solar cells (DSPV). They are treated as efficiently competitive technologies in the market. STAs are devices using parabolic discs for capturing thermal energy based on the thermoelectric effect, producing electricity with the help of a concentrating thermoelectric generator (CTEG). The thermoelectric effect is in turn governed by the Seebeck effect – which defines voltage generation from temperature difference – or its converse principle known as the Peltier effect (Chen, 2009). Every thermoelectric material is assessed in terms of the thermoelectric voltage induced in response to the temperature difference across it, and measured in terms of the parameter called the figure of merit (Z), which depends on the Seebeck coefficient.

Other applications include dye sensitised solar cells, which involve a semiconductor shaped by a photo-sensitised anode with an electrolyte and a photochemical system. It is also known as the Grätzel cell, based on its inventor (Kong et al., 2007). A third technology is the concentrated photovoltaic cell (CPV), whose operation is based on optical phenomenon of the lenses used to focus a large amount of sunlight over a small area of the constituent photovoltaic materials for generating electricity. Based on the extent of concentration, CPV systems are classified into three categories as follows: high concentration multi-junction cells (featuring high concentration ratios like 400X minimum), medium-concentration cells (concentration ratio between 3X to 100X) and enhanced concentration modules made of silicon modules (concentration ratio below 3X).

PV systems are key energy carriers for solar energy production, and hence need more research and development. Wasfi (2011) provided a review of the conversion of solar energy into electricity mostly concerning the performance of PV systems and solar cells. Solar thermal heating process was addressed in his study while explaining it to be an outcome of the complete solar spectrum. Based on this principle, mirrors are known to reflect most of the solar spectrum but retain the infrared to result in the covering glass which needs to be heated. Two methods are generally employed for conversion of solar energy into electricity:

- Thermal – using mirrors or suitable reflectors to concentrate solar irradiation to produce high temperatures which enable the water vapour or other liquid to act under high pressure in order to rotate turbines that generate electricity.
- PV effect – direct conversion of solar energy to electricity.

2.4.2. Photovoltaic Systems

A PV system is composed of PV panels, batteries, inverters, charging control units, load control units, circuit breakers and wiring. A solar cell is the basic example of solar technology, which functions based on the PV effect. Table 2.7 presents the specification of a typical solar cell for illustrative purposes.

Table 2.8: Solar cell specification (Wasfi, 2011)

Efficiency	**15 to 17.2%**
Maximum power (P_{max})	3.65 to 4.186 W
Open Circuit Voltage (V_{OC})	0.608 to 0.632 V
Short Circuit Current (I_{SC})	7.95 to 8.49 A
Maximum power voltage (V_{mp})	0.495 to 0.521 V
Maximum power current (I_{mp})	7.34 to 8.04 A
Dimension (mm x mm)	156×156 ± 0.5
Thickness (mm)	0.24 ± 0.04 to 0.16 ± 0.03
Connections Front	2 silver busbars (2mm wide) with 75 mm long
Connection Back	4.5 mm wide bus bar with silver/aluminium soldering pads and aluminium back surface field
Typical temperature coefficients	Voltage: ─ 2.11 mV/K Current: + 2.79 A/K Power: ─ 0.45 %/K

Batteries used in a PV system could be of different types: Lead acid (valve regulated and liquid sealed or vented) and Alkaline (Nickel-Cadmium or Nickel-Iron) batteries. Inverters can be of single phase (230 V) or three phase (380 V) configurations with a range of voltage options based on the required power output. Typical efficiency of inverters in a PV system ranges from 80 to over 94%, and are available in different load configurations to govern efficiency, including harmonic regulation, load controller, parallel operation and series operation (Wasfi, 2011).

Energy produced from PV systems is reliable, simple, available, long lasting, and clean. The production of this energy has grown recently because of the environmental awareness and negative impacts of climate change on human life. The utilisation of PV systems to generate electricity in developing countries has increased. However, the performance of PV systems is influenced by environmental conditions. In hot countries, such as KSA, the high temperature of PV systems is considered an essential factor leading to performance loss, where various investigations concluded that the PV panels' performance is affected by the increase in temperature (Rehman and El-Amin, 2012).

Park et al. (2010) investigated the thermal and electrical performance of semi-transparent PV panels, where they explored that the resultant power from these panels decreased up to 0.48% with applying a standard test conditions and 0.52% with actual ones with the increase in the surface temperature of the panel.

One of the major PV systems in KSA was installed in KFUPM in 2010 with 5.28 kW of capacity. It includes three arrays, each composed of 8 PV panels, and rated at 220 Wp. The figures below illustrate the technical specifications and dimensions of these panels, as well as the panel and arrays arrangements. This system is dependable and needs little maintenance and care of expert manpower. Analysis of the results demonstrated that the performance of these PV panels dropped with increasing panel surface temperature, while DC performance ratio reduced with increasing temperature. The highest achieved energy was at 35.8^{o} (Rehman and El-Amin, 2012).

1.	Rated capacity of each PV panel = 220 Wp
2.	Rated capacity of each PV array = (220*8 = 1.76 kWp)
3.	Total installed capacity = (1.76*3 = 5.28 kWp)
4.	Three 230 V single phase connections each assigned to one of the three phases and one three phase connection
5.	Open circuit voltage = 30.8 V
6.	Short circuit current = 8.23 A
7.	Maximum power voltage = 24.7 V
8.	Maximum power current = 7.71 A
9.	PV module type PolySol 220 TA 220 Wp
10.	Dimensions of each PV array = 1.6 m by 8.2 m
11.	Weight of each PV array = 17 kg
12.	Total weight = 51 kg
13.	Area required for the installation of three PV arrays = 13 m by 12 m
14.	Weight of each foundation = 4724 kg (1.6 m × 8.2 m × 0.15 m, concrete density = 2400 kg/m^3)
15.	Weight of batteries = 3000 kg

Figure 2.32: Technical specifications and dimensions of the panels (Rehman and El-Amin, 2012)

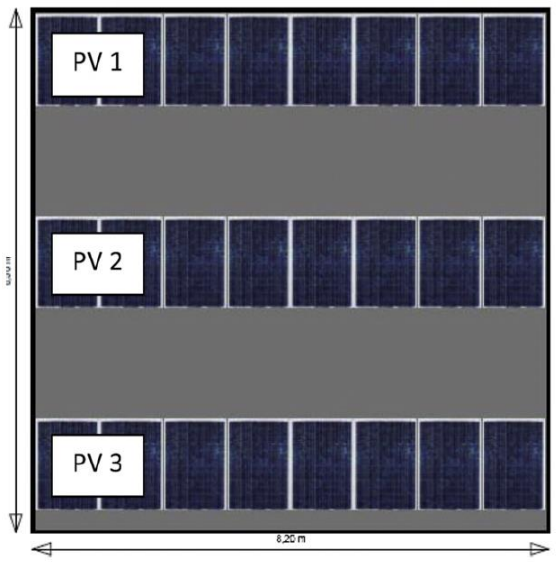


Figure 2.33: Arrangements of the panels and arrays (Rehman and El-Amin, 2012)

2.4.3. Concentrated Solar Power (CSP) Systems

In general, CSP systems capture solar energy using lenses or mirrors to concentrate solar energy taken from a large area onto a small area. This concentrated sunlight generates electricity when it is converted into heat, where this in turn can drive engines that are connected to power generators (Miller, 2010). The amount of generating capacity offered by the CSP market was 740 MW in the period 2007 to 2010. The majority was achieved in 2010, where around 400 MW of generating capacity were introduced in Spain, and another 509 MW in the USA. In the Middle East, various CSP systems have been established or are under construction, such as Shams-I SCP project in Abu Dhabi (RI, 2013).

CSP plants might include 100% accessibility in the energy production share, where these can provide both thermal energy and/or electricity. In this context, large scale plant may provide energy for an entire city, providing base load and also load-following. The CSP plants established in the Californian Mojave Desert over twenty five years ago, are still working. Lately, new plants are working, while numerous others are being developed in the USA, Middle East, Spain and Northern Africa; huge work is in progress (Roeb et al., 2011).

The CSP technique uses three types of technologies, namely trough, power tower, and dish/engine systems.

2.4.4. Parabolic Troughs & Direct Fresnel Technology

2.4.4.1. Parabolic Trough Collector Systems

Trough systems are widely used, and utilise large parabolic or U-shape mirror segments that reflect and concentrate incident radiation onto receiver pipes filled with circulating heat exchange fluid medium, such as oil. Parabolic troughs are often between 20 to 150 metres long and their width is about more than 5 metres. A system schematic is shown in Figure 2.34. These reflectors are placed and adjusted based on the sun’s location to focus sunlight on pipes. As the troughs follow the sun during the day, this implies that the entire collector, including the reflector assembly and receiver tube that is pivoted around the longitudinal axis. Since the gatherer must be turned about one hub, it is known as a solitary hub following framework. The absorbed heat is transferred to the heat exchange liquid, which circulates through the tubes.

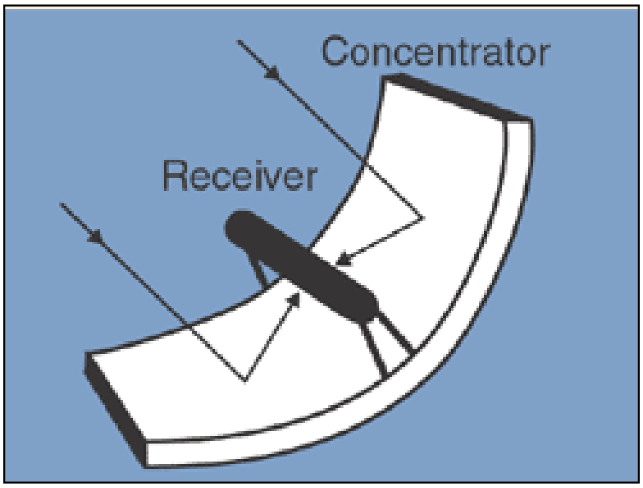


Figure 2.34: Trough system

Mirrored reflectors are tilted in the Sun's direction to heat oil inside the pipes to over 390°C. The thermal energy in the heat transfer fluid is utilised to boil water within a heat exchanger and superheat steam to run a steam turbine driving electrical generators (Roeb et al., 2011, EIS, 2015). This is outlined in Figure.2.35.

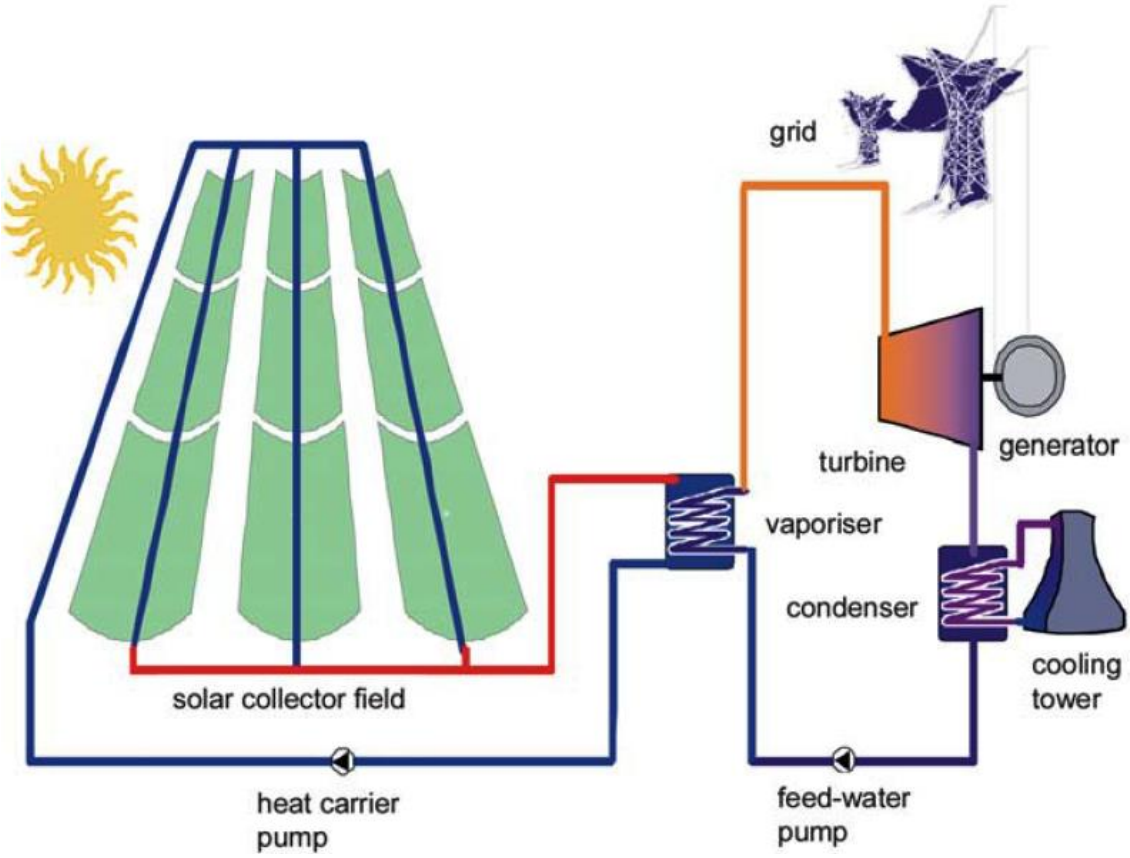


Figure 2.35: Schematic of power plant based on parabolic trough using two operating media (Roeb et al., 2011)

Thus, concentration technology is used in power plants to generate electricity from solar radiation. This technology depends on both the receiver area and mirror surfaces. When mirrors are fixed, the maximum is reached at a specific time only. Thus, various mechanisms are used to track sunlight. The reflecting surface position is optimised based on tailoring the orientation according to the sun's path. The sun's position is mainly characterised using two values, solar declination and azimuth angle (Gharbi et al., 2011).

A CSP plant is consist of a field of parabolic solar collectors, a steam turbine/electric generator set, high temperature thermal storage, and a condenser/cooling tower. Figure 2.36 illustrates a schematic of the CSP plant using trough technology with thermal storage.

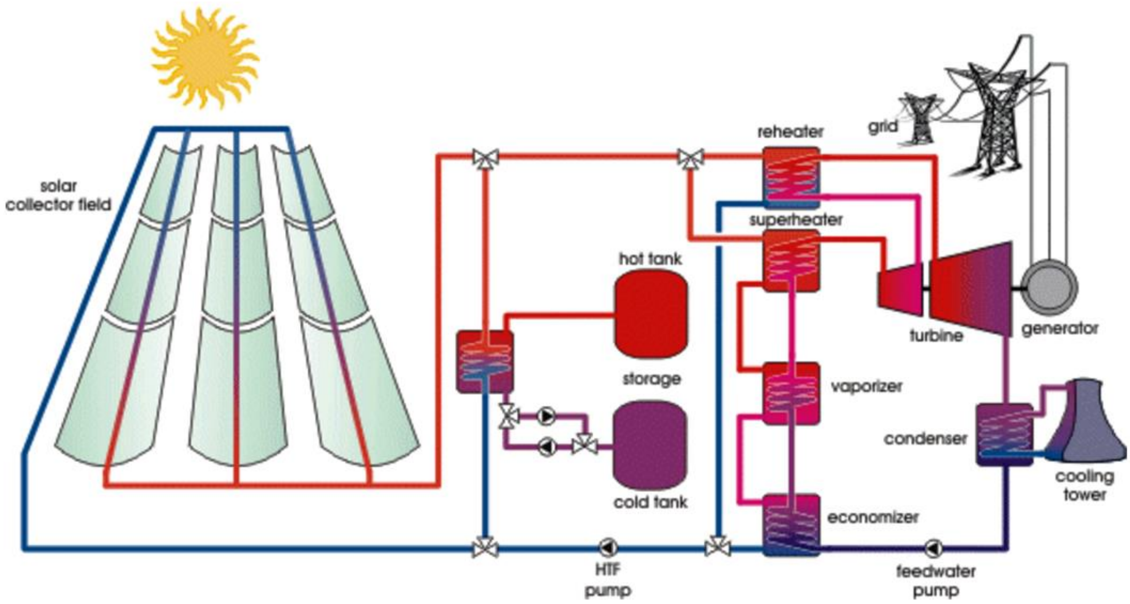


Figure 2.36: Schematic of a concentrated solar thermal trough system with thermal storage (Quaschning, 2004)

Solar field is the term used to describe the reflectors and collectors within a CSP plant, whether composed of parabolic trough collectors (PTC) or otherwise. With a single-axis tracking mechanism, solar radiation is reflected onto the absorber or heat collection element (HCE) placed at the line of focus of the parabolic trough (see Figure 2.37). Reflectors and absorber tubes move together and follow the daily sun path from sunrise to sunset (García-Barberena et al., 2012). CCP azimuth angle control has minimum impact on the total collected energy.

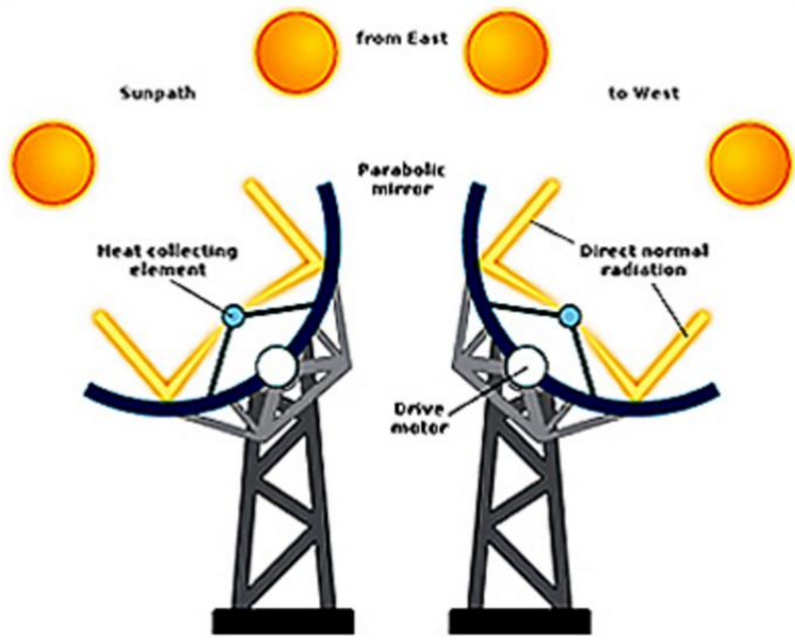


Figure 2.37: Solar collector assembly diagram with direct radiation path (Microtherm, 2016)

At the HCE, the energy collected is then transferred to a circulating fluid, typically a synthetic oil, termed the primary Heat Transfer Fluid (HTF), which drives a Rankine power cycle . The HTF is characterised by low vapour pressure and freezing point. The circulating HTF is pumped to through a series of heat exchangers, typically shell-and-tube designs, forming what is termed a solar steam generator (SSG), where incoming feed water is boiled off and the resulting steam superheated. Variations of the system employ molten salts rather than synthetic oil as HTF, or indeed apply a system to directly generate steam (Direct steam generator or DSG) (García-Barberena et al., 2012). The superheated vapour is directed to a turbine, which converts heat into work, turning the shaft of an electric generator. Exiting the turbine, saturated vapour is condensed in cooling towers, and is returned once more to the SSG. In order to smooth out resource fluctuations, and provide for non-daylight operation, thermal storage is included within the system, where excess solar energy is stored. Storage may take the form of molten salts or high boiling point oil with concrete blocks immersed within. This allows the system to continue functioning outside daylight hours or in overcast conditions (Janjai et al., 2011).

2.4.4.2. Fresnel System

A unique kind of collector based on a parabolic trough is the direct Fresnel collector. This comprises a few extended level fragmented mirror components that are located within a single plane. A Fresnel system mirror has one axis tracking, where each row has its own tracking system in a way that all mirrors reflect the incident solar radiation on a fixed safeguard tube set above the mirror, called the receiver. The position of the safeguard tube in this framework is in such a way that the mirror can only follow the sun in day time only. Figure.2.38 presents a photo of a direct Fresnel collector (Roeb et al., 2011).

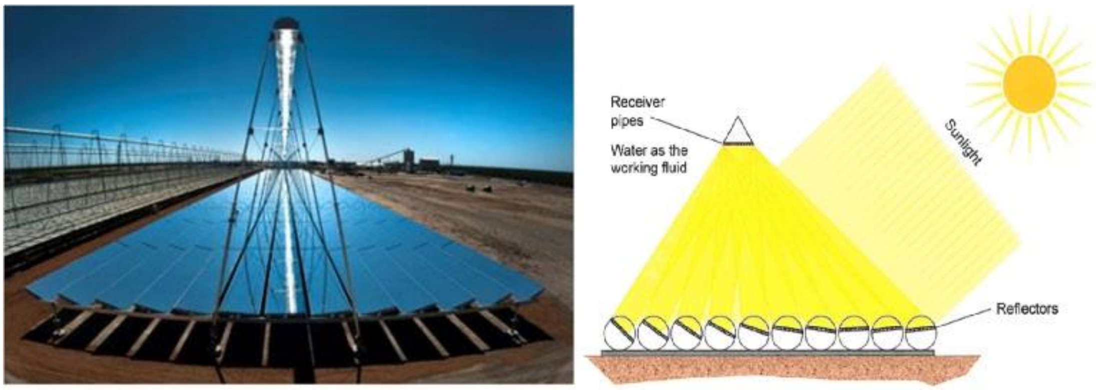


Figure 2.38: Scheme of Fresnel Collector (AREVA, 2016)

On account of the straight centre the attainable focus component is greater, and the more extreme temperatures along direct Fresnel troughs are restricted. Nowadays, focus components number around a hundred and a temperature of about 550 °C can be observed. Whereas the parabolic trough is in service, the direct Fresnel innovation is still at advanced development phase.

The direct Fresnel collector reflects direct solar radiation from various mirrors onto a stationary receiver. This receiver is composed of a sealed vacuum tube that has special absorptive coating that collects the solar radiation, which is converted to heat for later use. The main benefits of this type of collector are low weight, wind load and operating costs, simple evaporation and integration, high surface effectiveness, long lifespan and roof or floor installations (IS, 2015). The main benefits of this collector are its high effectiveness and low cost, where it can be utilised for collecting thermal energy or generating electricity (Xiao, 2007).

2.4.4.3. Main Elements of The Solar Field

Solar radiation collection by a solar field is different from one in PV cells. The main or primary functional components in a solar field are:

- Solar collector assembly (SCA)
- Heat Collection Element
- Mirrors

Detailed illustrations of each solar field element are presented in the following sections.

- **Solar Collectors Assembly (SCA)**

Sun tracking by an individual SCA is achieved in various ways, one of which employs a logic controller driving motors that orient the assembly. A GPS system provides input to an algorithm that generates the motor control outputs that appropriately orient the SCA towards the sun. Furthermore, maximum power tracking is assured using the differential voltage output from a shaded and exposed PV cells placed close to the HCE facing the reflector (Turchi, 2010).

- **Heat Collection Element (HCE)**

The HCE is an essential component that on the one hand, absorbs the solar radiation, and with a selective coating prevents the re-radiation of infrared waves (heat). On the other hand, HTF circulating through the HCE transports the collected heat away from the HCE surface. One design of HCE uses an evacuated glass encapsulating tube to isolate the absorber, a coated stainless steel tube, from the environment and limiting heat losses to a minimum, as illustrated in Figure 2.39 (Turchi, 2010).

According to Himinsun (2015), the heat collection receiver or the parabolic trough receiver (HCE) is a main element of the parabolic trough CSP system. This element is very important due to economic costs and efficiency. Trough power production systems are largely based on the optical and thermal reliability and performance of the collector element. This element has a long life span, high stability and high efficiency. It is designed to encourage the solar field to be more cost-competitive and more productive. The heat collection element is comprised of a metal tube that is 4,060 mm in length and

70 mm in diameter for common applications. It is coated by anti-reflective, selective absorbing and a heat-resistant material, with an AR-coated glass tube of 120 mm diameter. Its additional components involve an external glass tube where this component features an internal metal tube with self-cleaning technology.

Figure 2.39: Heat collecting element of a parabolic trough collector

The surface of the steel tube absorber is covered by a special coating, which maximises absorption of all the solar radiation spectrum, minimises reflection, and the re-radiation of long wave infra-red (heat) radiation. In order to maximise the solar radiation passed through the encapsulating vacuum glass, both outer and inner surfaces are treated with special anti-reflective coatings. Moreover, the vacuum within the HCE annular space is maintained using "Getters", which are metallic substances that absorb hydrogen and other gases that may 'leak' through the glass intramolecular spaces and deplete the vacuum.

- **Mirrors**

The parabola-shaped glass mirrors used in the solar field to reflect sunlight onto the HCE are typically monolithic or laminate glass with low-iron content. Despite the challenging service conditions, these have proven to be quite reliable, and have not exhibited any degradation over the long-term in reflective properties. Reflective performance is maintained through a regime of monitoring to ensure timely washing, whether light or deep, where a regular programme has been shown to be effective under difficult operating conditions (Turchi, 2010). Figure 2.40 shows parabolic reflector mirrors in service.

The PTC is characterised by the parabolic mirrors, whose shape reflects the parallel beam of sunlight onto a line at which the HCE is sited. They are made from glass panels and are considered second-surface silvered glass mirrors. This refers to a layer of reflective silver located on the rear of the glass. Mirrors are usually 4 mm thick.

Figure 2.40: Parabolic mirror facets

2.4.5. Power Tower Technology

Power tower systems, as depicted below, depend on large, flat mirrors for tracking and focusing the sun’s rays on a receiver. This is located on the tower top, where the concentrated sunlight heats a fluid to be utilised in generating steam as shown in figure 2.41. This is then used to generate electricity or to be saved and used later through thermal energy storage (TES) (EIS, 2015).

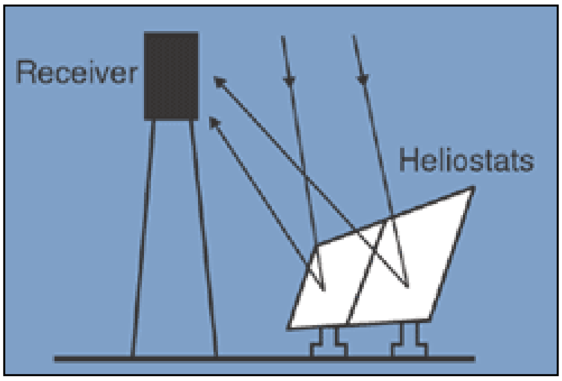


Figure 2.41: Power tower system

In a central collector, also called central receiver framework, sunlight is gathered over a large area using plane reflectors, called sun-tracking mirrors or heliostats oriented around a tower. These reflect solar radiation onto a receiver (boiler). The majority of the reflected energy is absorbed by the working fluid, where the heated fluid flows down to a thermal electrical power plant. This type of collector differs from other types in the collection of solar energy, where in this case, the majority of the energy gathered in the whole field is reflected optically onto a small central collection region, while in other collectors, it is piped around the working fluid (BFTS, 2013, Hang et al., 2008).

The main benefits of heliostats are that they are two-axis tracking mirrors that collect energy from the sunlight using mechanisms following azimuth and elevation angles. They present a great opportunity for on-site or local manufacturing, and have low associated costs, and can be applied widely in CSP projects (SolarReserve, 2015, Hang et al., 2008).

A heliostat field can comprise a few to a large number of heliostats, each separately tracking the sun on two axes. The heliostats reflect the sunlight onto a receiver that is commonly fixed above the heliostat field on the top of a tower. The receiver absorbs the sunlight as heat. Figure 2.42 presents a photo of a central collector framework (Hang et al., 2008).

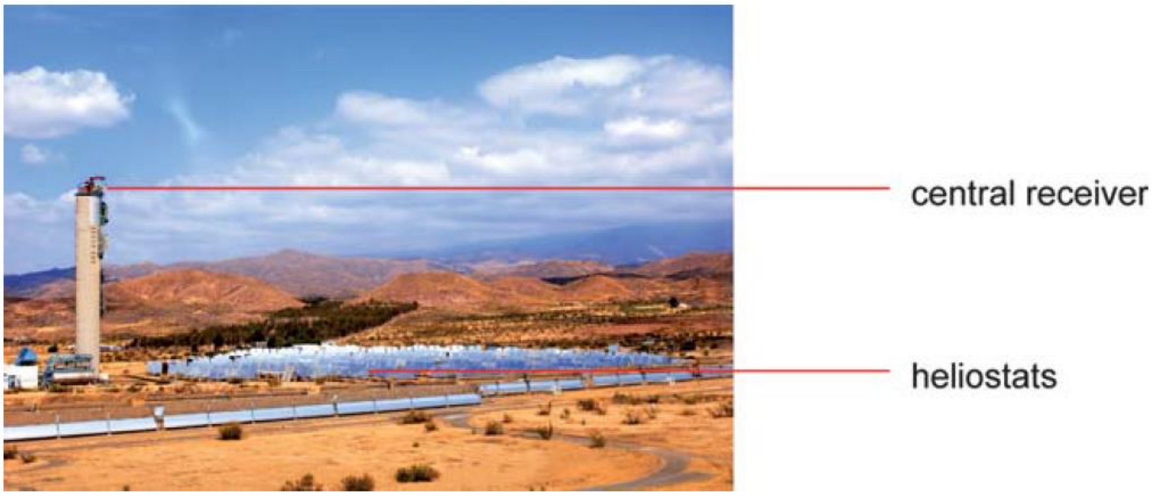


Figure 2.42: Scheme of central collector framework on top of a tower

A number of receiver designs for absorber incident sunlight exist. The receiver on the top of a tower might be a tubular receiving object comprising extended abutting tubular structures, which absorb the sunlight, and exchange the heat with a liquid flowing over and around the tubing. The hypothetical volume based collectors are alternatives that are comprised of permeable fired assemblies that are heated by the concentrated solar energy; for example, honeycomb-like structures, ceramic structures, or foams, as shown in Figure 2.43 . By means of a heat exchanger, the heat is passed to a conventional steam power cycle.

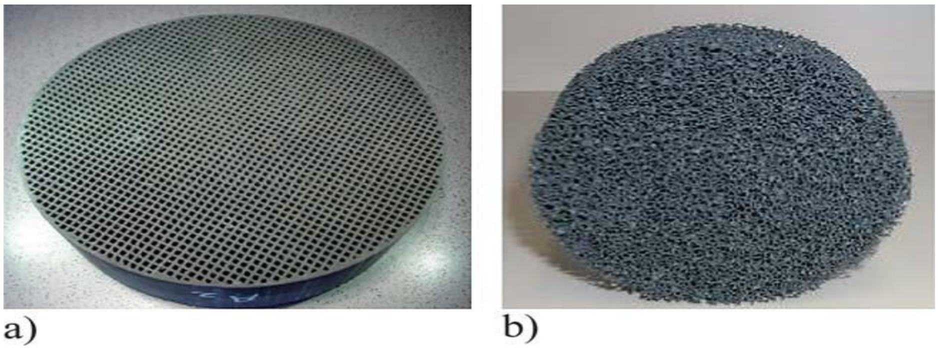


Figure 2.43: (a) honeycomb-like absorber structure and (b) foam absorber utilised as receiver assemblies on power tower (Roeb et al., 2011)

Temperatures of over 1000 °C can be achieved using the power tower with heliostat field, and values of about 1500 °C have been recorded. A sun oriented tower framework is adjustable and thermal power inputs of several hundred megawatts are reasonable (Roeb et al., 2011).

In current CSP power plants, thermal storage, as shown in figure 4.44, plays a significant role in the economic viability and operating conditions. Thermal storage minimises the effect of variation in solar radiation on electrical output, increases supply security, reduces thermal stress and extends the lifetime of the steam turbine. Large thermal storage usually uses phase change materials or sensible heat storage with temperatures between 300°C and 400°C. The turbine is an energy conversion device that takes the energy of a moving working fluid and changes it into work. The power block is the heart of CSP plants, where thermal energy delivered from storage, or from the solar field, is transformed into electrical energy.

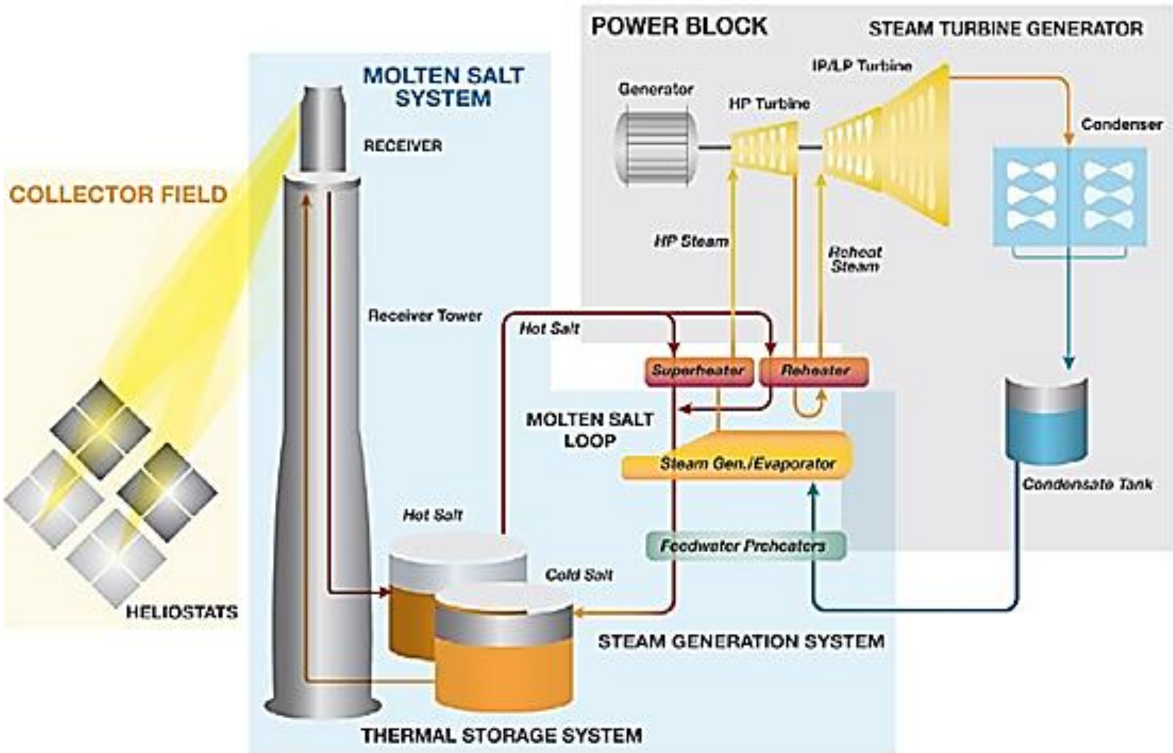


Figure 2.44: Schematic of CSP plant using solar power technology with thermal storage (SolarReserve, 2015)

Power tower systems as illustrated in Figure 2.44 are highly suitable in large scale power generation of 30 to 400 MWe. A system incorporating thermal storage in the form of molten salt would have two storage tanks, cold and hot. It typically operates on ‘cold’ molten salt at 290°C (554°F), which is then heated at the receiver to 565°C (1,049°F). As needed, the heat stored in the ‘hot’ salt is transferred at a steam generation system to produce superheated steam driving a Rankine-cycle steam turbine/electrical generator system. The ‘cooled’ molten salt is transferred to the ‘cold’ storage, and from there to the receiver as appropriate (Sargent et al., 2003, Szczygielski and Wagner, 2009) . Solar power towers are characterised by:

- Optical methods of solar energy reflection onto a single receiver with thermal transport minimised.
- 300× to 1500× concentration ratios, and 500 °C to 1500 °C working temperatures, resulting in high energy collection and power conversion efficiencies.
- Use of thermal storage facilities.
- Economies of scale in energy storage and power conversion systems (Purohit and Purohit, 2010).

2.4.5.1. Main Elements of The Concentrated Solar Power (CSP) Tower Technology

CSP tower technology is a promising development in renewable power generation. At this stage, the technology is in demonstration phase, and entering early commercialisation. The approach is characterised by higher working temperatures compared to parabolic trough technology, and as such is predicted to secure greater efficiencies and more competitive cost. A key feature of power towers are sun-tracking mirror reflectors or heliostats pivoted on azimuth and elevation axes, and reflecting incident sunlight onto the central receiver tower. The size of plant dictates the number of heliostats deployed, which may number from a few thousand to over a hundred thousand individually computer-controlled units. Due to their quantity, heliostats may represent half the project capital cost. Therefore, a key aspect involves optimisation of design of heliostat, especially the factors of assembly size, unit weight, quantity, and performance with respect to cost using various means. Through appropriate heliostat unit levelling solutions, the preparation costs of uneven sites with 5% or greater slope may be reduced. An example heliostat is shown in Figure 2.45. The key components in a CSP tower are presented next.

- **Heliostat**

The primary energy input driving a CSP plant is the incident solar radiation reflected by the heliostat arrays onto the central receiver on top of the tower. The term, heliostat, is derived from combining the words “helio” and “stat”, where the former means sun, while the latter denotes a static image of the sun throughout the day. A two-axis tracking mechanism controls the heliostat’s orientation towards the sun and the reflection of the image onto the receiver.

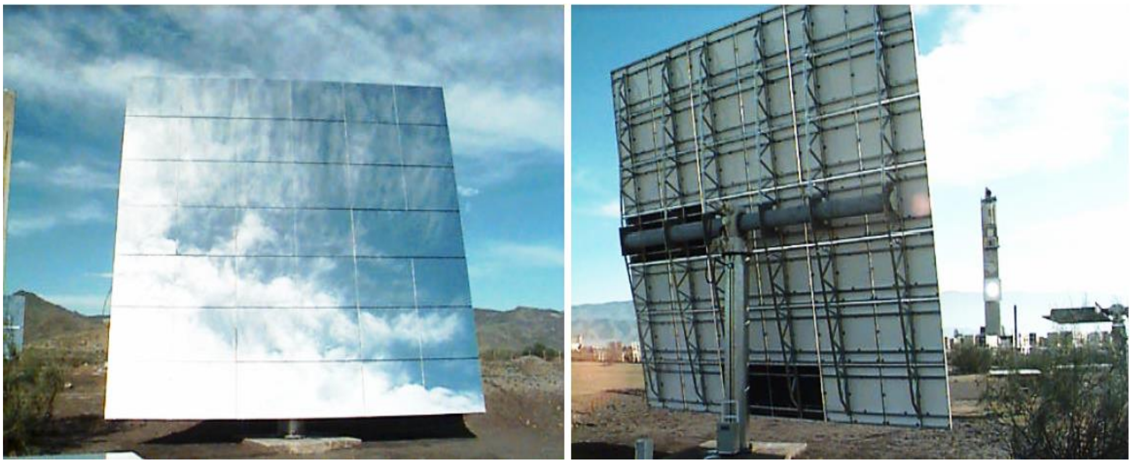


Figure 2.45: Solar power tower heliostats (Mancini, 2000)

Heliostats are nearly flat mirrors that collect and concentrate the solar energy on a tower-mounted receiver located 100 to 1000 metres distant; Figure 2.45 illustrates a typical heliostat with its basic components as shown above. The components include the mirror assemblies (typically glass and metal), the support structure, the pedestal and foundation, the tracking control system, and the drives (Mancini, 2000).

- **Receiver**

This component of the CSP tower system receives and absorbs the solar radiation deflected by the heliostat arrays. The radiation is absorbed as heat, which then needs to be converted into work later in the system cycle (Syafaruddin and Hiyama, 2010). Receivers vary in shape and technical functions, as shown in Figure 2.46.

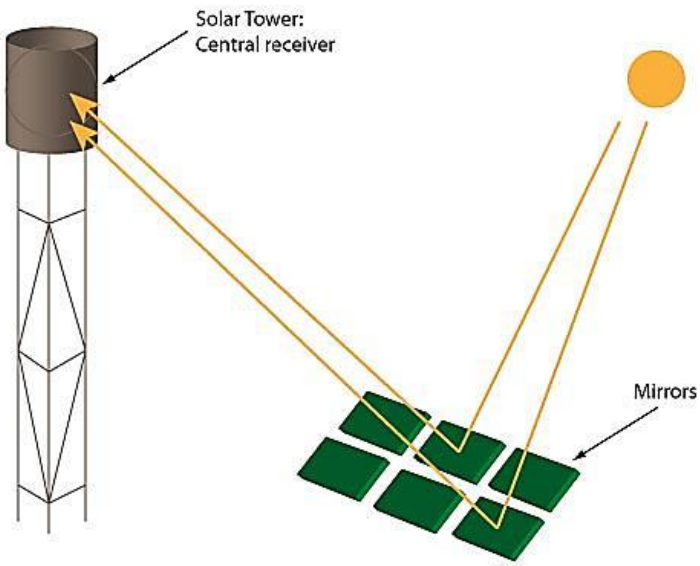


Figure 2.46: Solar tower receivers (Rhino, 2013)

The four types of receivers are:

i. Water/steam receiver
ii. Salt receiver
iii. Open volumetric air receiver
iv. Closed (pressurised) air receivers

The CSP solar tower receivers have the potential to raise system efficiency by up to 10 percent due to the following effective benefits:

i. **Natural steam circulation (steam)**
For best performance, the steam may be raised directly within a receiver boiler, and then circulated naturally by taking advantage of natural convection, minimising pumping.

ii. **Storing heat (molten salt)**
The molten salts allow energy production day and night, 365 days a year, by using heat from a storage tank filled with molten salt.

iii. **System optimisation**
Applying acknowledged boiler concepts to solar receivers ensures a cost-optimal design with increased performance and reliability.

2.4.6. Dish Power Technology

2.4.6.1. CSP Dish/Engine Systems

Dish/engine systems, shown in figure 2.47, uses a mirrored parabolic dishes to concentrate sunlight onto a receiver, sited at the dish focal point, where temperatures of over 2000 °C are achievable. The receiver has an external combustion engine incorporated that has thin tubes filled with helium or hydrogen gas that run outside the cylinders of the engine. The receiver then heats the gas, where it is expanded in the cylinders to drive reciprocating pistons to run a crankshaft that in turn runs an electric generator. The dish uses two-axis tracking moving the entire assembly, dish, receiver, and heat engine, to follow the sun throughout the day, and thus, capture the largest amount of solar energy (EIS, 2015).

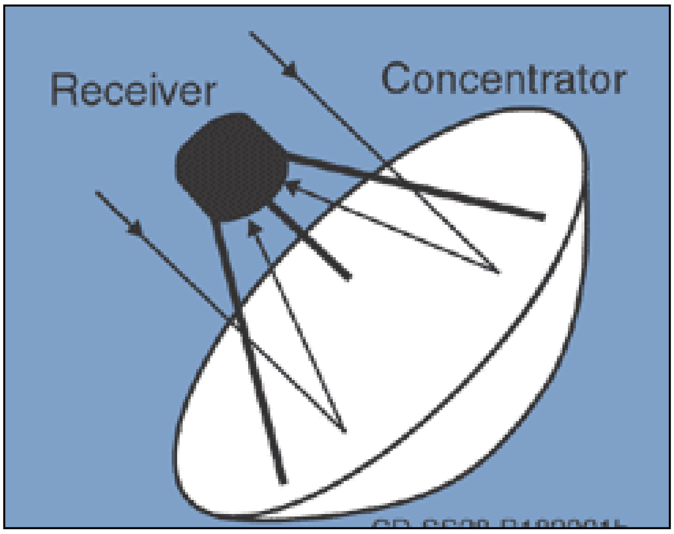


Figure 2.47: Dish/Engine System (EIS, 2015)

Currently, dish/engine technology relies on three main engine types, namely kinematic Stirling, free-piston Stirling, and Brayton turbine based engines. In addition, air receivers have been proposed, where hot air is fed to a steam generator. Stirling engines, whether kinematic or free-piston, work according to the Stirling thermodynamic cycle, and convert heat energy into work; in this context, solar thermal energy is converted into shaft power driving an alternator to produce electricity. These engines may employ hydrogen, helium, or others as working fluids. On the other hand, a Brayton system utilises hot compressed air to drive a turbine connected to an alternator producing electricity. In comparing current dish/engine systems, Stirling cycle systems may be designed with a capacity of 3– 30 kilowatts (kW), while capacity of Brayton systems may reach 200 kW. However, limiting factors are dish and heat engine sizes. January 2010 saw the first commercial demonstration of a CSP dish/engine system, which was based on a Stirling engine. Figure 2.48 displays a sun-oriented CSP dish/engine framework. Systems of 400 kW capacity and more are presently possible, but typically, due to certain constraints, are below 100 kW. For expanded power generation capacity, CSP dish/engine systems can be connected. However, the downside is their restricted dimensions. An additional disadvantage is the need for movement of the entire framework during daytime, and so all joining tubing must be adaptable. Given such constraints, sun based dish frameworks are usable at smaller scale, and dispersed power frameworks (K. Lovegrove, 2009). One issue that must be considered in selecting an appropriate sun based dish framework relates to induced shock loads on driving gears, resulting from wind gusts and storms (Prinsloo and Dobson, 2014).

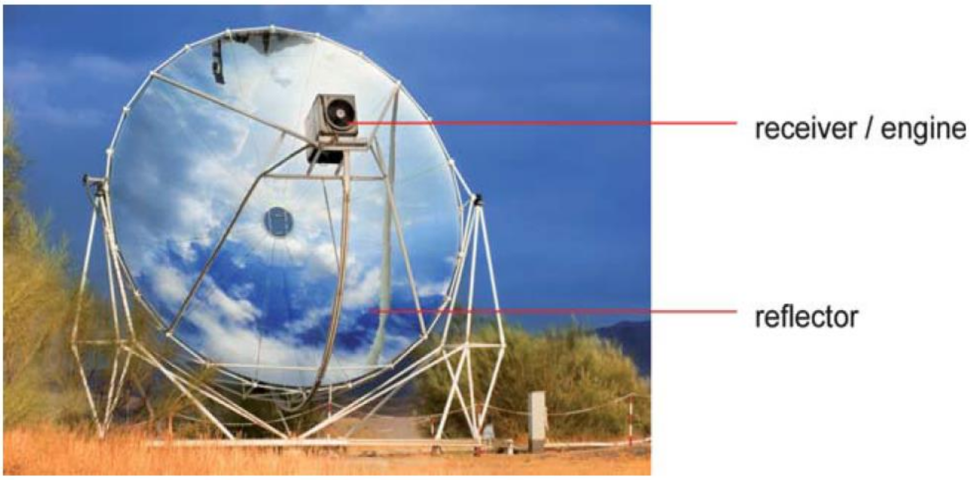


Figure 2.48: Photograph of a CSP dish/engine framework (Roeb et al., 2011)

Having described the main key CSP technologies, the primary objectives of using CSP systems, compared to non-concentrating systems are:

i. The working fluid attains higher temperatures, implying greater thermodynamic efficiency based on Carnot cycle (Sniderman, 2012).
ii. The heat efficiency is greater due to the lower heat loss with respect to receiver area (Siemens, 2010).
iii. Shiny surfaces involve fewer design elements, and are basically more straightforward than flat panel collectors. For a concentrating gatherer, the expense of each component of the sun gathering surface is consequently not as much as that of a flat panel collector.
iv. Owing to the moderately small receiver area, specific surface treatment, and isolation through vacuum are utilised to lessen heat losses and enhance efficiency are financially viable measures.

The drawbacks of CSP include:

i. Concentrator frameworks gather minimal diffuse radiation, operating principally using beam incident radiation.
ii. Some tracking mechanism is needed to empower the collector to follow the sun.

Mirror reflecting surfaces can lose this property with time, requiring intermittent washing and repair.

2.5. Economics of Solar Energy

A 2015 report published by Berkeley Lab demonstrated that solar energy cost in the US has reduced to 5c/kWh. In addition, the costs of established projects had decreased to more than half since 2009, while costs of median direct project have decreased from \$6.3/W in 2009 to around \$3.1/W in 2014. Furthermore, some of the established projects in 2014 have costs of around \$2/W, while other samples decreased from \$3.2/W in 2013 to \$2.3/W in 2014. Currently, costs of solar energy in the US have levelled at 0.17 \$/kWh, which is actually cheaper than the average price of electricity by one cent (Shah and Booream, 2015, Berkeley-Lab, 2015).

In contrast, the average total cost in KSA for a conventionally produced electricity unit was about SR 0.15/kWh in 2008. This rate is supported by government subsidy (Almasoud and Gandayh, 2015). It is currently around SR 0.14/kWh, which is less than than in the US, but higher than the local average electricity price (Shah and Booream, 2015). Almasoud and Gandayh (2015) reported that in the US market, the overall cost of energy production for a typical GCC utility is 12 ¢/kWh, which is equal to SR 0.45. On the other hand, the US Energy Information Administration (IEA, 2011) reported that oil prices will increase to 70\$ by 2015 and to 108\$ per barrel by 2020. This indicates that production of electricity costs from traditional production sources will quickly rise. Producing power from renewable sources would be cheaper than producing power from fossil fuels, along with other considerations, such as public health and environmental costs. In KSA, actual financial data shows that systems offering 10 MW and more of solar thermal energy can cost \$100/MWh, which is more than four times lower than the cost in 2009 (Casey, 2014). One of the established solar thermal plants in KSA is in Riyadh costing \$14 million (Kaye, 2012).

According to Almasoud and Gandayh (2015), the economics of solar energy are at their most favourable in areas with high solar radiation factors. Comparing solar energy with conventional production without considering the indirect costs of conventional energy is an unfair comparison. These indirect costs cover certain factors, like health and environmental impacts. Hepbasli and Alsuhaibani (2011) provided a study that attempted to address the present and future applications of solar energy along with research conducted in this domain, and to present available RETs in KSA. Reviewed topics related to solar energy involved solar energy education, water desalination, solar hydrogen, solar energy-related greenhouses, solar-powered irrigation, solar stills, PV systems, solar collectors, energetic solar radiation and solar radiation correlations. The study also covered some constraints, scenarios and barriers related to the main topic. Solar energy applications may satisfy an important portion of energy demand in KSA.

The following section offers an evaluation and investigation concerning the performance of solar energy forms in KSA.

2.6. Performance of Solar Energy Technologies

2.6.1. Concentrated Solar Power (CSP)

CSP systems handle fluctuating sunshine to power by through control of heat motor as opposed to PV, where light photons directly induce electric current.

A framework with thermal storage is expected to extend operational duration of a sunlight-based energy plant to meet demand in the evening period, as illustrated in Figure 2.49.

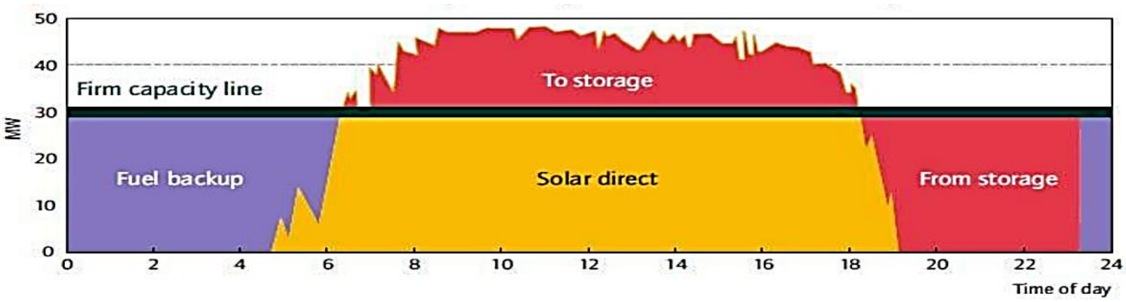


Figure 2.49: Storage frameworks and their functions (Chu, 2011)

In 2011, CSP was in effect generally commercialised, with capacity of around 1.17 Gigawatts, to which Spain contributed 582 MW, and the US about 517 MW. A total of around 17.54 GW of CSP projects are in progress around the world, with the US leading by around 8.67 GW, followed by with 4.46 GW being developed, and China with 2.50 GW. Table 2.8 and Figure 2.50 present CSP power creation and utilisation through to 2050.

Table 2.9: Electricity from CSP frameworks (Chu, 2011)

Countries	2020	2030	2040	2050
Australia, Central Asia,[+] Chile, India (Gujarat, Rajasthan), Mexico, Middle East, North Africa, Peru, South Africa, United States (Southwest)	5%	12%	30%	40%
United States (remainder)	3%	6%	15%	20%
Europe (mostly from imports), Turkey	3%	6%	10%	15%
Africa (remainder), Argentina, Brazil, India (remainder)	1%	5%	8%	15%
Indonesia (from imports)	0.5%	1.5%	3%	7%
China, Russia (from imports)	0.5%	1.5%	3%	4%

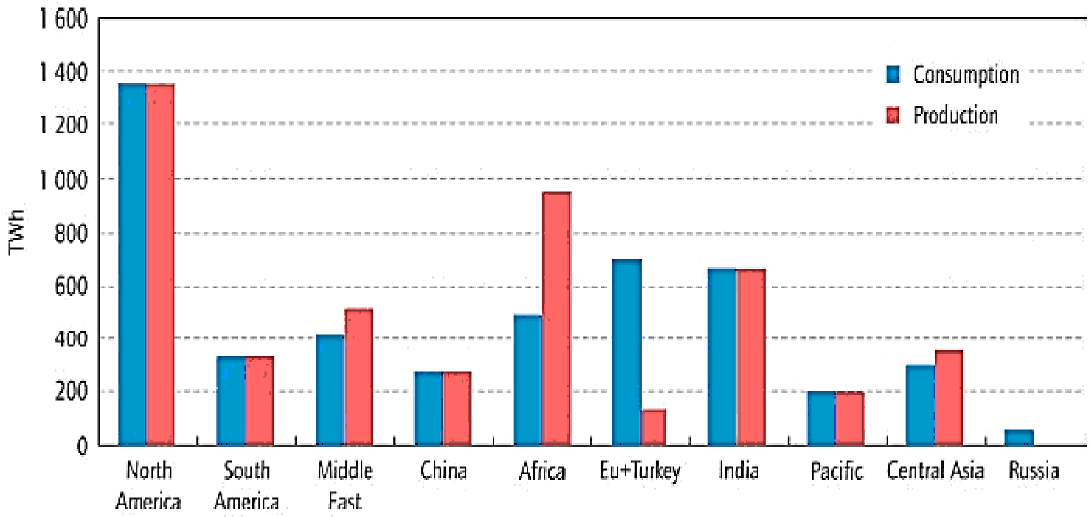


Figure 2.50: Consumption of CSP electricity by 2050 (Chu, 2011)

One of the main benefits concerning the CSP technology is that it resembles the majority of available power plants. In other words, the equipment used for fossil fuel based power plants can be utilised for CSP plants. Another benefit of the CSP technology is that it is a simple and non-polluting technology, where it can be used comparatively quickly, and can reduce the emissions of carbon dioxide (EC, 2009).

In practice, performance and efficiency of CSP technology are limited due to the following restrictions (VALENZUELA, 2010):

i. The Sun's intermittency: the magnitude and quality (diffuse versus beam) sunlight differs from day to day, and by seasons across geographical locations.

ii. Working fluid flammability: the oil used in certain solar plants is flammable, where several precautions must be taken to prevent fire if the temperature of the oil exceeds a certain limit. Furthermore, the working fluid may be toxic, which is a real risk.

iii. Current plant have low efficiencies rates compared to other types of plant due to low working fluid temperature, and the difficulty in gathering sunlight efficiently.

2.6.2. Photovoltaic Solar Panels (PV)

PV panels are devices for that convert sunlight into DC electricity by means of semiconductors. A PV array uses panels oriented towards the sun composed of numerous cells. PV cells are made from silicon with the addition of copper indium gallium selenide/sulphide, and cadmium telluride, and fabricated as either amorphous, polycrystalline, or monocrystalline cells (Chu, 2011).

Figure 2.51 illustrates the essential concept of how PV cells function. Electrons will radiate from substance (metallic, insulating objects, fluids and gasses) as a result of receiving solar radiation in the short wavelength; for example, visible light. The electrons are radiated in such a fashion that they may be called ‘photo-electrons’. Initially witnessed in 1887 by Heinrich Hertz, the phenomenon is termed the ‘Hertz effect’.

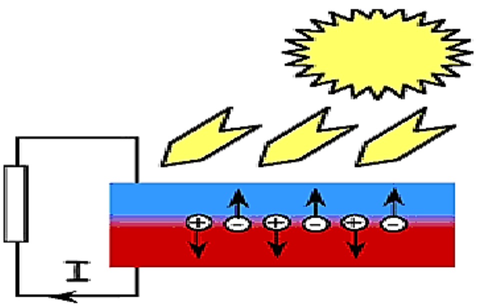


Figure 2.51: Schematics of PV panel

Cadmium telluride (CdTe) PV cells are type II-VI thin film semiconducting material, with a basic fabrication procedure, and thus, lower production costs. CdTe PV films represent the most advanced innovation in thin film. Additionally, it has a 8 months investment payback period; the shortest of all PV forms. The making of Copper indium gallium selenide (CIGS) cells is slightly more complicated than that for CdTe cells, resulting in higher costs and requiring greater technical expertise. Currently, CdTe PV thin films occupy a leading position due to the competitive cost per peak watt. Yet, CdTe suffers a problem of toxicity, and also raw material availability. At this time, it is difficult to foresee which thin film technology will secure greater prominence in the future. Figure 2.52 attempts to predict potential efficiency improvements in the next two decades (Chu, 2011).

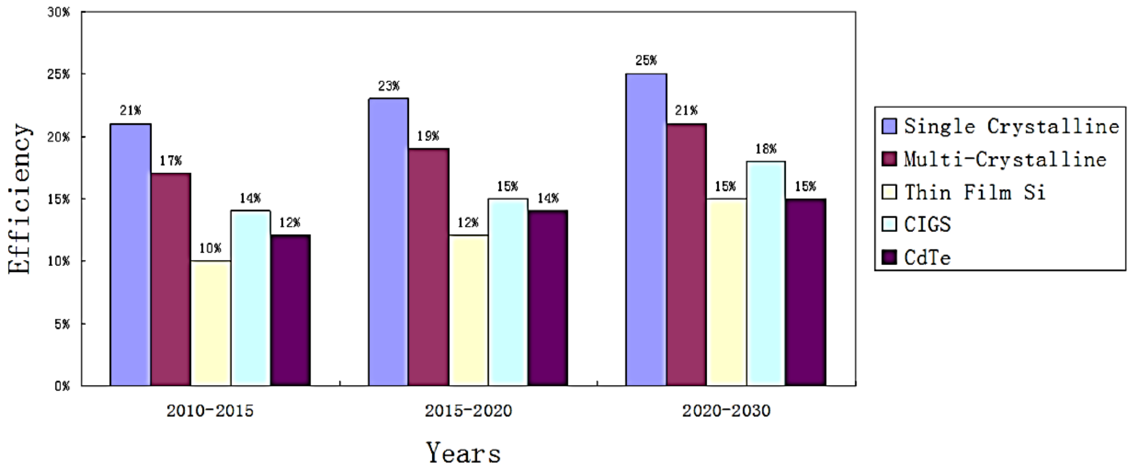


Figure 2.52: PV efficiency in future (Chu, 2011)

Despite, the positive outlook for the technology, a number of obstacles still need to be overcome. The unit cost of solar energy is higher than that of conventional small electricity generating plant. Market penetration of solar power applications lacks the added motivators of 'green' subsidies to enable competition with cheaper 'non-green' technologies. The absence of sunlight in the night period, or significantly reduced solar radiation under cloudy conditions. An energy storage facility is required in these circumstances. The variation of solar resource by location and season means it is not economic at all localities.

The typical daily yield of a PV panel authority at scope tilt in the US is 3 to 7 kW hour/m²/day, and less in zones such as European countries. Solar panels produce DC current, which needs to be converted to AC currents utilising an inverter, for existing AC powered consumer loads. This conversion comes at a power loss cost of 4 to 12%. Nevertheless, large voltage DC grid transfer has lower power wastage than in an AC network. Therefore, large DC voltage grids may be established, while implementing DC/AC inverters at the consumer load levels.

PV systems represent the most prominent solar-electric devices, and are expected to maintain rapid and consistent growth. The different types of PV cells have their own specific operating characteristics and relative advantages, and it is not clear which will surpass emerge as the industry leader in forthcoming decades. However, advances in PV systems will help states achieve a clean and sustainable future.

2.6.3. Concentrated Photovoltaic (CPV) Systems

CPV innovation utilises optical devices; for example, lenses to focus a large amount of light gathered from a large area onto a relatively small area. In CPV, a large amount of sun radiation is focused on a small solar cell, thus using less PV material to capture the same solar radiation amount as captured by non-concentrated PV cells. The CPV utilises effective, but costly multi-junction cells. CPV modules can be categorised based on the concentration degree as illustrated in the following table (Rhino, 2013).

Table 2.10: Classification of CPV modules (Rhino, 2013)

	Low Concentration	**Medium Concentration**	**High Concentration**
Degree of Concentration	2-10	10-100	>100
Tracking	Not necessary	1-axis tracking sufficient	Dual axis tracking required
Cooling	Not required	Passive cooling sufficient	Active cooling required in most instances
Photovoltaic Material	High-quality silicon	---	Multi-junction cells

A schematic description of PV functioning is shown in Figure 2.53. Energy packed photons supply energy to excite electrons in the consumption or semi-unbiased locations. They are excited and travel to the valence band from the conduction band. Contingent to space, openings and electrons are accelerated by the float field Edrift, which provides generation photocurrent, or by Escatt, which offers scattering photocurrent. From the coatings and assembly of the channel connection, the dimension of the consumption location is restricted and the hole of band is great, leading to tunnelling of electrons.

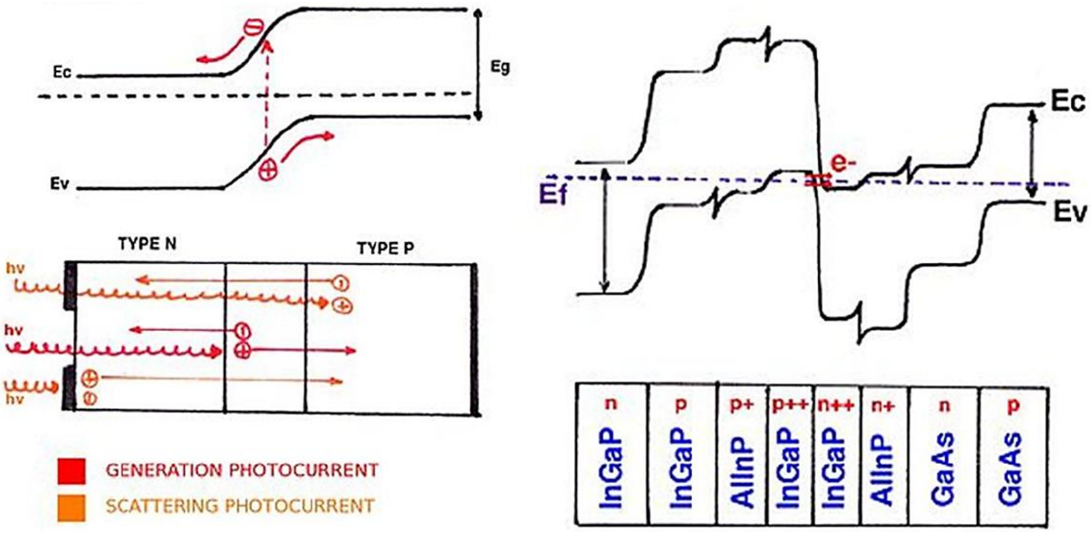


Figure 2.53: Schematics of photovoltaic effect and band structure of tunnel (Chu, 2011)

(Chu, 2011) has stated some advantages and disadvantages of CPV which are as follow:

The advantages of CPV include:

i. Despite the energy loss, it has the highest capability of being efficient among all the solar technologies.
ii. Dissimilar to conventional and more traditional flat panel systems, CPV frameworks are frequently cheap to construct, because less semiconductor is used in its manufacturing. This decreases investor risk and permits greater adjustments of strategies based on fluctuating marketplaces.

Some of the drawbacks of CPV are:

i. Similar to other concentration frameworks, CPV is incapable of gathering diffuse radiation. A few investigators suggest preparing the CPV module with a framework for tracking. However, CPV can gather more energy than non-concentrated PV, leading to greater performance in morning and mid-afternoon. Although the consumption of energy by the tracking mechanism is negligible, the moving components introduce problems of reliability with a rise in maintenance and manufacturing costs.

ii. Even slightly cloudy conditions may lead to null energy production. Unlike CSP, the storage framework which might mitigate such an issue is costly, where it is easier to construct a storage framework for thermal power than electrical power. Moreover, such variability is not desirable when the system is grid-connected.

iii. The cost of the multi-junction PV cell for High concentration PV (HCPV) price will be greater than the normal cell made of silicon for similar dimensions and sizes. This indicates that the concentration ratio should be hundred times greater to make the framework more economical than panels based on silicon. Nevertheless, this large concentration ratio will result in further necessity for tracking frameworks and panel cooling systems. Ultimately, these additional measures will lead to increased capital cost of the entire framework.

2.6.4. Dye Sensitised Solar Cell (DSSC)

DSSC is a low cost, new generation of solar cells, which transform sunlight into electricity. The PV material is a dye, which generates electricity when sensitised by sunlight. This material captures the sunlight photons and utilises their energy for stimulating electrons. It then injects the stimulated electrons into titanium dioxide. Electrons are then conducted away via the nano-crystalline titanium dioxide. The circuit is then closed via a chemical electrolyte, so electrons return to the dye. The movement of these electrons is an electric current, which may be used to recharge a battery or power any electrical device (GCell, 2015, Bowers et al., 2009).

DSSC is a photo-electro-chemical system, composed of three components, namely a semiconducting material sandwiched between an electrolyte and a photosensitive anode. In 1991, this cell, otherwise called the Grätzel cell, was designed by Michael Grätzel, the mechanism of which is illustrated in Figure.2.54.

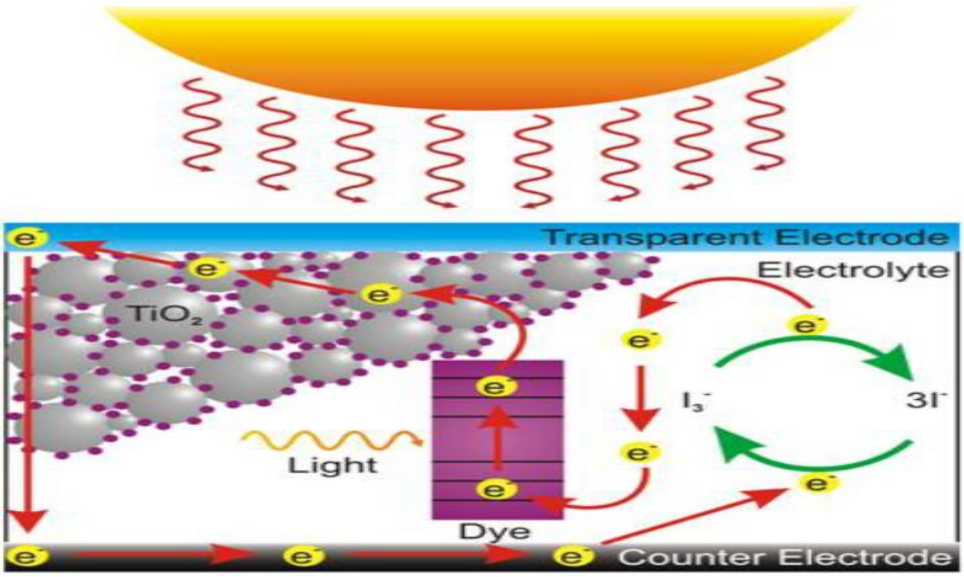


Figure 2.54: Mechanism of DSSC (Chu, 2011)

Daylight enters the cell via the straightforward spread, hitting the dye on the exterior layer of the TiO_2, affecting the dye such that electrons are infused within the TiO_2 conducting band. From that point, electrons travel by dispersion (as an aftereffect of an electron focus angle) to the anode on uppermost area.

The dye particle is missing one electron and will break down, if additional electrons are not given. The iodide colour bands in the electrolyte beneath the TiO_2, are oxidised to tri-iodide. Such a response happens immediately, in contrast to the time needed for the infused electron to re-join the oxidising dye particle. Maintaining such a re-joining response is fundamental, because it will viably impede the sun powered cell. The tri-iodide recuperates the lost electron by automatically spreading to the base, where the counter electrode shows the electrons moving through the external circuit.

The infusion procedure utilised as a part of the DSSC does not make an opening in the TiO_2, just an additional electron. Despite the fact that it is feasible for the recombination of electron once again within the dye, the speed at which it happens is moderate, contrasted with the rate at which the dye recovers the electron from the encompassing electrolytic material. Re-joining specifically from the TiO_2 to species in the electrolytic material is likewise conceivable in spite of the fact that for enhanced devices this response is fairly moderate. Indeed, electron exchange from the platinum covered anode to species in the electrolyte is essentially quick.

To a large extent, one can claim the efficiency of the DSSCs given their molecular organisation in the nano-assembly, with the dye molecules being tiny as their size is that of a nano-metre. For a rational sum of the incident light to be captured, one has to make the layer of dye molecules thick to some extent; i.e. they have to be thicker than the molecules themselves. This is possible utilising a nanomaterial as a platform to accommodate large numbers of the dye molecules in a 3-D matrix. This will augment the number of molecules for any specific surface area of the cell. It is a great risk of absorption of photon, and the dyes are extremely successful at converting these to electrons. The majority of the little losses that happen in the framework are because of transmission losses in the TiO2 and the unmistakable cathode, or optical losses in the front anode. The general efficiency for green light is around 90%, with the loss of 10% to a great extent represented by the optical losses in the top electrode. Generally, the maximum conversion efficiency for current DSSCs is around 10.9 % as at January, 2011 (Chu, 2011).

The benefits of DSSC are:

i. It utilises very cheap materials, which are very easy to construct, and are very attractive for engineers.
ii. They can be substitutions for present advances in ‘low thickness’ uses like roof sun based gatherers, where mechanical unwavering quality and lighter mass of the glass-less panel are critical components.
iii. The procedure of inoculating an electron straight into the TiO_2 is qualitatively dissimilar to that happening in a customary cell, where the electron is ‘advanced’ into the unique crystal. Theoretically, specified little proportions of production, the great-power electron in the silicon might recombine with its own hole and result in less current.
iv. Basic semiconductor frameworks endure discernible reductions in efficiency because the cells are heated up inside. DSSCs are ordinarily fabricated with just a thin coating of conductive elastic material on the reverse layer, permitting them to transmit heat away, and subsequently work at lower internal cell temperatures.

Some of the drawbacks of DSSC are:

i. Current efficiency is still moderately low compared to conventional semiconductor sunlight based cells.
ii. Dyes will degrade under bright illumination reducing cell lifespan and reliability of the cells including an obstruction coating will increase the expense and may reduce the effectiveness.
iii. DSSC innovation utilises a fluid electrolyte that has temperature dependability issues. At low temperatures, the electrolyte can stop, halting current generation, with possible permanent damage to the cell. High temperatures causes the fluid to grow, making fixing the boards a major issue.

2.6.5. Solar Thermoelectricity

Solar thermoelectricity, employing a CTEG, utilises a concentrating parabolic dish to capture and reflect solar radiation onto a receiver, integrating a thermoelectric device. The thermoelectric device is separated into two sections, cold and hot, delivering power according to the difference in temperature between the two sections applying a semi-transmitter.

Alternatively, when a voltage is applied to a device, it causes a temperature difference between both sides. At nuclear scales, an associated temperature difference charges transferors to travel from the hotter side to the cooler side. Presently, thermoelectric devices have met expectations in the space and vehicle industries.

Figure 2.55 presents the operation of a sun-oriented thermoelectric framework. The concentrator gathers and focuses the sunlight onto a small area, raising the temperature of the receiver absorber depending on the magnification. At that point, the electron stream from the hot to the cool section through the thermoelectric substance, creates a voltage at the productivity η (Chu, 2011).

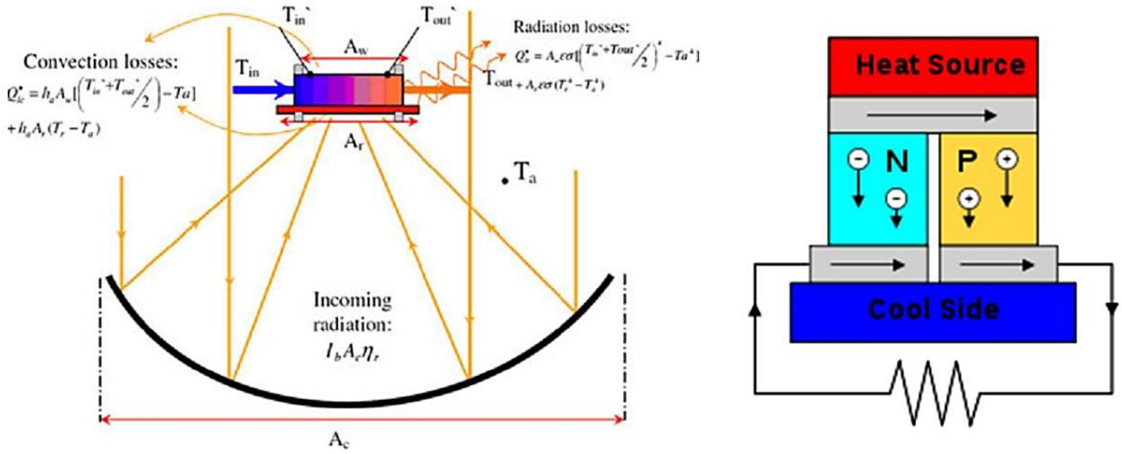


Figure 2.55: Mechanism of solar thermoelectricity framework (Chu, 2011)

The advantages of solar thermoelectricity framework include:

i. A basic framework that might be set on rooftops.
ii. Capable of operating in unforgiving situations.
iii. Noiseless operation.
iv. Efficient and limitless lifespan of realistic usability.
v. The thermoelectric component has basic assembly with no dynamic sections.
vi. Negligible failure rate.

Some of the disadvantages are:

i. The efficiency of the thermoelectric materials is still low; recently achieving only 1.3 to 2.0.
ii. Like the majority of the other CSP devices, it is not able to gather diffuse light and must depend only on direct radiation.
iii. Cooling frameworks are required to maintain the temperature of the cool side to provide aggregate effectiveness.
iv. Thermoelectric material like Bismuth telluride is lethal and very expensive.

2.7. Greenhouse Gas Emissions and Environmental Impact Among Various Electricity Production Techniques

In practice, power generation through burning fossil fuels results in large amounts of carbon dioxide and pollutants. Current electricity generation is widely dependent on fossil fuels, and so various efforts have been exerted to switch to renewable energy and nuclear power sources to reduce GHG emissions (CO_2, CH_4, N_2O, and chlorofluorocarbons). On the other hand, all energy generation techniques, including nuclear and solar ones result in pollutants within their life cycles (Service, 2005).

In recent years, there is wide interest in studying the emission of GHGs and their implications on global climate change. Based on the published report by IPCC, 27 gigatonnes of CO_2 is emitted in the world annually from various sources, while 10 gigatonnes is emitted from electricity production. This represents 37% of emissions worldwide. This is expected to increase up to 43% in the next twenty years. Thus, there is a need to construct new power generation facilities to reduce GHG emissions. Available electrical generation methods differ in their environmental impacts, costs, operation (including fuel activities), quantities of emitted GHGs and decommissioning. The four stages of material cultivation and fabrication, which incorporate the full range of resource extraction, processing of materials, and the amalgamation of final products. In the case of PV cells, the material cultivation includes mining, refining and purification of the silicon and/or other required metals and minerals for the cells, glass, frame, inverters, and other required electronics. Accounting for cultivation, production, operation, and decommissioning is known as the lifecycle method, where the normalisation of emissions with electrical production permits performing a comparison among various methods in gigawatt/hour, where the lower value indicates lower emission of GHGs (Fthenakis and Kim, 2007, Fthenakis and Kim, 2013).

The table below demonstrates the lifecycle of GHG emissions according to electricity production technique. The main effective factor on those emissions is the choice of facilities, where rates of emissions from power generation plants are dependent on individual facilities, which have site dependent and region dependent factors that affect these rates (WNA, 2012).

Table 2.11: lifecycle of GHGs emissions by various electricity production techniques (WNA, 2012)

Technology	Mean	Low	High
	tonnes CO_2e/GWh		
Lignite	**1,054**	790	1,372
Coal	**888**	756	1,310
Oil	**733**	547	935
Natural Gas	**499**	362	891
Solar PV	**85**	13	731
Biomass	**45**	10	101
Nuclear	**29**	2	130
Hydroelectric	**26**	2	237
Wind	**26**	6	124

The highest achieved intensities of gas emissions are for lignite and coal fired power plants. It is also demonstrated that solar PV, biomass, nuclear, hydroelectric and wind techniques have lower intensities of gas emissions compared to fossil fuel dependent production (WNA, 2012).

The main focus of the current study is on solar energy sources. The following sections explore the effects on decreasing GHG emissions.

2.7.1. Reduction of CO_2 Emissions by Solar Power

Carbon represents around 80% of GHG emissions, and will cause the majority of climate changes that may happen in the next century. Emissions of carbon dioxide started to increase in the last two hundred years, because of industrialisation and greater demands for electricity and the associated burning of fossil fuel (Arif, 2013).

In practice, the effect of energy generation techniques on the environment and climate is mainly represented by the intensity of carbon emission. This intensity is a measurement of the amount of CO_2 and non-carbon GHGs, including methane and nitrous oxide resulting from various human activities, such as fossil fuel extraction and gardening (Nelson et al., 2014).

The second largest contributor to GHGs emissions is the electricity sector, where this increases the need for using clean technologies to assist in reducing large sources of those emissions (CARB, 2008). The available fossil fuel techniques cause high intensity of carbon emission through burning fuels that are carbon rich. On the other hand, renewable techniques, such as solar power technique results in few or no CO_2 emissions in operation. However, it can cause CO_2 emissions during the manufacturing process. Therefore, solar energy can assist in reducing the emissions of CO_2 based on substituting more carbon-concentrated resources of power and heat. The reduction in the amount of CO_2 is based on the quantity of predictable power or heat to be substituted, and both the quantity and kind of consumed energy to manufacture, install and operate solar energy systems (UCS, 2014, Nelson et al., 2014). The following section discusses the ability of both solar PV and solar thermal power systems to reduce CO_2 emissions.

In PV power techniques, the intensity of CO_2 varies based on the materials used and the processes and effectiveness of the module. As an example, in Europe, the generated powers by PV systems with CdTe, multi crystalline silicon and c-Si materials are 15 gCO_2/kWh, 27 gCO_2/kWh and 38 gCO_2/kWh, respectively (Schotten, 2013). The balance-of-system (BOS) materials embed around 5 gCO_2/kWh. These amounts of energy can be doubled with the use of grid mix materials (Nelson et al., 2014).

For concentrating PV systems, which require a large amount of steel for constructing collectors in a small area, intensities of CO_2 are similar to those of using silicon material at 20-40 g CO_2/kWh in optimal places (Nelson et al., 2014). The CO_2 intensity is also influenced by the changeability in supply and changes in local orders. In summary, the accessibility, performance, process and CO_2 intensity of PV power demonstrate that this technique offers a considerable contribution to CO_2 emissions reduction over years, as shown in the following figure.

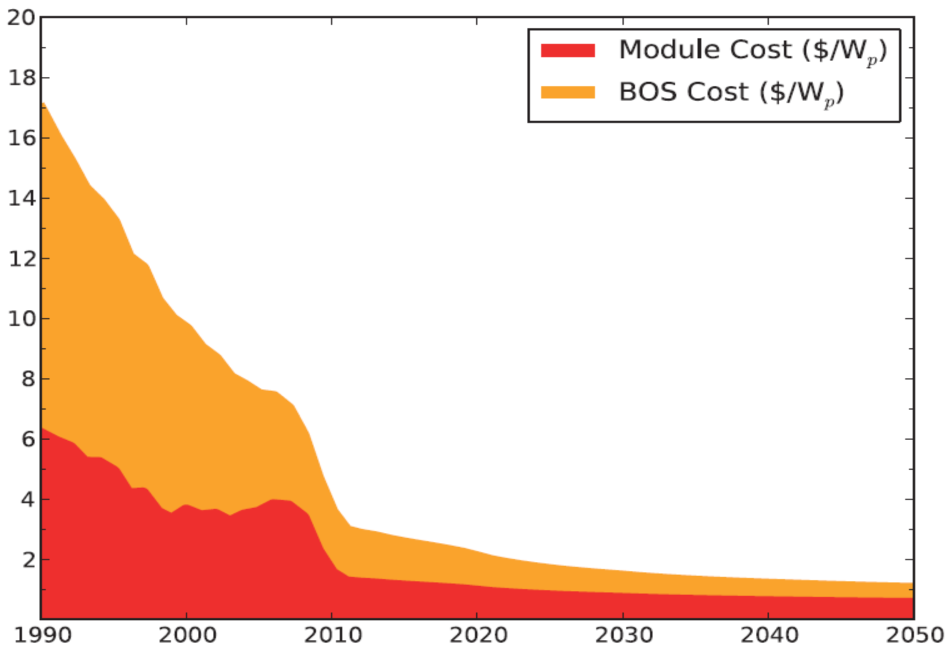


Figure 2.56: Reduction in CO2 emissions for PV solar technology over years (Nelson et al., 2014)

For CSP systems, the analysis concerning the lifecycle of these systems demonstrates that they offer 20-50 gCO_2/kWh (Nelson et al., 2014). The incorporation of these systems with energy ones, the consistency of output power and included thermal storage reveal that the need for related storage or flexible capacity for these systems is less than that of non-concentrating PV systems, as well as the need for restriction is also less. Since CSP systems are flexible by nature, they can assist in incorporating more variable capacity, such as PV systems, into electricity grids.

2.7.2. CO_2 Emissions in The Lifecycle of Solar Power and wind

The lifecycle of solar power includes four stages; material cultivation and fabrication (it incorporates the full range of resource extraction, processing of materials, and the amalgamation of final products as in PV cells. The material cultivation phase includes mining, refining and purification of the silicon and/or other required metals and minerals for the cells, glass, frame, inverters, and other required electronics) and is followed by production, operation and decommissioning. The amount of CO_2 emissions from solar power compared to wind power for each one of these phases is shown in the following figure (Nugent and Sovacool, 2014).

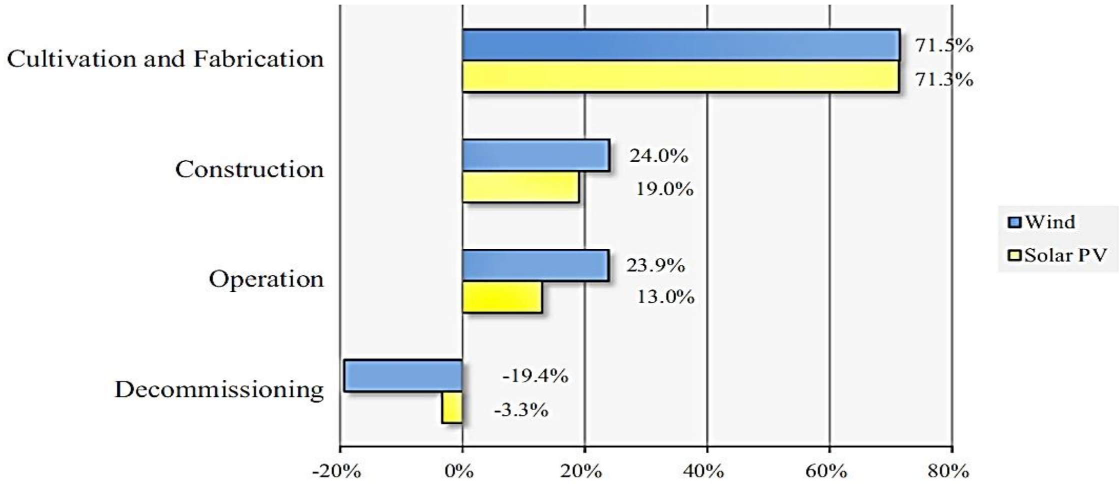


Figure 2.57: Amount of CO2 emissions from solar power compared to wind power for each during the lifecycle phases

Wind energy produces 34.11 gCO_2/kWh in its lifecycle, compared to 49.91 gCO_2/kWh for solar energy in its lifecycle. These values depend on several factors, such as resource inputs, techniques used, location, sizing, longevity and capacity. As shown in the figure, The cultivation and fabrication phase stands for the incorporation of extraction of resources, materials processing and combination of final products of the solar module. This phase is the responsible for the largest emissions proportion; around 71% for both the solar and wind technique. The production or construction phase represents the on-site production of materials transportation and generator to the target location. CO_2 is emitted in this stage for the solar technique due to the processing of balance-of-system materials and burning fossil fuels to send and assemble the system. This phase produces 24% and 19% of CO_2 emissions for the wind and solar techniques, respectively (Nugent and Sovacool, 2014).

The operation and maintenance stage represents the maintenance and cleaning of the solar module. This phase produces 23.9% and 13% of CO_2 emissions for the wind and solar techniques, respectively. The decommissioning phase includes the deconstruction, clearance, recycling and land recovery processes. It offsets 19.4% from the wind technology emissions and 3.3% from those of solar facility (Nugent and Sovacool, 2014).

Thus, wind turbines have lower CO_2 emissions in its lifecycle compared to those of solar energy. But, CO_2 emissions of solar techniques can be reduced based on increasing the size regardless of the fact that panels are modular and must have similar effectiveness for all sizes in a theoretical manner. This is because of the gains in both logistics and transportation. The increase in the lifecycle can result in a decrease in CO_2 emissions (Tremeac and Meunier, 2009).

Although wind energy results in lower CO_2 emissions compared to solar energy, winds are unreliable, where in some regions, the strength of winds is too low in a way that cannot support wind farms or turbines. In this case, the use of solar power is a great alternative. In addition, wind turbines generate less electricity than solar plants, in which many wind turbines must be constructed together to generate electricity. Furthermore, the construction of wind turbines is costly, and causes annoying noise pollution compared to solar facilities (Bratley, 2013).

2.8. SWOT analysis

This section discusses the main planning technique in the form of a Strengths, weaknesses, opportunities and threats (SWOT) analysis that are thought to require careful consideration for introducing any new or disruptive technology which in this case applies to large scale solar power generation.

2.8.1. KSA Solar Energy Technology Strengths

i. KSA geographic location, where huge amount of solar energy is received every day
ii. High economic growth in KSA
iii. Ability to produce solar energy on or off the grid
iv. Solar energy is a clean energy and is emissions-free
v. Solar energy provides a plentiful, discounted energy source
vi. Availability of large empty areas allows solar energy exploration for many applications
vii. The Sun is a renewable energy source
viii. Strategic plan initiated recently to generate power from renewable energy sources (more than 50 GW which include 25 GW generated from CSP systems) for the next 15 years
ix. Government support to related energy sectors

2.8.2. KSA Solar Energy Technology Weaknesses

i. Compared to oil generators, solar system installation costs are higher, where the costs of solar PV is \$0.13/kWh, cost of solar-thermal is \$0.24/kWh, while the cost of natural gas is \$ 0.07-0.13/kWh (Rozenblat, 2015).
ii. Areas that receive more solar radiations are usually remote
iii. Energy storage technologies have not achieved their full potential
iv. Constructed solar panels and systems are too bulky
v. Solar panel installation process introduces higher costs, but once they are constructed operation and maintenance costs are low
vi. CSP have not been fully explored or exploited in research and development, or applications

2.8.3. KSA Solar Energy Technology Opportunities

i. With solar energy expansion power capacity within the country will increase
ii. Solar energy sources allow KSA to publicly contribute to renewable promotion. This can be done by green building councils, through country and region groups, and through technical exchange in solar technologies
iii. Using solar energy will reduce power production and cost of transition,
iv. If development in the solar energy conversion is achieved, KSA can be a leading country in solar energy production. The Kingdom's geographical position and unutilised desert land are exceptional candidates for this.
v. Establishing regulatory entities to organise all related efforts to renewable energy sector
vi. The development boom that KSA is witnessing

2.8.4. KSA Solar Energy Technology Threats

i. Solar energy systems batteries involve hydrofluoric acid, and are manufactured from lithium which is flammable.
ii. Solar energy is influenced by its intermittency.
iii. Solar sources for electricity production are based on the quantity of light energy in a certain area.
iv. High temperatures decreases the efficiency of PV systems
v. Dusty weather affects solar systems efficiency.
vi. Lack of regulations for controlling sustainability measures.

2.9. Summary

KSA is considered one of the dynamic countries that faces high energy demand. The country's population has increased and electricity prices are low. This chapter provided detailed data from previous researches that are associated with energy consumption rates in KSA. This is done to fully understand and characterise energy demand in KSA. The literature provided detailed data on the implementation and use of renewable energy resources.

Investigation results show that solar energy potential is higher than wind potential, and so, KSA must increase its focus on solar energy. The third section provided a review of solar energy and solar energy technologies in the country. Detailed research reveals that alternative energy introduction will ensure decreased oil consumption. It will also ensure longer-term obtainability of hydrocarbons for export and usage as feedstock. The research presented shows the economic feasibility of renewables, all of which have negligible environmental influence, with attention to KSA's solar strength. Renewable energy resources are exposed to fluctuation in supply and thus are the best utilised in combination at times of peak requirements. This alternative can offer a continuous and mature electricity source throughout the year. The points covered have examined the current situation, and attempt to build an energy programme that can provide a substantial share to satisfy growing energy demand.

The following points present a general conclusion with respect to implementation of renewable energy sources in KSA:

- Renewable energy is an important energy source in the future of the whole world, not only KSA.
- KSA has great possibilities for solar energy exploitation. This energy is freely available, clean and renewable.
- Studies showed that the annual, average solar energy received at the Arabian Peninsula is approximately 2200 kWh/m^2.
- KSA introduced the first solar energy applications in 1960.
- A solar hydrogen production plant is located at the Solar Village in the capital of KSA, al-Riyadh. It is recognised as the first solar-powered hydrogen-production plant, and produces 350 kW.

- Solar energy development is insufficient as a result of numerous difficulties. Yet, for KSA, harnessing solar energy in various forms remains quite attractive.
- Study and solar energy field experience provide valuable lessons. These suggest that countries with the same climatic conditions as KSA can effectively use solar energy.
- In the application of solar energy projects, key experience various activities, including data collection and analysis, and instrumentation, calibration, monitoring, and assessment has been gained.
- Medium and low solar energy applications are economically and technically feasible, and must be supported and encouraged by the government of KSA.
- Wind energy sources in KSA have not yet been completely explored.
- Developing countries have put effort to discover renewable systems applications that have been advanced in industrialised countries.
- In order to effectively implement renewable energy systems in KSA, government subsidies are needed.
- Interaction between industries, including local research centres and regional renewable research centres, should be promoted.

CHAPTER 3

MODELLING OF RENEWABLE ENERGY SYSTEMS FOR THE KINGDOM OF SAUDI ARABIA (KSA)

3.1. Introduction

This chapter presents the research approach and methods applied to all aspects of this work. The first aspect covered in the previous chapter was the literature review, which presented the key information related to the research. With the literature review completed, it was clear that there was a gap in data, information, and measurements, given the research objectives of proposing designs and performing feasibility studies of two solar power plants at different sites using parabolic trough and power tower technologies. Consequently, it was necessary to gather relevant data and measurements from KSA, as will be discussed in due course within this chapter. The chapter summarises the methodology followed in collecting data related to the research and the two CSP plant designs.

On the other hand, this chapter describes those projects implemented in the area of solar energy in KSA, and their locations. The chapter then discusses the motives that led to the choice of sites and technologies for the two CSP power plants. Each plant is described and discussed in a dedicated chapter, namely Chapters 4 and 5.

A survey conducted of key software proposed for use in this research is also presented. Subsequently, the software applications chosen, SAM and RETScreen, are examined. These programs possessed features that fulfilled the purpose of achieving the objectives of the research, in facilitating CSP plant design and evaluation, following a robust scientific method. The chapter also presents extensive descriptions of SAM and RETScreen, and the process followed by the user for each, including the available analytical and design features, and the way results are presented. It is worth noting that the two proposed CSP stations investigated are sited alongside two functioning fossil fuel power stations. From this perspective, comparisons will be made, and designs and feasibility studies of the two solar power stations are discussed, along with the facts and figures on the current conventional power stations. In addition, the effects of the two designs on the prevailing conditions in the Saudi energy industry are discussed. In addition, the chapter provides background on some design formulae relating to solar radiation the aspect of power generation.

Figure 3.1 briefly illustrates the methodology and roadmap of the research, as will be followed in the thesis chapters.

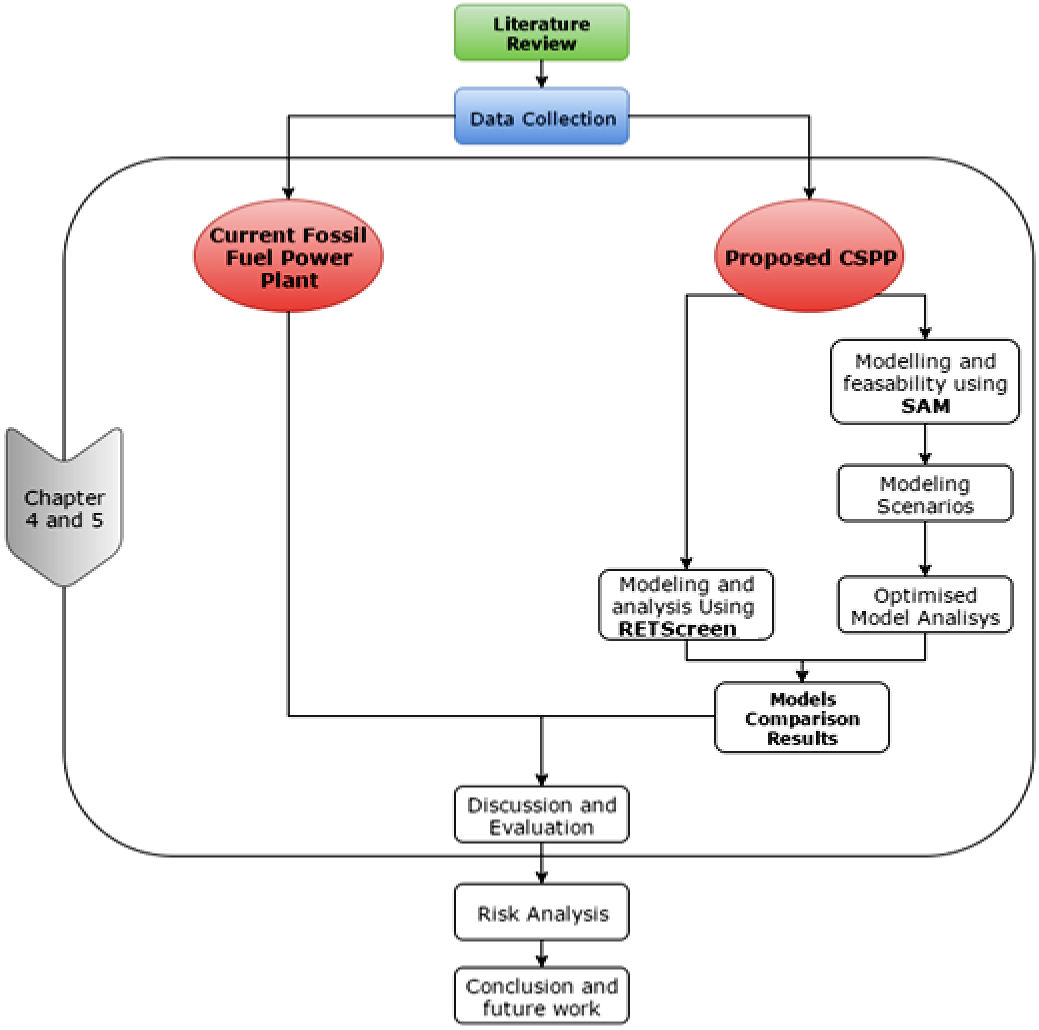


Figure 3.1: Flowchart mapping the layout of the thesis in presenting the research work

3.2. Data Collection

Generally, two types of research approaches can be applied to data collection, namely primary (practical) and secondary (theoretical) research. Both types are used to collect data in this work, and as such, are explained in the following sections.

3.2.1. Primary Research

Primary research involves the collection of data by the researchers themselves using various methods, such as distributing questionnaires, conducting interviews, making observations, performing action or ethnographic researches, conducting case studies or longitudinal studies, or investigating life histories. Primary research is applied in this work, as it is applicable and usable, can offer precise and reliable answers to the research questions and offers up to date data. Primary research can be divided into two types, quantitative and qualitative (Johnson and Christensen, 2008, JENNIFERC, 2014).

- Quantitative research is investigative and methodical in nature. It has many forms or ways to be accomplished; the most popular one is based on writing and distributing a questionnaire to a sample of the target population. However, this approach was not used in this work for reasons or limitations that prevented adoption of this approach. Some minor reasons were a potential lack of validity, in that there is no efficient way to know if participants are truthful. Moreover, there is margin for differences among participants in understanding the questions, where they may answer based on their interpretations of questions. Additionally, open-ended questions may result in a large amount of data, which needs time to be analysed. Furthermore, respondents may answer the multiple choice questions randomly without reading the questions or they may not answer some questions, where this affects the accuracy of the study (Statpac, 2014). The primary reason that prevented adoption of this approach is generally the lack of knowledge in this area, and the lack of researches and studies and even projects in KSA, despite the recent trend toward renewable energy. Indeed, the sample would also be small and not representative.

  The other approach used in this project was the quantitative approach using simulation programs to analyse, and predict data and results. Two simulation programs were used, namely SAM and RetScreen.

- Qualitative research focuses on how respondents in the research are thinking. This type of research is typically based on conducting face-to-face interviews with the defined sample. In the current work, face-to-face interviews and site visits are employed to gather statistical data and facts like future energy plans and strategies, amount of governmental support, the availability of regulations, ongoing projects and the planned projects, detailed data about energy generated and consumed in the country and road map of renewable energy technologies to be implemented in KSA.

Table 3.1 offers a comparison between quantitative and qualitative researches.

Table 3.1: Comparison between qualitative and quantitative researches (Johnson and Christensen, 2008)

Criteria	**Quantitative research**	**Qualitative research**
Aim	Aims to study the feasibility of solar power generation using mathematical and statistical techniques like simulation program providing predictions	Aims to study social interactions and opinions
Target Sample	Large	Small
Understanding and description	It seeks explanation and control	It seeks to understand complicated interrelationships
Method of selecting respondents	random	Not random
Variables under investigation	Studying specific variables	Studying all variables
Data analysis type	Statistical relations	Themes, features and patterns
Subjectivity and objectivity	Critical objectivity	Expected subjectivity
Respondent performance point of view	Expected and regular	Individual, situational, dynamic and social
Allow and create	It depends on creating situations to evaluate the hypotheses	It permits things to occur naturally
Final report	It provides a statistical report that contains correlation coefficients, comparisons concerning means and statistical significance of results	It provides a descriptive report that contains contextual clarification and direct quotations from participants

Thus, this work adopts a mixed methods approach (MMA), where it used both qualitative and quantitative methods. Indeed, face-to-face unstructured interviews and site visits were conducted to collect data. Also, simulation programs were used to predict or assess the feasibility of solar power generation in the area chosen for the study, based on the collected data and statistics gathered in the qualitative research part. A visit was conducted to KSA in 2012 to collect general and specific data from managers and engineers in various government entities and companies, working in the field of energy and research. In practice, information published in scientific journals and publications is not enough to carry out a research. Hence, the qualitative research was conducted to enhance the foundations of research design and analysis. In the beginning, issues concerning the energy field in KSA, especially solar energy were examined. The face-to-face interviews and site visits were conducted as follows:

3.2.1.1. Face-To-Face Interviews

Face-to-face unstructured interviews were conducted with five managers and engineers, who are decision makers in the energy generation field in KSA, where their answers to the questions were recorded. The interview data offers general and practical information, which helped greatly in responding to the research question. The following table includes the names of the five managers and engineers, specifying their job, email address and the institution where they work.

Table 3.2: Information concerning interviews respondents

Respondent name	Institution	Job title	Contact Website
Dr. Abdullah Al-Shehri	Electricity Cogeneration and Regulatory Authority (ECRA)	Governor	www.ecra.gov.sa
Dr. Ibrahim Babelli	KACARE	Head of KACARE plans and strategies	www.energy.gov.sa
Dr. Abdul rahman Al-Odhaibi	King Abdulaziz City for Science and Technology	Researcher in the field of energy in KACST	www.kacst.edu.sa

Respondent name	Institution	Job title	Contact Website
	(KACST)		
Eng. Bakhyat Al-Doasari	SEC	Director of Project Management Studies in SEC	www.se.com.sa
Eng. Yaser Al-Zahrani	SEC	Director of power generation engineering department	www.se.com.sa

The collected data from the conducted unstructured interviews focused on the following topics:

i. The future of energy production from renewable sources, especially solar energy
ii. Future plans to increase the produced power to cover the growth in both consumption and need
iii. The availability of regulatory policies for energy production from renewable sources, especially solar energy
iv. Strategic plans for solar projects in the production of electricity
v. Current research projects concerning the design of expected plants that use solar energy

The following topics were also covered in interviews with the group of managers and engineers:

i. Available advisory studies for current and future energy plans and strategies
ii. Current and future regulations that apply to all sectors—residential, commercial, industrial and governmental, with regard to the organisation of consumption and its management
iii. Forms of support offered by the government to the electricity industry

iv. Policy on renewable energy of all types, especially solar energy, in KSA, which includes policies of renewable energy in residential, commercial, industrial and government sectors
v. Current projects in the field of renewable energy
vi. Sources and costs of energy production, and related government support
vii. Obstacles that face KSA relating to solar energy projects

In addition, data concerning the following topics was collected from the managers and engineers interviewed:

i. Available electricity generation capabilities in MW per year from 2001 to 2012
ii. Available electricity generation capabilities needed in MW annually for the next twenty years (up to 2032)
iii. The number of existing stations, the number of available units and their types in each station, the capacity and efficiency of each unit separately in MW
iv. Energy produced from plants based on the types of units; steam, gas, and combined cycle from 2001 to 2012 for each year
v. Annual expected energy output demand depending on the types of units for the next twenty years (up to 2032)
vi. Energy produced annually based on the business segments; middle, west, east and south from 2001 to 2012
vii. Expected annual energy output based on the business segments for the next twenty years (up to 2032)
viii. Current and predicted energy from alternative sources by type of source
ix. Production cost of kilowatt hours per year from 2001 to 2012
x. The complete strategic plan for electricity production for the next twenty years, including the expected production and consumption, number of subscribers, cost of implementing this strategy and the expected cost per kilowatt hour
xi. Constraints that face companies in producing power from renewables, and proposed solutions for these constraints to help in creating renewable energy plants
xii. Environmental obligations, which must be considered in constructing new power plants

Data were updated based on contacting managers and engineers by email until December, 2014

3.2.1.2. Site Visits

Two site visits were conducted to Wadi Aldawasir Mini-Power Generation Grid and Shuaibah Power Generation Grid. In these visits, data concerning operation and engineering production were collected from two engineers. The collected data was then used in the following two chapters in the design and study of establishing two solar energy plants using different technologies. Table 3.3 includes the names of those two engineers, and specifies their job, email address and the institution where they work. Also, a visit was conducted to SEC headquarters in Riyadh.

Table 3.3: Information concerning site visits respondents

Respondent name	Institution	Job title	Contact Website
Eng. Khursheed	Juba in Wadi Aldawasir Mini-Power Generation Grid (Juba Power plant (PP))	Station engineer	www.se.com.sa
Eng. Tawfeeq Al-Jaber	and Shuaibah Power Generation Grid (Alshuaibah Power plant (PP))	Station engineer	www.se.com.sa

The table below summarises the type of research conducted to collect data from each organisation

Table 3.4: Type of research at collection data stage applied to each organisation

Research Chart	ECRA	KACARE	KACST	SEC	Juba PP	Shuaibah PP
Interview	Yes	Yes	Yes	Yes	Yes	Yes
Site Visit				Yes	Yes	Yes

MS/Excel sheets were prepared, and included operational information and specifications for both stations, Wadi Aldawasir Mini-Power and Shuaibah Power Generation Grids.

Data were updated based on contacting managers and engineers by email up to December, 2014.

3.2.2. Secondary Research

On the other hand, secondary research represents data published in previously conducted researches, historical data, official statistics, diaries, government reports, letters, mass media products and Web information. In this work, various articles, books and websites were used to gather background information concerning the work conducted and assist in building the methodology based on determining the current problems and gaps that are not covered in previous researches and then offering a contribution.

3.3. Case Studies for Solar Power Generation

KSA is the fastest growing consumer of electricity in the Middle East, with demand that is increasing by 5 percent annually. KSA is also the 15th largest primary energy consumer, as recorded in 2005 (Sait, 2012). By 2020, 2.0 GW of new electricity generation capacity needs to be installed. Considering the overall renewable energy outlook for KSA, a more specific approach must be taken towards a solar power framework. A number of solar power generation projects have been deployed in the country, which enjoys an annual average solar radiation of over 2200 kWh/m^2. Some of the main solar projects in KSA are the solar village in Riyadh, and a solar hydrogen production plant at the same site, as well as solar-powered water desalination projects. A pilot plant was set up in 1984 in Yanbu, and subsequently, the first PV-powered desalination plant (as well as water pumping plant) was completed in 1994, 70 km from Riyadh at Sadous Village. Forthcoming solar energy projects, include a new solar power desalination plant at Al Khafji using concentrated PV and capacity of 30,000 m^3/day, the Saudi Atlas Project (a joint research and development project between ERI and NREL), a solar hydrogen production plant based on 350 kW PV, 50kW solar thermal dish project, solar-powered highway devices project, solar dryers, solar water heating project and a solar energy education and training project.

Moreover, significant solar power projects were implemented in KSA, as mentioned above and in previous chapters. Hepbasli and Alsuhaibani (2011) presented a list of solar power projects conducted by ERI. A short insight is given in Table 3.5.

Table 3.5: List of solar energy projects undertaken by ERI

Period	Location	Type	Capacity	Application
1981-1987	Solar Village	PV system	350 kW (2155 MWh)	AC/DC electricity for remote areas
1981-1987	Saudi universities	Solar cooling	-	Developing solar cooling laboratory
1986-1991	KAU, Jeddah	Solar hydrogen	2 kW (50 kWh)	Testing of different electrode materials for solar hydrogen plant
1987-1990	Solar Village	Solar-thermal dishes	2 pieces, 50 kW	Advanced solar Stirling engine
1987-1993	Solar Village	PV test system	3 kW	Demonstration of climatic effects
1988-1993	Solar Village	PV hydrogen production	350 kW (1.6 MWh)	Demonstration plant for solar plant hydrogen production
1988-1993	Dammam	Energy management in buildings	-	Energy conservation
1989-1993	Al-Hassa, Qatif	Solar dryers	-	Food dryers (dates, vegetables, etc.)
1989-1993	Solar Village	Solar hydrogen generator	1 kW (20-30 kWh)	Hydrogen production, testing and measurement (laboratory scale)
Since 1990	Solar Village	Long term performance of PV	3 kW	Performance evaluation
1993-1995	Solar Village	Internal combustion engine	-	Hydrogen utilisation
1993-1997	Solar Village	Solar collectors development	-	Domestic, industrial, agricultural
1993-2000	Solar Village	Fuel cell development	100 – 1000 W	Hydrogen utilisation
1994-1999	Sadous Village	PV water desalination	0.6 m^3	PV/RO interface per hour
1994-2000	12 stations	Solar radiation measurement	-	Saudi solar atlas
1994-2000	5 stations	Wind energy measurement	-	Saudi solar atlas
1996	Southern regions of KSA	PV system	4 kW	AC/DC electricity for remote areas
1996	Muzahmia	PV in agriculture	4 kWp	AC/DC grid connected
1996-1997	Solar Village	Solar-thermal desalination	-	Solar distillation of brackish water
1996-1998	Solar Village	PV system	6 kW	PV grid connection
1999-2000	Solar Village	Solar refrigeration	-	Desert application

As an outcome of the previous effort in establishing the twelve stations recording solar parameters, KACARE published an atlas in December 2013 documenting the renewable resources available in KSA, as a contribution to the country’s sustainable energy aspirations. The Atlas combined the datasets of solar and wind measurements with satellite-generated model data, and targeted a user-base of interested parties, including researchers, developers, policy-makers, and government bodies. Currently, KACARE is compiling a unique dataset on the solar resource in KSA from a network of 35 measuring stations (Figure 3.2), increasing to 50 by late 2015. In addition, those stations established in 2013 and 2014 are also engaged in determining resource variability in spectral, spatial, and temporal terms, as well as the effect of aerosols. In conclusion, the solar energy potential of KSA is quite substantial, as evidenced by regional satellite mapping and ground station data (Atlas, 2015).

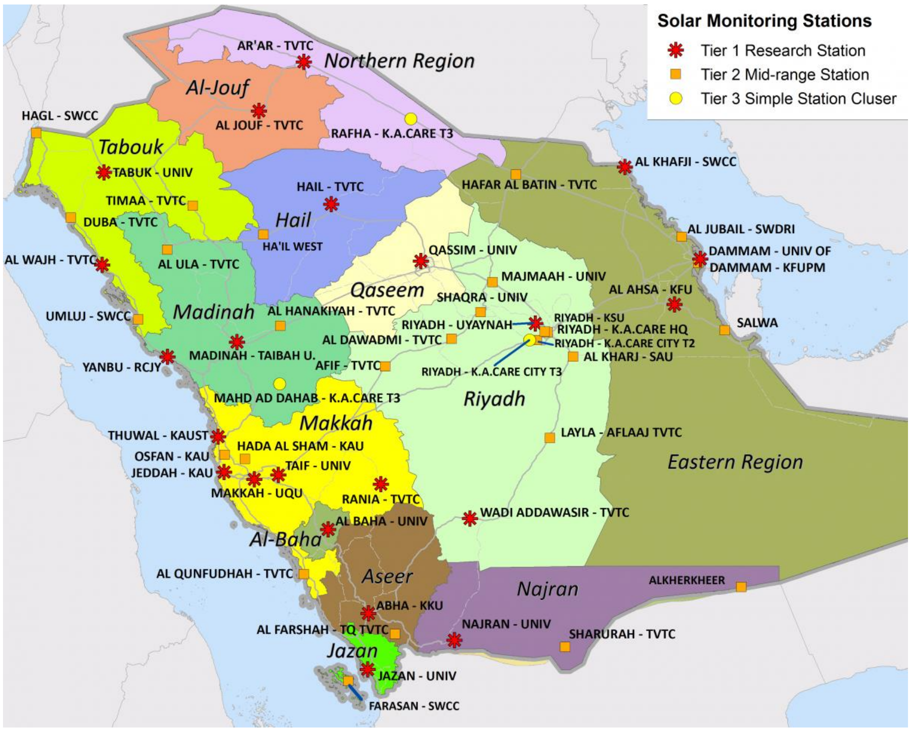


Figure 3.2: Solar and wind resource monitoring stations (Atlas, 2015)

On the basis of the data available, the sites for the CSP stations to be researched in this work were selected. Section 3.4 below presents the justifications for the selection of sites and technologies for the two power stations.

3.4. Locations of Proposed CSP Plants

Annual average solar radiation in the Arabian Peninsula is about 2200 kWh/m^2, which makes it one of the most promising renewable energy resources (Hepbasli and Alsuhaibani, 2011).

A network of 12 stations was established across KSA to monitor solar parameters such as Global Horizontal Irradiation (GHI) and Direct Normal Irradiation (DNI). These stations are located at Abha, Al-Ahsa, Gizan, Qassim, Jeddah, Madinah, Qaisumah, Sharurah, Jouf, Solar Village, Tabouk and Wadi Aldawasir, which is the first case study in this research. Locations of the proposed stations are presented in Figure 3.3. Shuaibah, which is the second case study in this research, is also shown in the same figure.

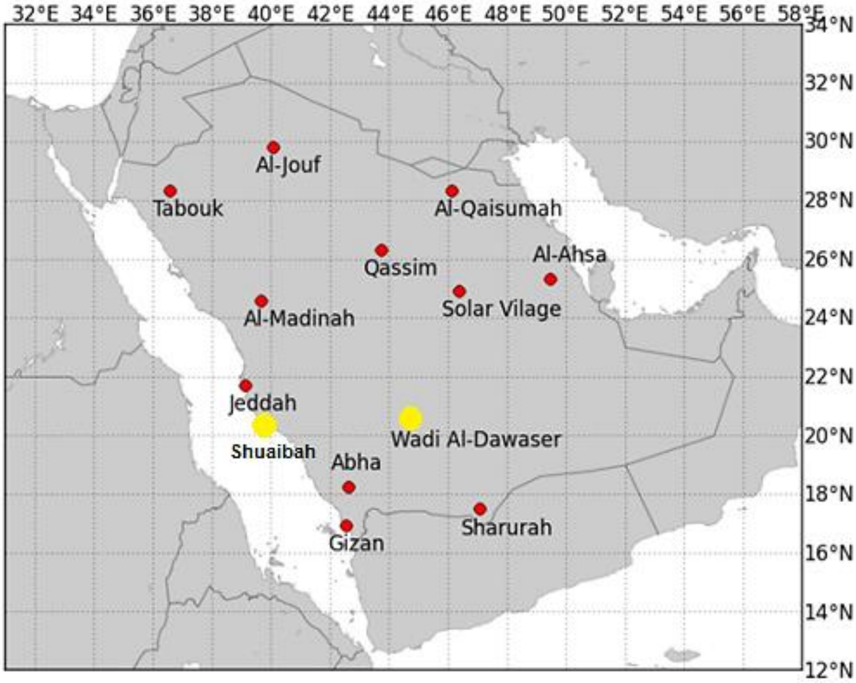


Figure 3.3: KACST/NREL network of meteorological stations providing GHI and DNI measurements in KSA (SolarGIS, 2013)

Table 3.6 presents a summary of the long-term mean values for the global solar radiation incident on a horizontal surface, and daily duration of sunshine. Across the locations of 35 solar monitoring stations in KSA, the mean daily duration of sunshine is 8.89 hours, equivalent to 3245 hours of sunshine annually, while average global solar radiation incident on horizontal surfaces is 5591 Wh/m². The maximum and minimum global solar radiation values across KSA were recorded in Bisha (2.56 MWh/m^2/yr) and Tabuk (1.63 MWh/m^2/yr), respectively (Sahin and Rehman, 2012). This is expected given the geographical distribution of solar radiation values in Table 3.3. Moreover, the site of the proposed CSP plant at Wadi Aldawasir is in the area of high solar radiation close to Bisha, and Al-Sulayyil in the southern extents of KSA. On the other hand, lower solar radiation values are recorded in the northern areas of KSA, such as Hail, Sakaka, and Tabarjal. According to Table 3.3, the minimum sunshine daily duration is 7.4 hours at An-Numas (Latitude = 19.10, Longitude 42.15, and Altitude = 2600 meters above mean sea level). On the other hand, the maximum sunshine daily duration is 9.4 hours at Hail (Latitude = 27.47, Longitude 41.63, and Altitude = 1010 meters above mean sea level). While these data provide concrete conclusions regarding the geographical distribution of the solar resource, it is recognised that KSA in its entirety lies within the so-called solar belt (defined between 40˚N and 40˚S latitude), explaining its overall favourable solar regime (Sahin and Rehman, 2012).

Table 3.6: Long-term daily mean values of sunshine duration and global solar energy

Station#	City	Lat (deg.)	Lon (deg.)	Alt (m)	S (h)	H (MWh/m^2yr)
1	Qurayyat	31.33	37.35	2	9.0	2.03
2	Tabarjal	30.52	38.38	3	9.0	1.72
3	Tabuk	28.38	36.58	773	9.1	1.64
4	Tayma	27.63	38.48	820	9.2	2.04
5	Hail	27.47	41.63	1010	9.4	1.91
6	Al-Ula	26.62	37.85	681	9.1	2.12
7	Qatif	26.55	50.00	8	8.4	1.73
8	Zilfi	26.30	44.80	605	8.9	2.04
9	Unayzah	26.07	43.98	724	9.3	2.00
10	Uqtalas-Suqur	25.83	42.18	740	9.1	2.23
11	Hutatsudair	25.53	45.62	665	9.0	2.15
12	Al-Hofuf	25.50	49.57	160	8.7	2.07
13	Shaqra	25.25	45.25	730	9.2	2.21
14	Hanakiya	24.85	40.50	840	9.1	2.21
15	Riyadh	24.57	46.72	564	9.2	1.87
16	Madina	24.52	39.58	590	9.1	2.32
17	Dawdami	24.48	44.37	0	8.8	2.17
18	Derab	24.42	46.57	0	8.7	2.26
19	Al-Kharj	24.17	47.40	430	9.1	2.03
20	Yabrin	23.32	48.95	200	9.1	2.06
21	Al-Aflat	22.28	46.73	539	9.0	2.19
22	Khulays nearby Jeddah	22.13	39.43	60	8.9	2.18
23	Sayl Kabir	21.62	40.42	1230	8.9	2.46
24	Turbah	21.40	40.45	1130	9.0	2.09
25	Taif	21.23	40.35	1530	8.9	1.98
26	Sulayyil nearby Wadi Aldawasir	20.47	45.57	600	9.0	2.40
27	Bisha	20.02	42.60	1020	9.2	2.56
28	Juarshy	19.85	41.57	2040	8.5	1.98
29	Modaylif	19.53	41.05	53	8.5	2.32
30	Al-Numas	19.10	42.15	2600	7.4	2.21
31	Kwash	19.00	41.88	350	8.5	1.70
32	Kiyad	18.73	41.40	30	8.4	1.87
33	Sirr-Lasan	18.25	42.60	2100	8.7	1.84
34	Abha	18.22	42.48	2200	8.7	2.13
35	Najran	17.55	44.23	1250	9.1	2.53

This quick presentation of past projects in the field of solar energy, as well as the project sites and locations of weather and solar radiation measurement stations, as mentioned in the previous section 3.3, pave the way to presenting the reasons for selecting the solar power stations proposed in this research.

The reasons for selecting Wadi Aldawasir as the site for a solar power station using parabolic trough technology, alongside an operational oil fired power station are as follows:

i. The city is situated in a desert climate and environment representative of the desert conditions prevailing in vast expanses of KSA, including the capital, Riyadh, hosting the largest population concentration in KSA, and as such, the highest energy consumption of all cities in KSA.
ii. The site contains a measurement station recording solar radiation and weather data, as was mentioned previously in Section 3.3, which provides precise readings for the most important design tool input, solar radiation.
iii. The current power station at the site produces electricity distributed in an isolated network that is not connected to the National Grid. This contributes to more effective readings and evaluation of the design.
iv. The site is close to the location of Al-Sulayyil by about 20 km, as mentioned previously in Table 3.2, which is distinguished by specifications suitable for solar power stations, due to registering the highest levels of solar radiation in KSA. It also lies on almost the same latitude of Bisha, which is also close, and has recorded high levels of solar radiation.
v. The availability of extensive and flat terrain, owned by SEC, which allows positive impacts on the two designs, in both technological and financial terms.
vi. The existence of infrastructure at the site, such as the substation, which will impact positivity on the feasibility and economic studies.

The reasons for selecting the Shuaibah site to establish a solar power station using power tower technology alongside a currently operational fossil fuel power station are as follows:

i. The site represents a second type of environment prevailing in KSA, namely the coastal environment. It is also situated close to Jeddah, the second largest city in terms of population, with medium energy consumption.

ii. It is located close to an industrial zone dedicated to electricity production and water desalination, which is the largest worldwide. This makes it an attractive location to implement the technology, and achieve good financial returns from the design.
iii. The availability of large flat expanses of terrain, owned by SEC, which reflects positively on the design in its detailed aspects.
iv. The current power station and proposed CSP plant serve the public National Grid.
v. The existence of huge and strong infrastructure at the site, including the substation, which will impact positivity on the feasibility and economic studies of the Shuaibah case study.

Both parabolic trough and power tower technologies were selected for Wadi Aldawasir and Shuaibah, respectively. These are solar thermal CSP technologies characterised by high efficiencies compared to other solar technologies. In addition, these technologies have been implemented in other locations worldwide, which generally record lower solar radiation values than KSA. Some of the strengths of these technologies were previously mentioned in *Chapter 2* of this thesis. These have been taken into consideration in deciding the type of technology used in both sites.

One of the most prominent reasons underlying the use of CSP technologies at both sites is the absence of any solar power station using parabolic trough or a power tower technologies in KSA, as was apparent from the presentation of solar projects in Section 3.3.

3.5. Software Selection for Large Scale Solar Power Generation Feasibility Study

Increasingly, examining or improving systems performance is achieved using modelling and simulation tools. Indeed, simulation is a key tool in technological progress in this domain, where substantial advances has been secured in approaches and software. Hence, research and analysis in systems and operations has witnessed wide use of such tools, with a large variety of offerings on the market with accessible pricing, and expanded language support. This has also encouraged appearance of highly specialised simulation packages focused on specific tasks. Among many others, the twelve key simulation software packages in wide use in the solar energy domain are: ESP-r 11.5, HOMER, INSEL, PV DesignPro-G, PV F-Chart, PV*SOL Expert, PVSYST 4.33, RETScreen, SAM, SolarDesignTool, SolarPro, and TRNSYS.

The feasibility study for large scale solar power generation involves selection of the appropriate software tools. There are many software modelling and analysis tools for solar projects. Some are used for small scale solar applications, while others are used for large solar scale projects. Freely available building and renewable energy software tools recognised by the US Department of Energy are shown in Table 3.7. A complete list can be found in (Tech, 2015).

Table 3.7: List of solar applications software tools

Software Name	Developer	Applications
SAM	NREL, USA	SAM, renewable power systems design and project planning
RETScreen	Natural Resources Canada	Renewable energy systems
HOMER	NREL, USA	Remote power, distributed generation, optimisation, off-grid, grid-connected, stand-alone
TRNSYS	University of Wisconsin, USA	Solar systems
SolarPro	Laplace Systems Co, Japan	PV systems
INSEL	Insel Company, Germany	Renewable Energy systems
TOP Energy	GFaI e.V., Germany	Simulation and optimisation of energy systems, energy efficiency
SUNDI	Institute of Electrical Energy Technology, Germany	Solar systems, solar irradiance, solar patterns and solar shading
HelioScope*	Falsom labs, USA	PV system design
Roanakh	Solar Living Institute, USA	PV system design

HOMER, RETScreen, and SAM are widely used for simulation and design of solar technology projects. RETScreen and SAM have been selected for this project for multiple reasons.

i. Free software, and accessibility
ii. Detailed performance model
iii. Database available for input of required parameters
iv. Close relevance to solar energy technologies
v. User-friendly interface for input, simulation and output

SAM and RETScreen are used for assessment of the case studies that are presented in subsequent chapters.

3.6. Modelling of Thermal Solar Systems

Parabolic trough and solar tower systems are the most efficient and widely-used types of solar collector design in CSP technologies. The most important step in the feasibility and economic evaluation of CSP plants is solar radiation assessment. Calculations of long term data provides information about availability of solar energy for the specific area. In this work, major solar energy factors are assessed using:

- SAM
- RETScreen

The subsequent sections provide more details about these two software applications.

3.6.1. Solar Advisor Model (SAM) Software

3.6.1.1. Overview

SAM is a freely distributed, general purpose solar systems performance and economic simulation software application, which uses the TRNSYS engine. It was developed jointly by the US Department of Energy and NREL. SAM is capable of handling a variety of solar systems, including generic fuel, PV, CSP, solar hot water, etc. using performance and economic models, and associated assumptions, generating hourly results as appropriate (Wagner and Gilman, 2011). Using SAM, parameters relating to sizing, costing, and other financial and system elements may be varied, where the effects can be gauged from the generated results, including energy/power output, mean, maximum, and minimum efficiency, levelised electricity cost, and importantly, costs of infrastructure, operation, and maintenance (NREL, 2013). SAM was designed principally to assist decision-making in solar energy projects, and as such, contributes to assigning priorities and guiding projects, as well as providing a priori information on the level of investment, both for execution and follow-on, in research and development. SAM is considered most appropriate for use alongside benchmark studies of cost and technology, as well as examination of market penetration. The software treats those issues of interest to engineers, managers, researchers, and both technology and incentives policy developers, and applies Solar Energy Technologies Program (SETP) technology in a systems-driven approach (SDA). The latter marries the advances realised through R&D with market needs to identify how such improvements may contribute to performance and costs. Furthermore, SDA can assist in the efficient distribution of resources. SAM facilitates the examination of different modes of financing, and employs cost models specific to each renewable energy technology. SAM currently integrates SETP technologies, such as flat panel and concentrating PV, and CSP dish/Stirling, parabolic trough, and tower systems. The levelised electricity cost is determined from the total direct and indirect costs (Lalwani and Singh, 2010).

A number of high-level models are deployed within SAM as integrated systems to account for thermal storage systems, and also heat losses in piping networks. SAM's component models may be built on sets of empirical correlations, analytical functions, or descriptive factors for the underlying physical processes (Ho, 2008). However, SAM does not include explicit spatial and temporal process models for the subsystem component levels. In terms of economic and performance models, these are based on the NREL-developed EXCELERGY model. Therefore, SAM is able to provide a holistic set of outputs, namely predicted energy produced along with cost, and cash flow data. As it is MS/Excel-based, SAM may exchange data with other MS/Excel-based models, enabling useful extensions.

The method followed for modelling the two case studies using SAM is shown in figure 3.4. Sections on the SAM analysis of each proposed CSP plant are given in Chapters 4 and 5. The overall modelling steps follow the systematic procedure shown in the flowchart below.

The approach used in designing the two solar power stations with SAM followed the steps below:

i. Examination and analysis of the solar resource assessment of both sites using the software's tools, which provides the first basic design allowing further detailed design or the re-evaluation of solar radiation, and hence, choice of a different site with better solar radiation characteristics.
ii. The technologies to be used for the stations were selected based on the reasons mentioned previously. These were then chosen from the various technology options

provided by the software. In this case, these were parabolic trough and power tower technologies.

iii. The weather data file was verified and uploaded. This contained all the data related to design of solar power stations; for example, DNI, temperature, and wind speeds at the project site.

iv. Defining and inputting the technical and design information for the proposed plant. This section covers several sheets of the software. For example, sheets specific to solar fields or heliostats, collectors, or power block.

v. Inputting financial information related to the plant, comprising several aspects such as capital costings, and financial predictions relating to studies of the market environment in KSA, and the Saudi financial system.

vi. Working on a technical design, and selection of the optimal design of the plant in terms of sizing in terms of solar multiples (SM) or number of subsections, as well as the inclusion or otherwise of thermal storage. All these components and their sizes, and space they occupy impact on the financial analysis and cost of the plant, as well as the unit cost of electricity.

vii. Following investigation and designation of the optimal design, the results and analysis of this design are presented. This clarifies the technical and financial results of the project.

The results of the optimal design are discussed and compared to the existing fossil fuel power plant, along with the impact of the design on the energy sector generally.

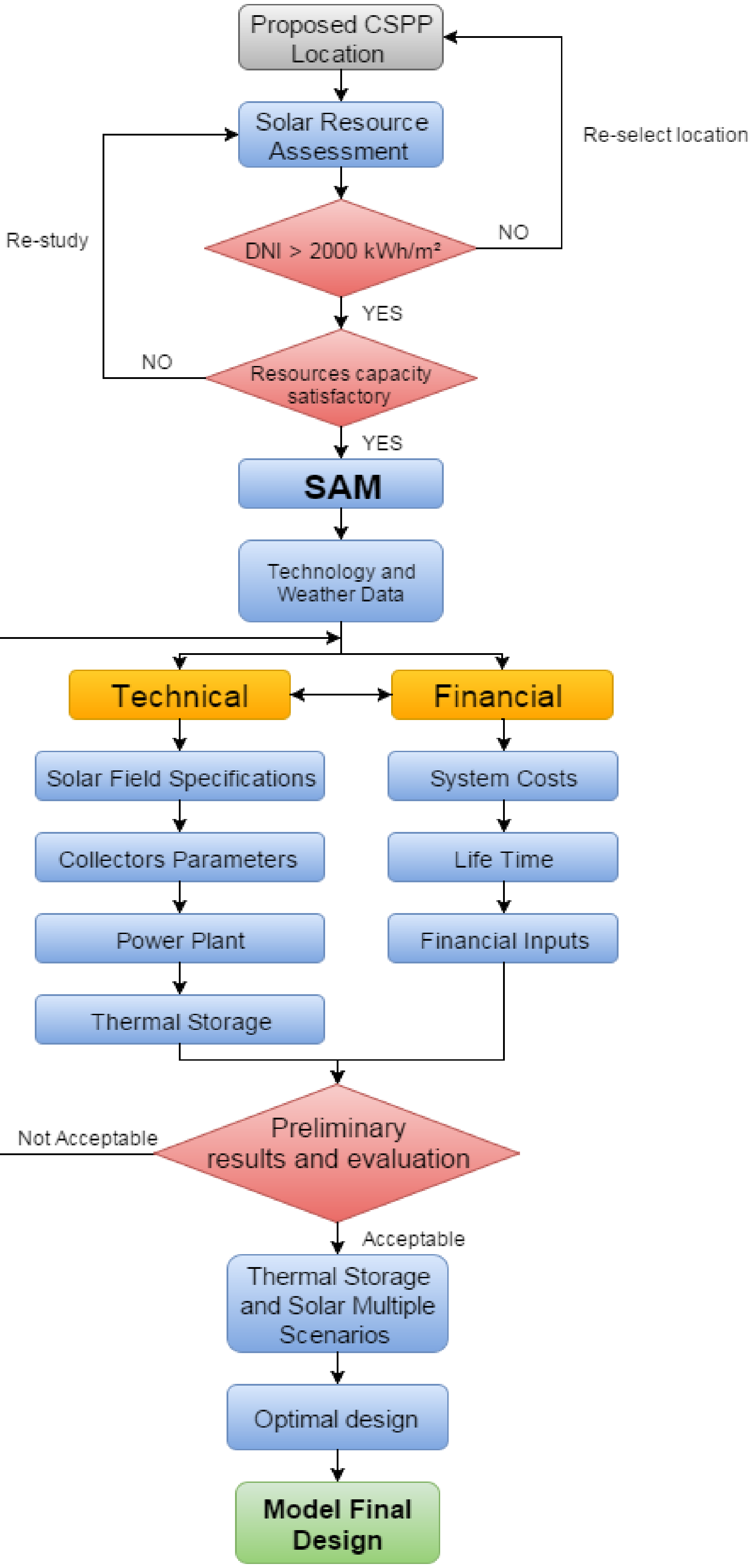


Figure 3.4: Flowchart describing modelling followed for the two case studies using SAM

3.6.1.2. Application

Following the presentation of data in the previous section about SAM, it is important to mention that the software contains a number of pre-defined technologies that the user may select, in order to initiate the design process.

A new project is started by choosing one of the following performance models:

- Photovoltaic (detailed)
- Wind
- CSP parabolic trough (empirical)
- CSP linear Fresnel molten salt
- Generic system
- CSP generic model
- CSP linear Fresnel direct stream
- CSP power tower direct stream
- Photovoltaic (PVWatts)
- Solar water heating
- Biomass combustion
- High concentration PV
- Geothermal
- CSP tower molten salt
- CSP parabolic trough (physical)
- CSP dish Stirling

Each of these performance models are provided with application specific sub-models. A generic system, for instance, can be modelled as: Residential (distributed), Commercial (distributed), PPA single owner (utility), PPA partnership flip with debt (utility), PPA partnership flip without debt (utility), PPA sale leaseback (utility) and No financial model. A CSP generic model can similarly be modelled through the same category sub-models, with the first option – Residential (distributed), being removed. Once a model is selected, a main window similar to the one shown in Figure 3.5 is accessed. Navigation menu input items include Location and Resource, Solar Field, Power Block, Thermal Storage, System Costs, Degradation, Financial Parameters, Incentives, Electricity rates, and Electric Load. Once the required location is chosen, data for the rest of the menu items are loaded by default, and may be edited if required. Location details for sites in the KSA are not provided by default, so the user will either have to input all data or import a suitable data file from the SAM library. The model can be simulated in terms of Parametrics, Stochastic, P50/P90 and Macros that are available in the simulation menu. Once simulated, output is obtained in graphical as well as specific data form, either as single values, monthly data, 25 values data, annual data or hourly data. A results summary typically looks like the one shown in Figure 3.6. Output also provides essential information on cash flow and utilises hourly data to present a daily plot of hourly energy, time series, profiles, heat map and statistics. A report is then generated to present all relevant results in a properly formatted and summarised PDF file, showing plots for monthly energy and project cash flow.

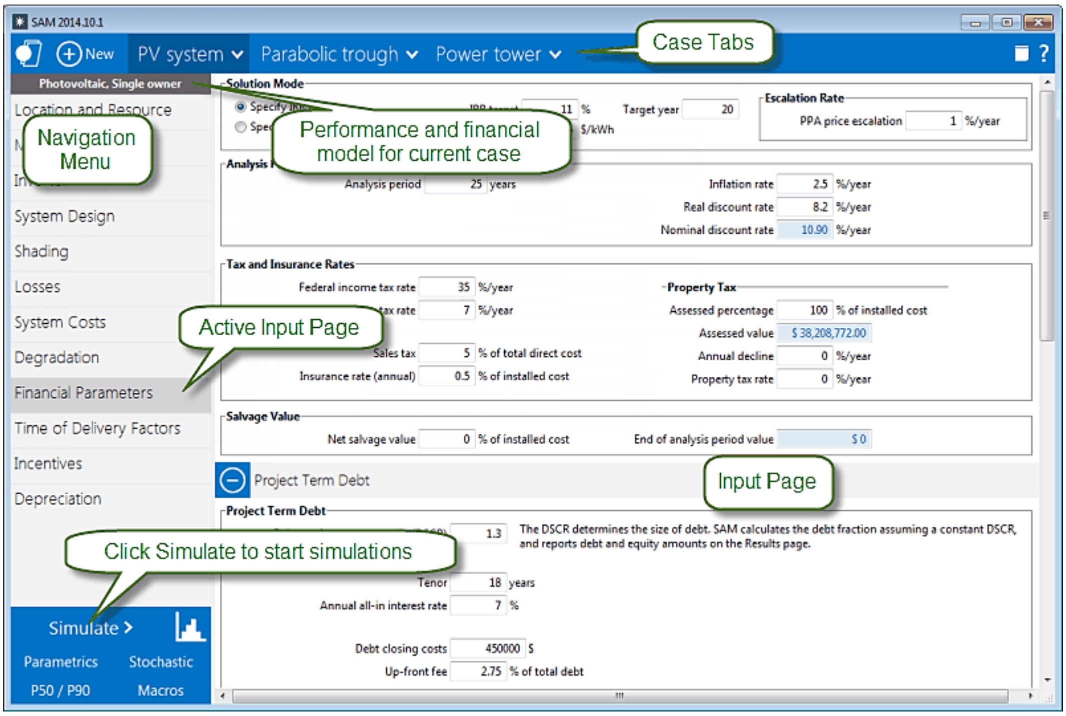


Figure 3.5: User Interface for SAM software

A more generic and useful approach to using SAM involves reviewing an existing analysis. This is done through the following steps (Gilman et al., 2008):

i. Opening the file with the analysis information
ii. Saving a copy of the file for reviewing
iii. Reviewing graphs and tables on the results summary page
iv. Reviewing input variables of interest in the input pages

On the other hand, a new analysis is created when the new project is analysed, which involves following steps:

i. Opening an existing file from a previous analysis
ii. Reviewing the input pages and suitably modifying the variables.
iii. Running the model and viewing results. Custom graphs are often created for meaningful display of results.
iv. Inputs are refined, and steps 1 to 3 are repeated until satisfactory results are obtained.

Advanced analysis options are also provided, and are based on the user's expertise in handling SAM's tools. Parametric variables can be defined for sensitivity analyses, while external spreadsheets can be linked for detailed analyses. Figure 3.6 presents the results of estimated electricity generation and annual cash flow for a PV system for illustrative purposes (Blair et al., 2014).

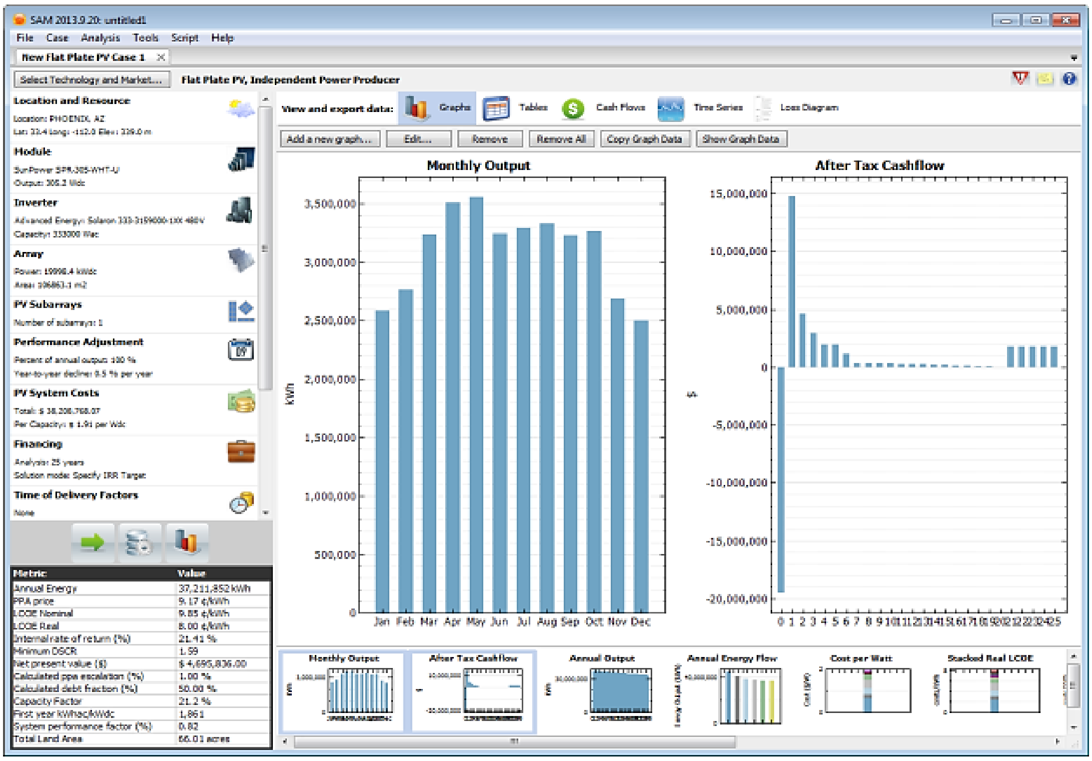


Figure 3.6: Main window for SAM showing results for a PV system

The user interface shown in Figure 3.5 is one of the model structure aspects of SAM, besides the calculation engine and programming interface. The user interface allows the user to input values to variables, while defining simulation control variables and running simulations. Results obtained are in the form of tables and graphs that are accessed through the user interface, which inherently performs three basic functions, presented as follows:

i. Providing access to input variables, which are otherwise predefined with default values.

ii. Allowing control over running simulations in SAM, particularly for optimisation problems and sensitivity analysis.

iii. Providing access to output variables in tables and graphs on results page and export files to other spreadsheet applications.

The SAM calculation engine, which is called the SAM Simulation Core (SSC), and programming interface enable interaction with external programs allowing use of modules from the SSC library in Windows/OS X/ Linux while writing codes with C++, C#, Java, Python, or MATLAB (Blair et al., 2014). Analyses are performed to study weather, performance, financial parameters, cost and governing model results. Four analysis options are provided in SAM, namely parametric, sensitivity, statistical and probability of exceedance (P50/P90). Models developed in Microsoft Excel or TRNSYS simulation platform can be analysed with SAM. They can be enabled through its scripting language, SamUL.

A set of case studies provided by NREL show how data may be acquired, and the SAM file generated containing explicit inputs, as well as how results may be analysed. These techniques were taken into consideration when simulating Wadi Aldawasir and Shuaibah CSP plants. Data relies on many input data used in simulations done by NREL for the current CSP plant Andasol-1 in Spain, for which simulation results differ from the real result of the plant by 2.6%. The NREL case studies included the Spanish Gemasolar solar power tower electricity-generating plant. This is the first commercial plant worldwide with a central tower receiver and heat storage using molten salt. By reviewing the SAM simulation results and plant real data, it was found that simulation results differ from the real plant data by 4.1% at most. Therefore, some inputs will be used when simulating subject case studies.

3.6.2. RETScreen Software

3.6.2.1. Background

RETScreen, short for Renewable Energy Technologies Screen, is a popular, freely distributed, software dedicated to clean energy management, and applicable worldwide. It was developed by a collaboration of Canadian industry, academia and the government. RETScreen was designed to facilitate the evaluation of RETs, and energy-efficient technologies (EETs), in terms of energy production, energy savings, economic viability, and costs, as well as reductions in GHG emissions, and managing project risks. The software assists stakeholders, including policy-level decision makers, financial planners, and system engineers and architects, to model and analyse RET, EET, and cogeneration projects. Based on a series of MS/Excel spreadsheets, RETScreen employs a five-step standard analysis toolkit, covering analyses of energy production, life cycle costs, GHG emissions, financial performance, and sensitivity/risk (Lalwani and Singh, 2010). Fundamentally, RETScreen enables sound decision-making regarding the financial feasibility of RET, EET, or cogeneration projects (Thevenard et al., 2000, NRCAN, 2012).

3.6.2.2. Objectives

RETScreen software development objectives have been set by the RETScreen International Clean Energy Decision Support Centre. The objectives include building the capacity of decision-making entities, planners, and industries for implementing renewable energy, cogeneration and energy efficiency projects (Tansi, 2012). The software helps minimise feasibility study costs prior to application. It also helps with the decision-making process through proper knowledge dissemination. It also helps users on refined analyses of technical and financial viability. The most important objective is to cut down reliance on conventional energy sources, while increasing market utilisation of RETs. The software developers applied three primary strategies to attain the set objectives. These consisted of developing enabling tools, knowledge transfer, and providing project implementation. Enabling tools reduce time and cost required for the analysis, which thereby leads to increased implementation of RET projects.

RETScreen offers a range of different models to address different RETs such as CSP, wind energy, small hydro, PV systems, combined heat and power (CHP), biomass heating, solar air heating, solar water heating, passive solar heating, ground-source heat pumps, and energy efficiency (Leng, 2005). Various projects and reports are testament to the success of RETScreen International Clean Energy Decision Support Centre in meeting its objectives. A summary of the results and impacts of this software in terms of user savings, installed capacity, installed value and reduction in emission of GHGs is presented in Table 3.8.

Table 3.8: Results and Impacts of RETScreen® on an international level (Leng, 2005)

Performance Indicators	Present Impact (1998-2004)		Future Impact (1998-2012)	
	Canada	World	Canada	World
User Savings	\$240 mn	\$600 mn	\$1.8 bn	\$7.9 bn
Installed Capacity	320 MW	1,000 MW	4.9 GW	24 GW
Installed Value	\$ 750 mn	\$ 1,800 mn	\$10 bn	\$41 bn
GHG Reduction	130 kT CO_2/yr	630 kT CO_2/yr	3.6 MT CO_2/yr	20 MT CO_2/yr

RETScreen's top priorities are addressing high energy costs, global warming issues, climate change control and sustainable living. RETScreen's main activities aimed to:

i. Establish an extensive database of verified global input parameters to suit any project.
ii. Develop and integrate a datamining expert system that leverages the abovementioned database to fit the user's project needs.
iii. Expand the climate data within RETScreen to include more locations, and so enhance its utility.
iv. Link sources of data, whether climate- or renewable resource-related, to the software. This includes feeding quasi-real-time data into the software from the NASA weather monitoring satellite network.
v. Integrate the abovementioned activities into a system offering a Smart Project Identifier, a Virtual Energy Analyser, project lifecycle Performance Tracker, and Financial Risk Assessor.
vi. Develop effective training aids and learning materials.

The abovementioned activities resulted in:

i. Appreciable reductions in the cost, time, and effort spent on identifying and evaluating potential areas for investment in clean energy.
ii. An estimated \$20 billion or more in savings secured by late 2022.
iii. The software being employed in a net worth of nearly \$100 billion of capital project investment.

iv. Reductions of over 50 MT CO_2/year in GHG emissions.

v. Substantial improvements in energy security, economic development globally, and GHG and pollutant emissions levels.

RETScreen may be run on any computer with MS/Windows XP or later, MS/NET Framework 4 or later, and MS/Excel 2003 or later, whether a physical PC or as a virtual machine with the previous specifications running as a guest on Apple or Linux host systems. Moreover, a Windows-based version named RETScreen Plus runs without MS/Excel.

3.6.2.3. Application

RETScreen software has been considered for the current analysis due to its rapid feasibility study creation. Moreover, RETScreen is more user-friendly than HOMER and other software mentioned in section 3.5, and is more technically equipped (Tansi, 2012). RETScreen can be used to access a database of global climate, fed by data from NASA satellites and ground measurements. Relevant data thereby allows analyses of all RET projects around the world. This can be done through 35 different languages that are built-in within the database. The equipment database comprises manufactured components. Training materials are widely available for independent study, university courses or general training courses. Webcasts, case studies, instructor notes, are user manuals are also available (OpenEI, 2011).

The application has been developed by NRCAN's CanmetENERGY core team, which is also the leader and primary funding source for RETScreen International. A wide expert network is involved in the application database technical support. The software involves analysis for parameters, as provided in Figure 3.7.

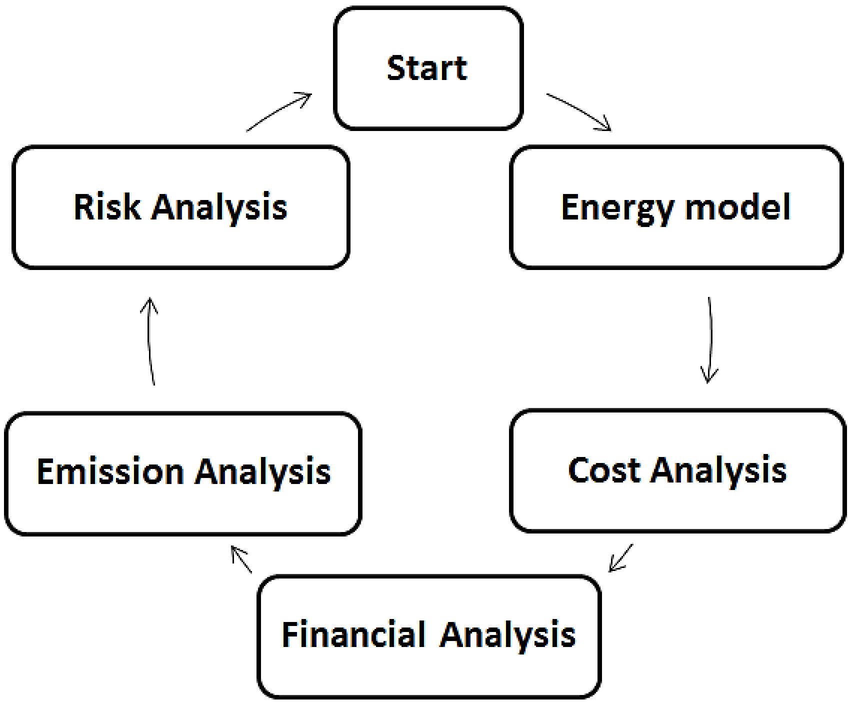


Figure 3.7: Components of RETScreen analysis

RETScreen software helps determine load and design energy efficiency measures and sources of renewable energy. The reasons for using RETScreen for energy modelling are:

i. It can be utilised to determine the applied load.
ii. The virtual system can be modified and built quickly.
iii. Components can be swapped out for performance comparison.
iv. System size can be varied quickly to meet the goal of energy offset.
v. Reports can be created showing reduced pollution, financial and energy savings.

Five steps must be followed for standard analysis of the renewable energy project. These steps are:

i. Site selection and site conditions.
ii. Modelling the energy.
iii. Analyse the cost.
iv. Analyse the emissions.
v. Analyse the financials.
vi. Risk and sensitivity analyses.

The method followed in modelling the two case studies using RETScreen is shown in figure 3.8. Sections presenting the results of the RETScreen analysis will be presented in Chapters 4 and 5. The modelling steps involved the systematic procedure shown in the flowchart below.

After using SAM in describing the proposed CSP station, and providing the technical and financial results of the design, RETScreen will be used, to provide additional analysis of the CSP station design. This software facilitates environmental and risk analysis, which is not included in SAM.

In brief, the steps taken in using RETScreen involve inputting design and financial data in each sheet of the software. In turn, results are returned on the same sheet. The design and results will be presented and discussed for each CSP station in Chapters 4 and 5, respectively. In relation to the risk analysis, this will be discussed for the two CSP stations in Chapter 6.

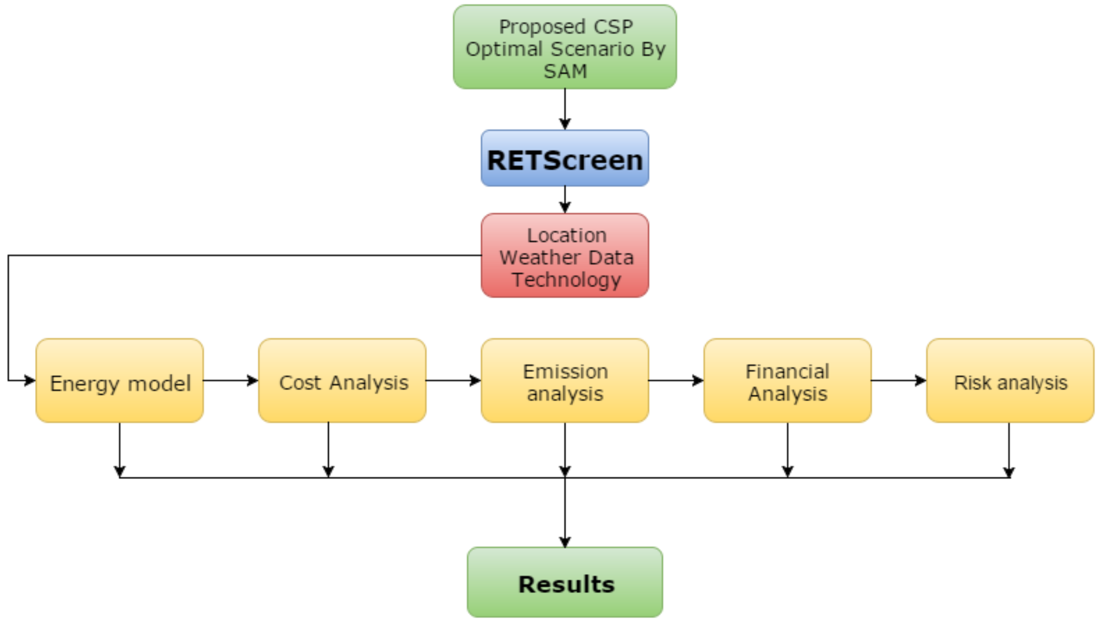


Figure 3.8: Flowchart describing modelling followed for the two case studies using RETScreen

The RETScreen interface is very user-friendly, with the input and output options organised in the form of spreadsheets. In order to start a project analysis, a general information section is used to input data, such as type of project, facility, analysis, climate, and site conditions. The RETScreen program may not provide accurate location, but gives the nearest one. If a location is determined, the climate variables can easily be extracted by the program. Figure 3.9 presents the start worksheet where this information is entered. Language, currency and unit settings are also set in this worksheet.

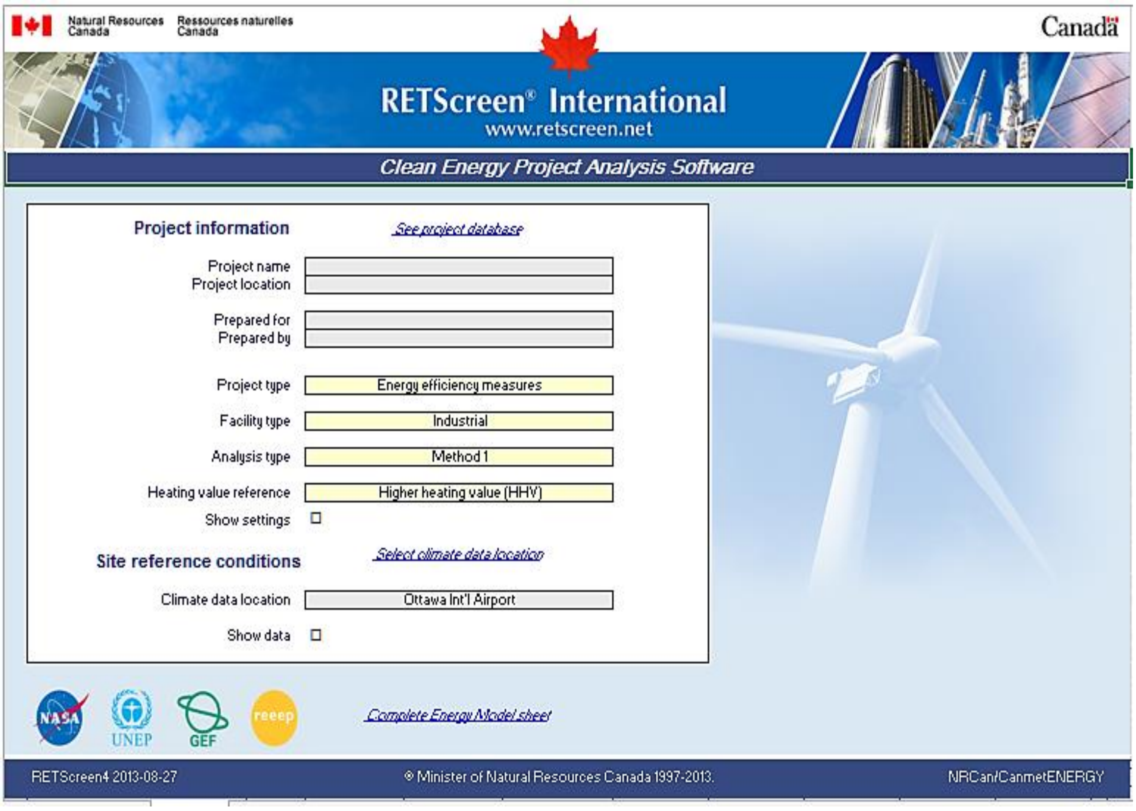


Figure 3.9: The Start Worksheet in RETScreen

A proposed system is evaluated using the Energy Model worksheet – as shown in Figure 3.10 for the purpose of illustration.

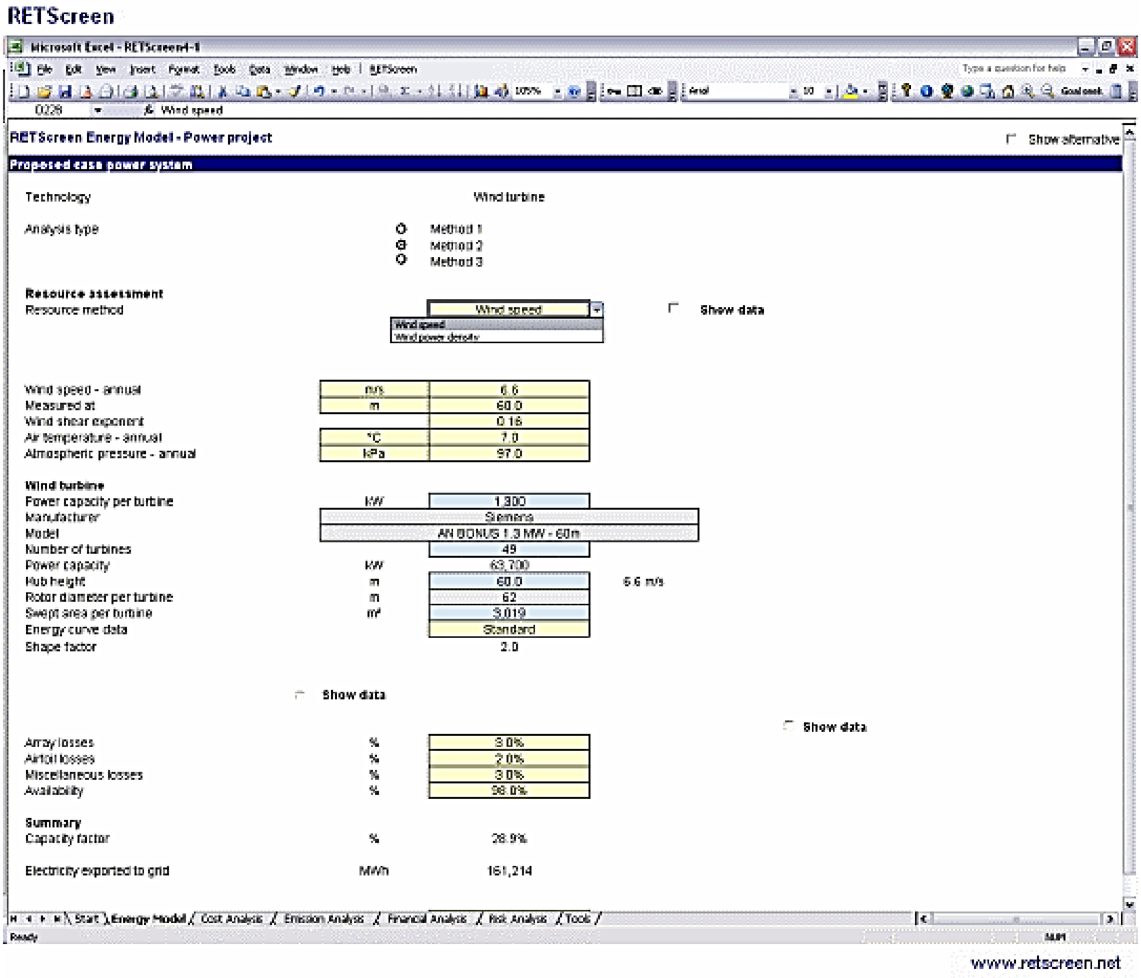


Figure 3.10: The Energy Model worksheet in RETScreen

The next step in the process is to find cost and credit estimates of the proposed system. They are generally presented either as an initial cost or an annual or recurring cost. The Cost Analysis worksheet is used for this purpose, as shown in Figure 3.11.

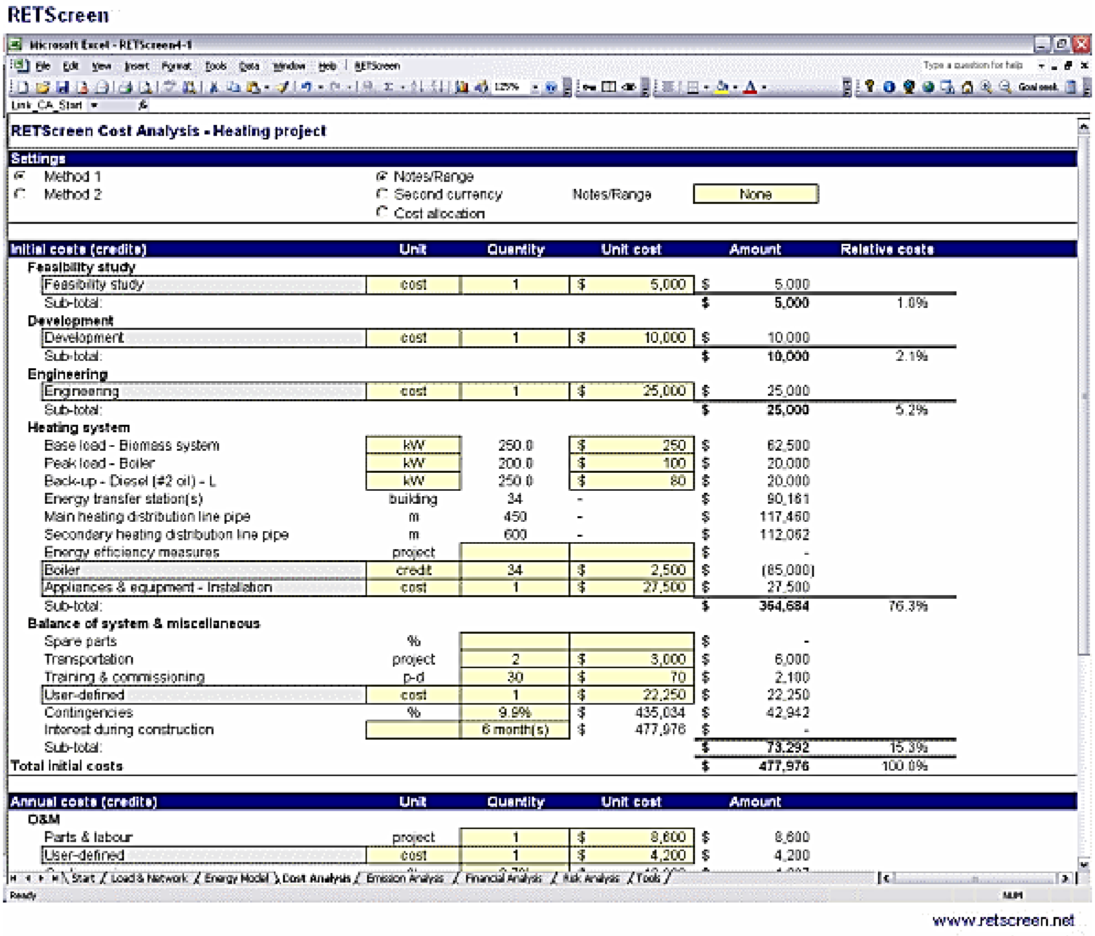


Figure 3.11: The Cost Analysis worksheet in RETScreen

The user can enter price-related and other information in this worksheet. Supplier contact information can also be selected from the RETScreen Product Database (NRCAN, 2014).

The following worksheet is the Emissions Reduction Analysis. It is used to calculate GHG emissions for the proposed system. Five main sections in the worksheet are:

i. Settings: Analysis type is specified along with global warming factors.
ii. Base Case Electricity System (Baseline): used as complementary to section number 3.
iii. Base Case system GHG summary (Baseline): GHG baseline information is described.
iv. Proposed case system GHG summary (Project): Emission profile is accessed.
v. GHG emissions reduction summary: Results from the previous four sections are summarised.

Annual carbon dioxide reduction is estimated as an output from this worksheet.

The financial analysis worksheet is used for the project's revenue flow. This analysis requires information organised in six different areas:

i. Financial parameters
ii. Financial viability
iii. Annual income
iv. Yearly cash flows
v. Project costs and savings/ income summary
vi. Cumulative cash flows graph

Financial input items include discount rate, debt ratio, equity etc. Output items are financial viability parameters calculated in the worksheet, such as Internal Rate of Return (IRR), Net Present Value (NPV), simple payback, etc. This information helps the user with the decision-making process, while considering the relative financial parameters (NRCAN, 2014).

The subsequent worksheet is the Sensitivity and Risk Analysis worksheet. This is used to assess the risk and sensitivity parameters for a particular project. The worksheet is arranged in two separate sections. The sensitivity analysis section involves estimating key financial indicators and their effect on the technical and financial parameters. A prerequisite for using the risk analysis section is statistics knowledge, since Monte Carlo simulation is performed to estimate the relationship between important parameters and financial indicators.

Different databases provided in RETScreen can be used for well-defined input values. The available database set in RETScreen is (OpenEI, 2011):

i. Product Data: database of existing renewable energy products
ii. Climate Data: database of meteorological information for the case model, with two optional sources that can be accessed from ground-based measuring stations and the NASA global satellite system.
iii. Hydrology Data: Database of hydrological information for Canada.
iv. Project Data: database of case studies and examples.
v. Energy Resource Maps: database of world data sets that are integrated into the RETScreen software.

3.7. Mathematical Background

Proper solar energy system design is possible only with proper knowledge of local solar radiation. Models used in software applications such as SAM and RETScreen are based on calculations that define key physical and financial parameters, which constitute the overall mathematical model. Some parameters are addressed in the following sub-sections.

3.7.1. Levelised Cost of Energy (LCOE)

The cost of the electricity produced from the solar thermal power plants is considered one of the most important metrics used in assessing the viability of a renewable power generation scheme. This is due to the fact that it is part of the financial assessment and feasibility (Hernández-Moro and Martínez-Duart, 2013). The is expressed as follows:

$$LCOE = \frac{\sum_{n=0}^{N} \frac{C_n}{(1+d)^n}}{\sum_{n=1}^{N} \frac{Q_n}{(1+d)^n}} \qquad (3.1)$$

Where C_n the cost of the plant in year n; Q_n *(kWh)* is the energy generated in year n; d is the discount rate; and N is the analysis period.

3.7.2. Solar Angle

Concentration of solar radiation changes on the earth surface due to the elliptical orbit of Earth around the Sun. The angle between the plane through the equator and sun-earth line is called the solar declination angle (Kreith and Krumdieck, 2013). It varies from -23.45 to +23.45^o and is calculated as:

$$\delta_s = 23.45 sin\left[\frac{360(284+n)}{365}\right] \qquad (3.2)$$

Where n is the number of the day with January 1st as the reference.

The Sun's position is described by two angles. The first is the solar altitude angle α and the other is the solar azimuth angle, α_s. The angle between the horizontal plane and collinear line with the Sun rays is called the solar altitude angle. The angle between the horizontal projection line of sight of the Sun and due south line is called the solar azimuth angle. The angle defined by the line of sight of the Sun and the vertical is called the solar zenith angle, z.

$$z = 90 - \alpha \tag{3.3}$$

Solar altitude and zenith angles are not fundamental, but their values are used to calculate fundamental angles like hour angle h_s, latitude L and declination angle δs. Solar hour angle is based on 24 hour time. The Sun needs this time to move 360^o around the Earth. It is expressed as :

$$\mathrm{h} = 15° \, (t_s - 12) \tag{3.4}$$

Where t_s is solar time and is given by:

$$t_s = \mathrm{t} + \mathrm{EOT} + (l_{st} - l_{local}) \, 4 \frac{\mathrm{min}}{\mathrm{degree}} \tag{3.5}$$

$$\mathrm{EOT} = 0.258 \cos \mathrm{x} - 7.416 \sin \mathrm{x} - 3.648 \cos 2\mathrm{x} - 9.228 \sin 2\mathrm{x} \tag{3.6}$$

$$x = \frac{360 \, (n-1)}{365.242} \tag{3.7}$$

3.7.3. Hourly Solar Radiation Models

Hourly data are used to predict the average daily global radiation. Solar radiation models are also used to evaluate beam and diffuse radiation. Extra-terrestrial solar radiation is the solar irradiation that is outside the Earth atmosphere. It is constant on a horizontal surface with a value of around 1350 W/m^2. It is also known as the solar constant I_o.

Solar irradiation at sea level horizontal surface can reach up to 1 kW/m^2. Solar irradiation can be modelled using basic formulations, which are not accurate due to the complex nature of various effects and processes within the Earth's atmosphere. Empirical formulations can be applied, such as the following equation for solar irradiation:

$$I = I_0 \left(\frac{D_o}{D}\right)^2 \tag{3.8}$$

$$\left(\frac{D_o}{D}\right)^2 = 1.00011 + 0.034221 \cos(\mathrm{x}) + 0.00128 \sin(\mathrm{x}) + 0.000719 \cos(2\mathrm{x}) + 0.000077 \sin(2\mathrm{x}) \tag{3.9}$$

For given monthly and daily date, hourly data for solar radiation can be calculated using simple formulas:

$$I_h = I_{b,h} + I_{d,h} \qquad (3.10)$$

$$I_h = I_{b,N} \cos z + I_{d,h} \qquad (3.11)$$

Beam radiation for hourly ratios is

$$I_{b,h} = r_t H_h - r_d D_h \qquad (3.12)$$

Beam radiation for aperture area is only needed for PT systems. The expression for beam radiation is:

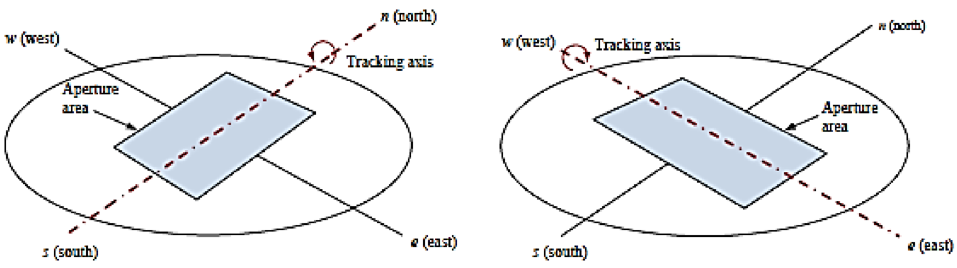
$$I_{b,c} = (r_t H_h - r_d D_h)\frac{cosi}{sin\alpha} \qquad (3.13)$$

Where r_t and r_d are horizontal hourly ratio and horizontal daily ratio, respectively.

H_h is the average daily total on horizontal surface

D_h diffuse irradiation on a horizontal surface.

Two different tracking models are used for optimal performance of PT collector. They are shown in Figure 3.12.



(a) East-West (North-South axis tracking) (b) North-South (East-West axis tracking)

Figure 3.12: Tracking mode for PTCs

3.7.4. Single Axis Solar Tracking

PTs are designed to track around one axis. Until Sun central ray and aperture normal area are coplanar, the tracking device keeps on rotating the collector on its axis. Figure 3.13 and Figure 3.14 show the rotation of collector around its axis.

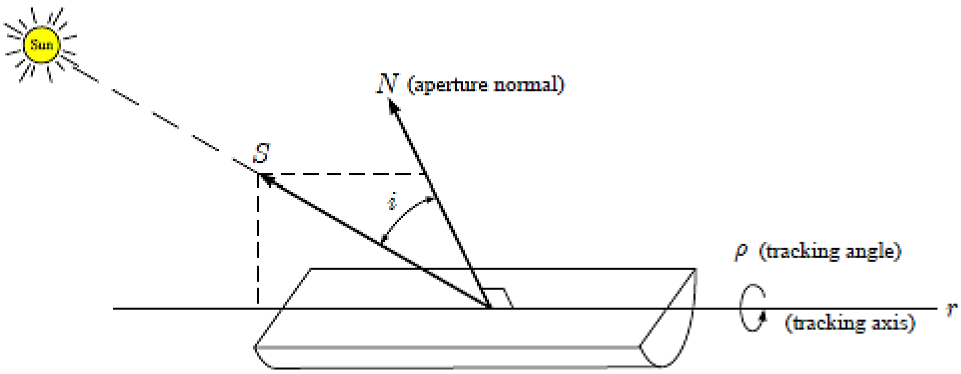


Figure 3.13: Single axis tracking aperture

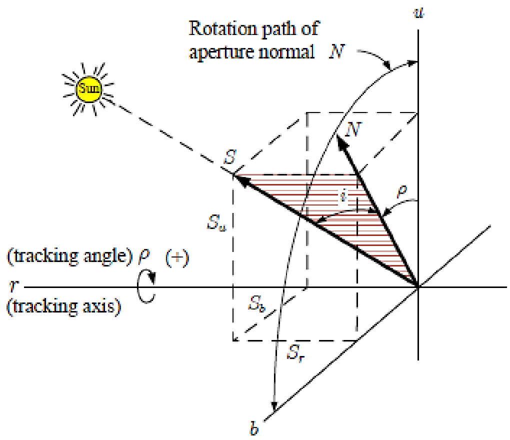


Figure 3.14: Single axis tracking system coordinates

Both i and p can be defined using vector S (central ray unit vector)

$$\tan(\rho) = -\frac{S_u}{S_b} \qquad (3.14)$$

$$\cos(i) = \sqrt{S_b^2 + S_u^2} \qquad (3.15)$$

3.8. Summary

A high level introduction to energy systems in KSA was given in the previous chapter. It identified several solar energy projects undertaken from 1981 to 2000 by ERI—the premier working body within KACST. ERI was involved in establishing a network of stations for solar radiation monitoring in KSA. This is an important part of the country’s aggressive investment aimed at securing a leading role in the renewable energy market. The Saudi Renewable Energy Atlas project and solar resource measurement stations were outlined. Among twelve established stations, two are considered for assessment, namely Wadi Aldawasir and Shuaibah. A proposed CSP plant in Wadi Aldawasir would be equipped with parabolic trough technology, while the one at Shuaibah would be equipped with a solar power tower. Analyses of performance for each are presented in Chapters 4 and 5, respectively. The analysis is based on observing the location details of the main geographical centres within the KSA, along with sunshine duration and hourly solar radiation on horizontal surfaces.

Focus is on modelling solar thermal systems, which is the technology selected. A short discussion on parabolic trough technology and solar tower was presented. Two software tools are used, namely SAM and RETScreen. These software tools were reviewed in terms of their background, modelling performance and application procedure. Both software tools are based on MS/Excel models for physical and financial processes in solar power technology. SAM was developed by NREL, and consists of integrated systems for piping heat losses and thermal storage, while cost and performance models are built-in. Models are run to produce hourly data for energy output, cost and cash flows. In total, 16 performance models are available in SAM. Each is composed of sub-models that define a specific application such is residential, commercial, PPA single ownership, of PPA partnership etc. A brief software introduction is also provided. RETScreen modelling and simulations were dedicated to evaluating energy costs, global warming issues, climate change control and sustainability. RETScreen was developed by NRCAN. It is operated though six main steps. They include climate data, energy modelling, cost analysis, emission analysis, financial analysis, and risk-sensitivity analysis. Definitions of several basic technical parameters like solar angle, hourly solar irradiation, and single axis tracking were presented.

The basis for selecting SAM and RETScreen software tools was addressed, while other software tools were listed. This chapter provided the insight necessary for a thorough assessment of the Wadi Aldawasir and Shuaibah CSP case studies, which are presented in subsequent chapters.

CHAPTER 4

WADI ALDAWASIR MINI-POWER GENERATION GRID

4.1. Introduction

This chapter presents a case study of parabolic trough solar thermal technology for power generation in Wadi Aldawasir, KSA. As a proven technology, which can provide an economically viable energy output, parabolic trough technology was chosen for this location. In addition, its thermal block may be combined with that of the existing Power plant (PP). It is thought that if thermal blocks of both existing PP and newly constructed Concentrating Solar Power Plant (CSPP) are combined, cost savings could be achieved. Finally, this parabolic trough technology can sustain high temperatures without affecting system performance. This is not the case with other solar technologies, such as PV, which would experience operational problems in the harsh desert environment.

In this chapter, information was gathered, including weather, technical and financial data, for the design and feasibility assessment, which needs to be completed before actual project implementation. The data is organised into two different groups, and used to assess project technical and financial feasibility. The information set focuses on analysing the location and its climate. Details of main CSPP components are also included. The second part of the chapter includes SAM and RETScreen software analysis that covers detailed data about climate, energy modelling, gas emissions, sustainability and risk analysis. A detailed description for these information categories is provided throughout this chapter.

4.2. Wadi Aldawasir

Wadi Aldawasir is a city located in the South-West (SW) of the central region of Riyadh province in KSA. The site of the proposed CSPP is located at 20 23' 22.00" N latitude and 45 12' 32.00" E longitude, as shown in Figure 4.1. The region extends over 48,900 km^2 and is home to around 107,783 people living in 19,803 buildings. The majority of population lives in the main town, while the rest live in the suburbs (CDSI, 2015).

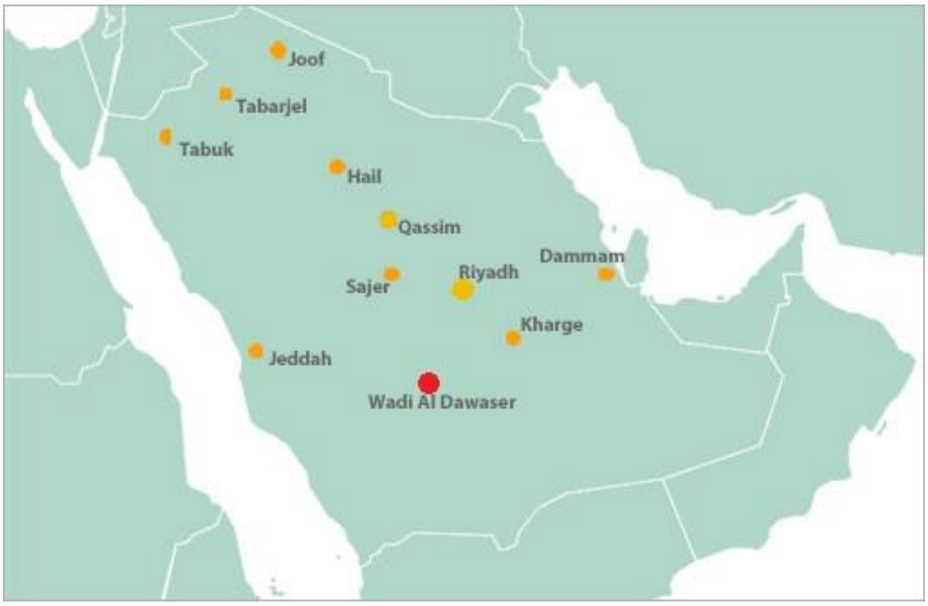


Figure 4.1: Location of Wadi Aldawasir

Power for Wadi Aldawasir region is delivered mainly by SEC through a local oil-fired PP, named Juba aerial image shown in Figure 4.2. In late 2012, Juba PP had a generation capacity of 270 MW. However, in 2013, an additional 130 MW was installed, raising generation capacity to 400 MW. The plant uses 13 steam turbine units, with average efficiency of 22.5%. The individual capacity of Units 1 to 7 is 20 MW, Units 8 and 9 generate 15 MW maximum each, Units 10 and 11 each have a capacity of 50 MW, while the last two newest units have a capacity of 65MW each. The plant annually uses 5,265,185 barrels of crude oil at a cost of 26.6 $\$/m^3$. Power generated in the power station is distributed to users through an isolated 132 kV grid network as this region is not connected to the national electricity grid as shown in figure 4.3.

Figure 4.2: Juba PP at Wadi Aldawasir

Region electricity interconnections are given in Figure 4.3. The Juba power plant provides electricity for around 17,890 buildings while the remaining buildings rely on private generators (CDSI, 2015).

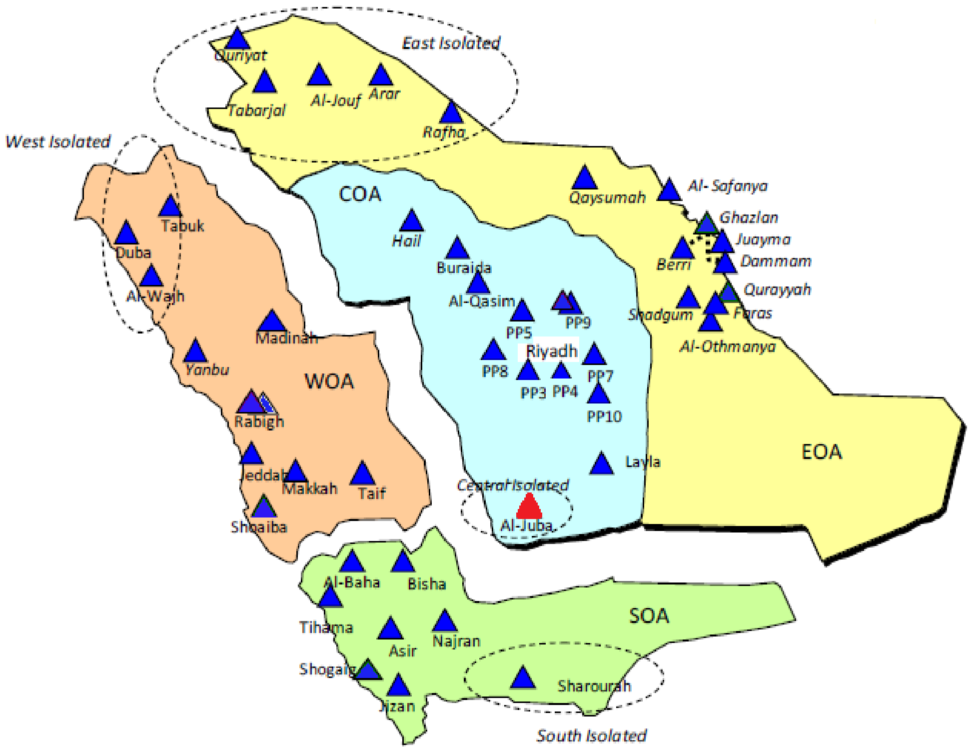


Figure 4.3: Power transmission isolated grid of Juba PP

Population growth and economic development have put enormous stress on the existing power generation facilities. There are expansion plans for the existing power infrastructure mainly for the power plants. This work investigated the feasibility of using CSPPs for future capacity expansion in electricity generation, so as to address government commitments to reduce fossil fuel consumption, and provide a proposal for exploiting the abundant solar energy.

The present case study aims to explore the design of a parabolic trough CSPP, and determine how feasible it is for generating power in Wadi Aldawasir.

4.3. Energy Demand Profile at Wadi Aldawasir

Extensive energy consumption data for Wadi Aldawasir region is provided by SEC. Data includes weekly maximum loads monitored in the 2009-2014 period. The data is summarised in Figure 4.4. It may be noted that the maximum load was 337 MW, recorded in late August 2014. The annual energy generated from the plant was 1,325 GWh.

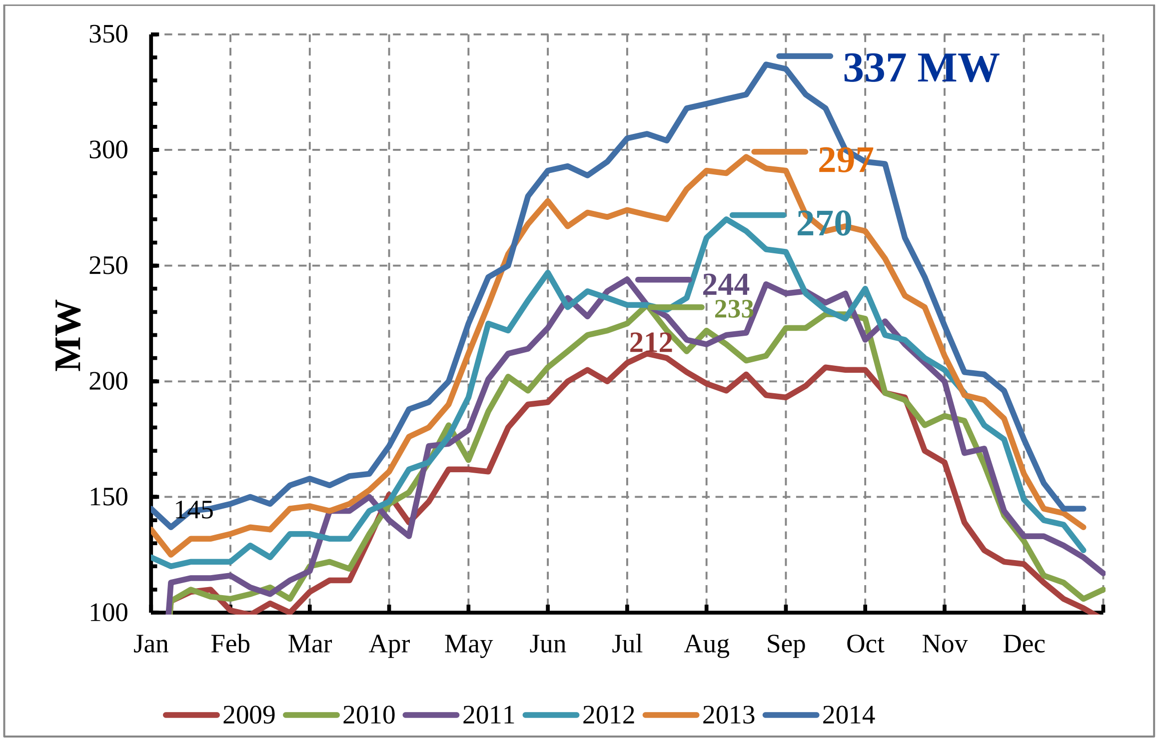


Figure 4.4: Monthly maximum loads 2009 – 2014 of Juba PP

4.4. Design and Feasibility of CSP Integration Into The Mini-Grid

4.4.1. Site Specification

This section covers the main steps for modelling and analysing the parabolic trough CSPP at Juba. The NREL methodology was used in this process. The solar resources assessment is mainly based on DNI. Indeed, the region's available land and well-established parabolic trough technology make for an ideal for power generation setup. SAM and RETScreen software were used to design the CSPP and perform feasibility simulations. Moreover, input parameters are discussed in detail, and their importance highlighted. Simulation results are presented including energy yield and economic implications. The main study objective is to simulate a CSP plant that is customised for the region's context, and evaluate the proposed CSPP performance. Economic modelling and financial analyses are also one of the key study aims. Cost of the CSPP and the levelised cost of energy are assessed and presented. Parabolic trough technology was selected for this assessment, because it is a very mature, well-commercialised technology (Vergura and Lameira, 2011, Zhang et al., 2013). The site proposed for the CSP plant can be described as follows:

i. The Juba PP uses fossil fuel (crude oil), and is isolated and not connected to the national grid. This allows more accurate evaluations and comparisons.

ii. Solar resource assessment at the site is promising with high annual DNI of more than 2400 kWh/m^2.

iii. Natural land conditions are appropriate for CSPP construction, with availability of vast areas of land owned by SEC around the current PP.

iv. The central location in KSA means that Wadi Aldawasir is well-connected to other cities by roads and airport, which facilitates site access.

4.4.2. Solar Irradiation at The Site

CSP potential for this mini-grid system was investigated by collecting and assessing DNI information. For the purpose of this assessment, DNI data used in the SAM software was obtained from satellite sensor data, and verified against ground-measured data from the Saudi Renewable Energy Atlas (Simulation, 2012, Atlas, 2015). Measured GHI is 2433 kWh/m^2/year. Average annual DNI at the site was found to be 2754 kWh/m^2/year. These results provide a good indication for CSPP at the selected site. In addition, a satellite image of the DNI distribution for the country, shown in Figure 4.5, indicates that this location lies in the promising direct solar irradiation belt.

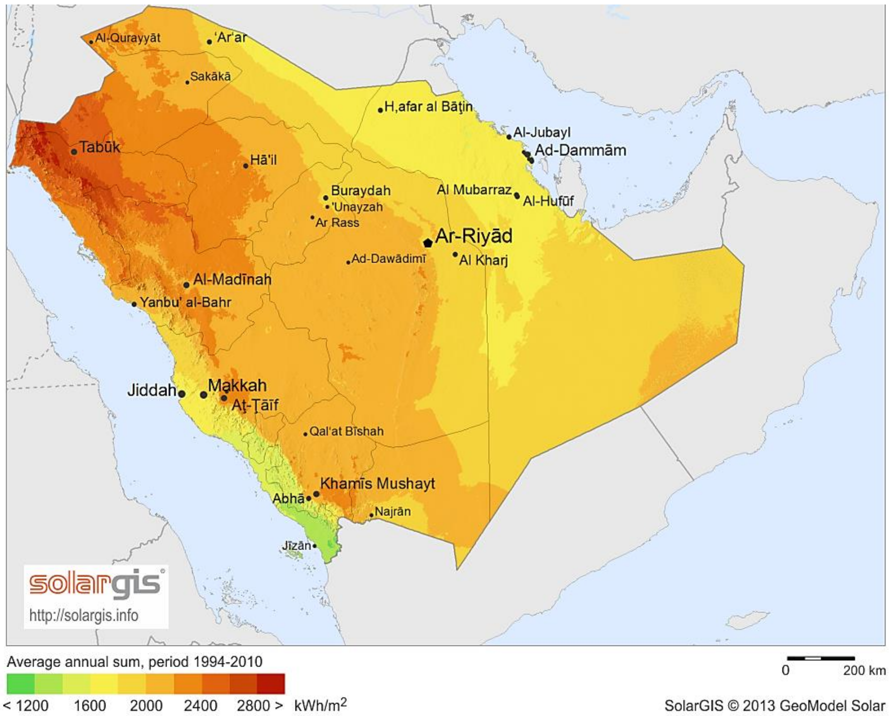


Figure 4.5: DNI map for KSA

The amount of radiation that is received on the Earth’s surface can be displayed in many different ways. One of these is GHI, referring to the overall amount of shortwave radiation that reaches the ground. DNI refers to the overall amount of incident energy in the solar range that is measured in a unit time on a certain area on the Earth’s surface, which is perpendicular to the sun direction. It is based only on atmospheric extinction of solar energy. Its measurement is usually undertaken with the help of a pyrheliometer positioned on a solar tracker, whose role is to ensure that the trajectory of the solar beam is guided into the field of view of the instrument throughout the day. The correlation of the horizontal component with the direct solar irradiance is highly important and is attained through the value of the direct solar irradiance multiplied by “the cosine of the sun’s zenith angle”. Playing a crucial role in the set-up of any solar technology, this value is given by the Diffuse Horizontal Irradiance (DIF) and the DNI from the sun, the relationship between them being denoted by the equation (Dekker et al., 2012):

$$GHI = DHI + DNI * cos(\theta) \qquad (4.1)$$

Where θ refers to solar zenith angle.

Measurement of GHI is performed by a pyranometer with a hemispherical view that is horizontally mounted. Conveyed in W/m^2, the overall quantity of global, both direct and diffuse, radiation that is received from the sun each year on a horizontal surface at a specific location is presented in Figure 4.6. It may be noted that DNI is more than 500 W/m^2 between 08:00 and 17:00. This would make the system perform for 9 hours daily meeting demanded peak load. Figure 4.7 presents GHI variation for each month of the year at Wadi Aldawasir region. It may be noted that the maximum value is recorded during summer months due to the high amount of sunlight received at the Earth’s surface. Minimum values are obtained during winter months, especially during December and January, when the Earth’s surface receives less sunlight. From figure 4.7, it can be noted that the maximum GHI obtained during May reaches 1,100 W/m^2, while the minimum value of 700 W/m^2 is obtained during January. Reduced GHI during January happens as less solar radiation reaches the Earth’s surface.

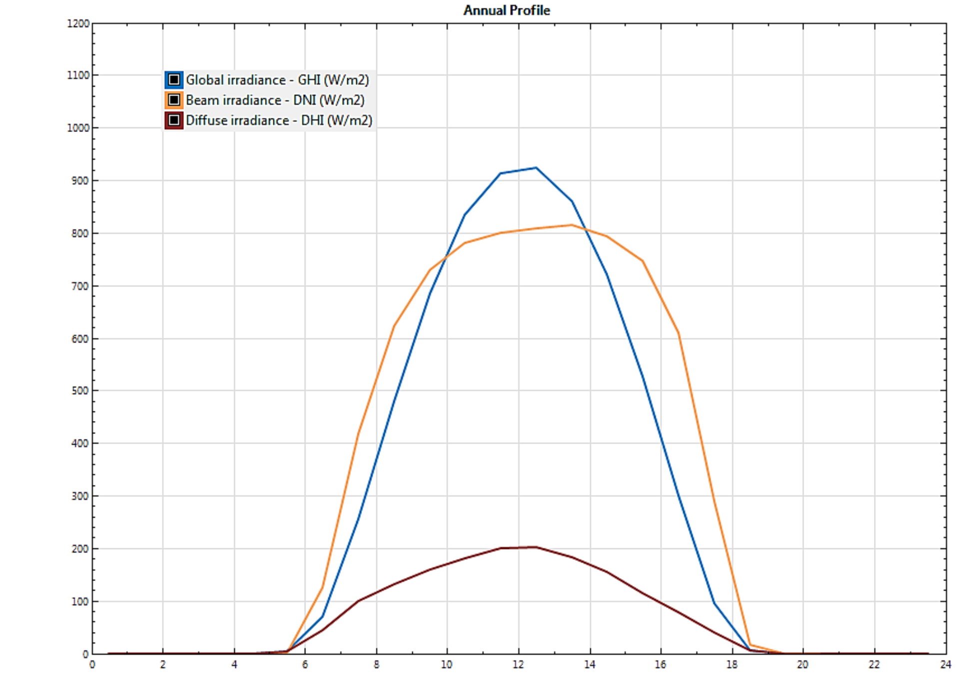


Figure 4.6: Annual Global Horizontal, Beam and diffuse Irradiation at Wadi Aldawasir

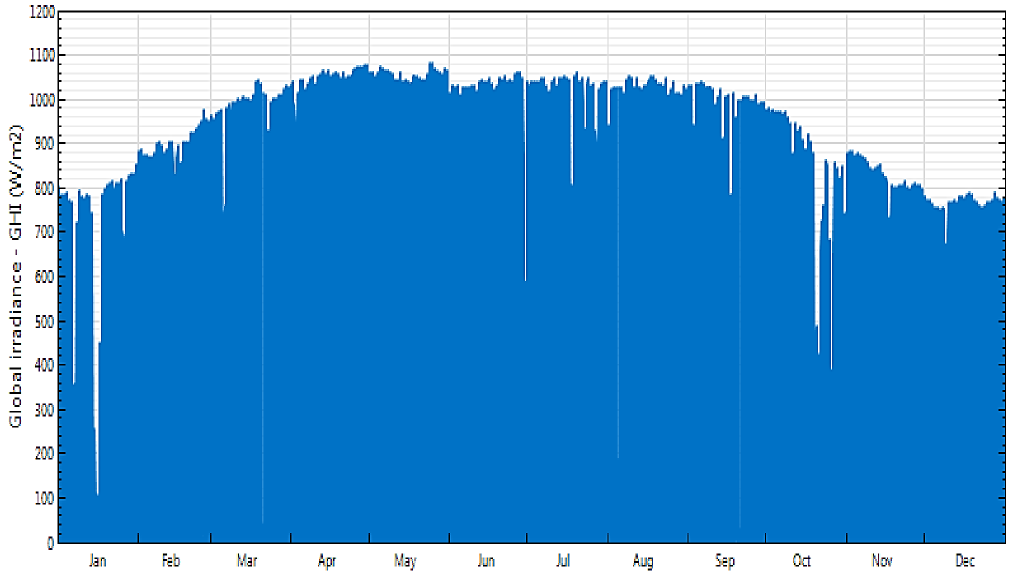


Figure 4.7: GHI at Wadi Aldawasir

The expression of the quantity of solar radiation that is received in a restricted field of view focused on the sun or DNI takes the form of W/m^2. Its variation is shown in Figure 4.8 for Wadi Aldawasir. It can be noted that this value is not constant throughout the year, as it increases during summer months and decreases during winter months. Its maximum is 1,000 W/m^2 in March, while the minimum is about 700 W/m^2 in October.

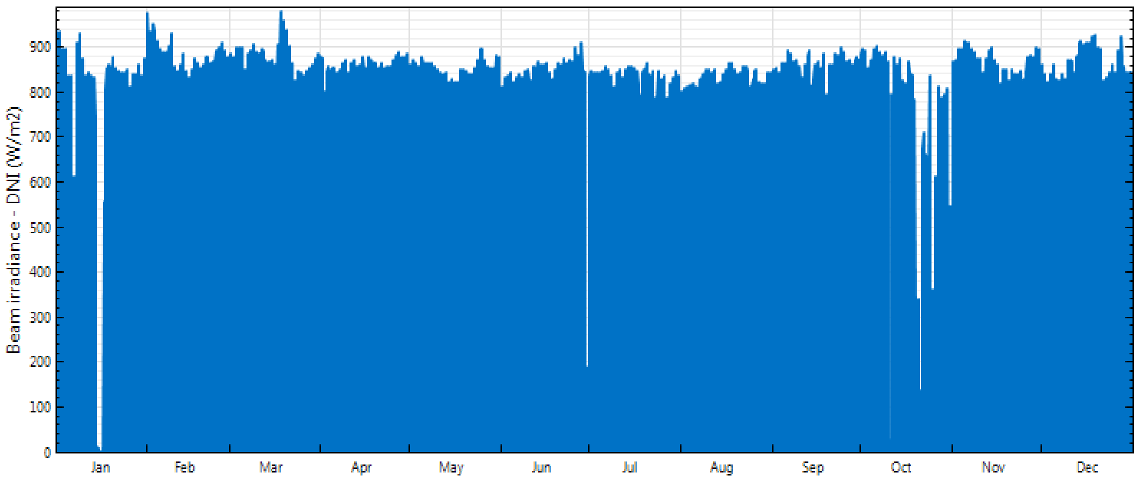


Figure 4.8: Beam normal irradiation (DNI) at Wadi Aldawasir

4.5. Simulation of The Proposed CSPP Using SAM Software

SAM simulation software was selected for modelling and feasibility assessment, as it has been used successfully to simulate existing CSPPs (Gilman et al., 2008). It is used to estimate CSPP performance, including energy production and financial parameters.

The acquired input data and formulated hypotheses will form the basis of the simulations that will be conducted. Trough technology (e.g. efficiencies, solar potential and discount rates) can be employed by users to introduce different CSPP technical and financial parameters into the software. Simulations focus on plant operation and performance, and the calculation of important indicators of financial feasibility are undertaken . SAM's design screens for this case study are located in the appendices (A.1).

4.5.1. Radiation Input Data

The flat surface of Wadi Aldawasir has a mean solar potential of about 2,400 kWh/m^2 per year, with solar radiation peaking in March and September. This suggests that parabolic trough solar thermal technology is a suitable option for power generation.

Even though monthly average and hourly DNI data are available from ground measurements, they cannot be used directly in simulation, because SAM software uses the EnergyPlus Weather (EPW) data format. Satellite data obtained was calibrated using ground measurements over a 15-year period (1998–2013) and translated for the simulation into EPW format. The reason is that in-depth weather data, such as DNI, dry bulb and dew point temperatures, relative humidity, barometric pressure and wind speed, are needed by SAM software (Gilman, 2014).

4.5.2. SAM Model Input Parameters

The case study uses the EPW climate file for Wadi Aldawasir, while system specifications are taken from NREL and Solar Power and Chemical Energy Systems (SolarPACES). The financial system of KSA constitutes the basis for the financial assumptions formulated. The case study and overall plant design is based on the following premises:

- The greater flexibility and greater uncertainty added to performance forecasts are the reasons why the CSP "physical trough" SAM software technology is applied in this case study instead of the "empirical trough" model.
- The CSPP will operate as an independent power producer, because SEC is the only company in control of the electricity sector. SEC is a government-owned company that seeks to implement state policies and strategies in terms of providing electricity services from primary energy sources, while in receipt of significant government support.
- Molten salt was selected as a heat HTF since it has higher operating temperatures than oil, provides gains in power cycle conversion efficiency, costs less than oil, provides more energy-dense and direct thermal storage, and has higher freezing temperatures. However, molten salt as a HTF is more corrosive, but this fact cannot be addressed in SAM software and in the plant feasibility stage.

The key steps adopted in the design follow the same order of pages within the program. They are generally arranged as follows:

SAM software simulation processes can be summarised as follows:

i. Location, Sources
ii. Solar field
iii. Collectors
iv. Receivers

v. Power Cycle

vi. Thermal storage

vii. System costs

viii. Life time

ix. Financial parameters

x. Optimise SM and TES capacity scenarios

xi. Generating and showing the simulation results for the optimal design

A flow chart diagram of the simulation algorithm was also presented in Figure 3.4.

4.5.2.1. Technical Input Parameters

- **Location, Sources and weather data**

The first step is to include proper weather data for the actual CSPP location. The location and resource tab in SAM software allows direct selection of the location and resource parameters that are available in the SAM software database. Unfortunately, the SAM database does not include weather information for Wadi Aldawasir. Therefore, these were sourced from satellite data, placed in the relevant EPW data format, and directly uploaded into the software as explained earlier.

Once the weather data file was downloaded, the geographical and climate data were analysed and presented through the program. Some significant findings were revealed, especially in terms of the DNI, which is considered the most important element in the design of CSPPs, as shown in Figure 4.9.

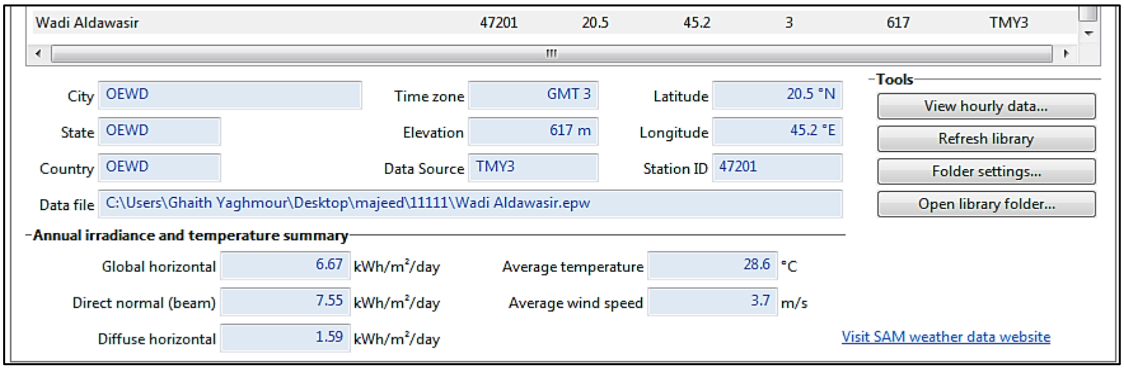


Figure 4.9: Location and resource data

- **Solar field**

The second page related to the solar field contains one of the most important components of the plant. These are the solar field parameters through which SM and field aperture area are computed.

In this design, the first option was adopted, because of unavailability of a specific area for the design to be built on, as the design at hand depends on the plant's capacity to produce 100 MW and since sizing the solar field can be determined via two alternatives offered by SAM. The first is to use SM as the design parameter which normalizes the size of the solar field with respect to the power block gross power output. For instance, a system with an SM of 1 is sized for the solar collector to provide the power block with exactly enough energy to operate at its design capacity under reference solar conditions. For systems with SM higher than 1 means that the solar filed provides more thermal energy than required by the power block which must be stored or dumped for systems without storage.

On the other hand, the field area is explicitly conveyed by the second option of field aperture in square metres.

The best solar field aperture area for a system at a specific location must be established to determine the size of the solar field of a parabolic trough system in SAM. The electricity output of the system usually increases, the greater the size of the solar field area, resulting in a decrease in the LCOE of the project. However, when solar resources are ample, the amount of thermal energy generated by an excessively large field will overwhelm different system components, including the power block. Furthermore, the greater output of a large field will no longer offset the high costs of set-up and operation once the size of the solar field surpasses a given point.

Hence, several points must be addressed by an effective solar field design:

i. The time interval within a year when the thermal energy produced by the field is enough to drive the power block at its rated capacity should be expanded as much as possible;
ii. Costs of set-up and operation should be reduced;
iii. TES and fossil backup equipment should be used in an effective and economical way.

To select an optimal solar field area, it is important to consider whether it is best to choose a larger solar field that could increase the electrical output of the system and electricity revenue or a field of smaller size that could make set-up and operation more cost-effective.

The LCOE comprises the quantity of system-produced electricity, set-up costs, and system operation and maintenance costs. Therefore, it is a helpful metric for determining an optimal solar field size.

In order to optimise the solar field, the aperture area associated with minimal LCOE must be determined. By applying the first option mentioned above, expressing the solar field aperture area as a SM, parametric simulations could be undertaken in SAM and graphs of LCOE versus SM could be developed to establish the ideal SM.

To perform this test, the following steps were taken into consideration following the directions of the SAM program guide:

1. Retaining all the default data in the program.
2. Identifying the plant capacity from the power cycle page in the program so that the estimated net plant output is 100 MWe, according to the design required for the plant.
3. Undertaking a simulation from the parametrics page involving two determinants, namely LCOE and SM, so that the highest value of the SM is 2.

After carrying out the above steps, it was possible to work out Figure 4.10, which shows that the optimum value of the SM is 1.25, as adopted in the design.

It is important to know that the features of the power block design, include 111 MW gross output rating, SM=1, and absence of thermal storage. At no point is the power block driven at its rated capacity, generally producing electricity at a rate of less than 80% of its rated capacity (NERL, 2011). Therefore, as noted in the figure, the cost is noticeably high in SM = 1

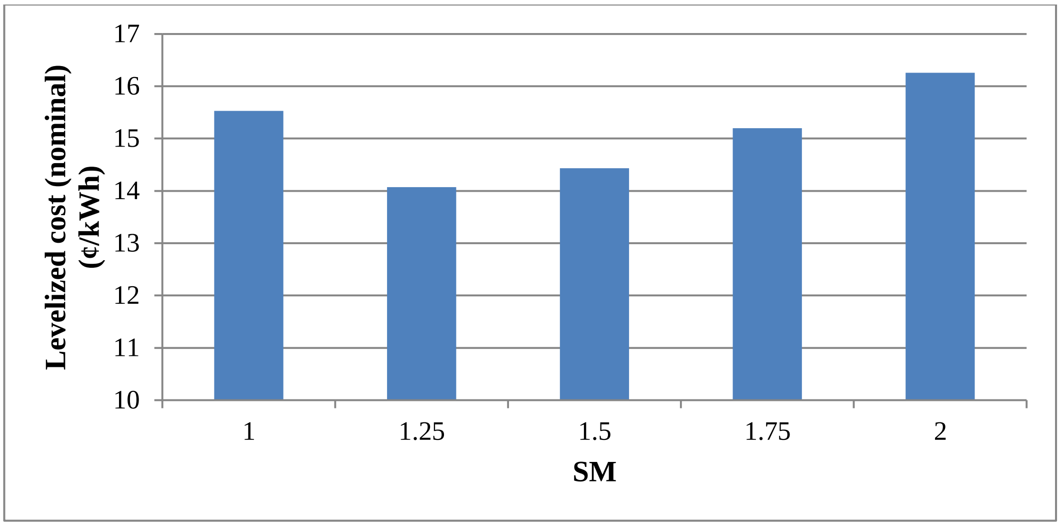


Figure 4.10: Optimal SM test

After identifying the direct SM, the second step entails determining the HTF and its characteristics, as it affects the other readings and calculations of the entire design, in particular, the data pertaining to the solar field.

Many HTFs may be used in the operation of the solar field. Nine very popular types of these fluids with their distinctive characteristics and specifications are available as choices in the SAM program. Hitec Solar Salt was chosen, because the viscosity of the molten salt is much higher than other fluids, which eventually causes a much higher pressure drop across the solar field. In addition, the density of the molten salt is much higher than the other HTFs. It is important to mention that if the solar parameters design remain unchanged, but HTF is changed, it is most probable that the complete solar field may not be optimally designed. Therefore, prior to starting the design of the solar field the type of HTF needs to be selected from the SAM Library. It can be noted that field HTF minimum and maximum operating temperatures have changed. Both have significantly increased, where Hitec solar salt HTF minimum operating temperature is 238°C, while the maximum temperature is 593°C (Raade et al., 2011).

Therefore, HTF input data needs to be customised for this particular case. The design loop inlet temperature will remain unchanged at 293°C, because it is mainly driven by the steam saturation temperature in the boiler. This is already higher than the minimum operating temperature of the HTF. However, the loop outlet temperature needs to be increased to a realistic value below the maximum HTF operating temperature, such as 550°C, which was chosen in this design.

The other specifications for HTF, such as minimum and maximum flow rates, and minimum and maximum header velocities, have a direct relationship with pressure in the pumps and the receiver's absorber tube inner diameter, and since viscosity of the molten salt is higher, pressure will increase too, which will eventually lead to higher pressure drop across the field. Therefore, pressure drop needs to be lower than the maximum pressure of the tubes that will be used.

As will be elucidated later in the receiver's page, absorber tube inner diameters for all available types of receiver types are available in the program, where 0.066m is chosen. After the adoption of this value for the receiver tube diameter, the following data was utilised based on calculations undertaken in NREL for the same type of HTF, and the same diameter. It was found that the minimum and maximum HTF flow rates are 1.75 kg/s and 12.8 kg/s respectively, while minimum and maximum header velocities are 0.7 m/s and 1.2 m/s, respectively. Therefore, all the necessary HTF data was entered into SAM, as demonstrated in the design screen in the appendices (A.1). It should be noted that the data in shaded boxes are dealt with through the program, and cannot be modified, because they have been calculated based on the aforementioned inputs, which are in the white squares (Wagner, 2014, Wagner and Gilman, 2011).

The next step involves entering the irradiation at design, as a design point for the solar field. A value of 800 W/m² was adopted based on the analysis of annual energy falling on the site, given that the value of the DNI would be higher than this figure for most of the year, as displayed in Figure 4.11:

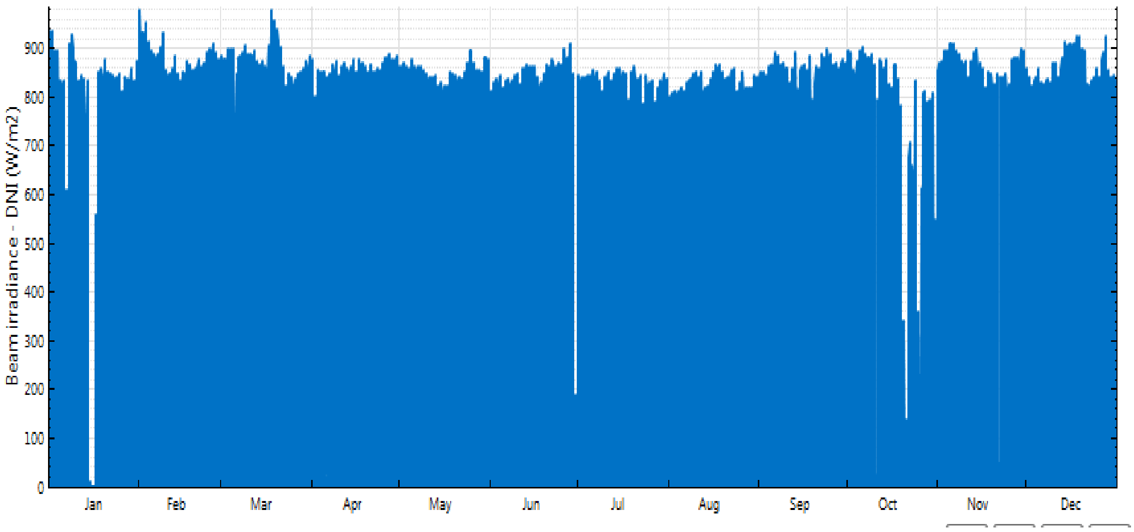


Figure 4.11: Annual DNI at Wadi Aldawasir

One of the most important design steps for the solar field is the number of field subsections, which determines the location and shape of header piping. The power block is supplied with HTF by header piping, the location and form of which are dictated by the number of field subsections. Hence, the piping structure, including number of subsections and branches, must be given close attention.

The number of field subsections is calculated from the data and figures resulting from the previous completed steps, as well as the specifications and dimensions of the collectors, receiver, power cycle and TES. These will each be clarified in more detail in forthcoming sections. Given that this number has a direct effect on the solar field and the energy produced from the plant, it will thus affect the results of the financial analysis and the value of Power Purchase Agreement (PPA). Therefore, the way to achieve the ideal for this number will be a relationship with the PPA of the project. Such a relationship is computed to reach the optimal number, in accordance with the program guidelines (Wagner, 2014).

The method adopted in achieving the optimal number of field subsections, includes the following:

1- Entering the previously achieved data.
2- Determining the plant capacity in the power cycle page of the program so that the estimated net plant output is 100 MWe, according to the required design of the plant.
3- Retaining the default values in the other pages of the program.
4- Undertaking a simulation from the parameters page between two parameters, namely, PPA and number of field subsections, so that the highest value of the subsection is 12 to achieve various values of PPA at all numbers of field subsections.

Simulation was performed to determine PPA price, depending on the number of subsections in the field. Results of this test show that two subsections lead to the lowest PPA price. Parametric simulation results are shown in Figure 4.12. Therefore, the value of 2 was adopted for the number of field subsections.

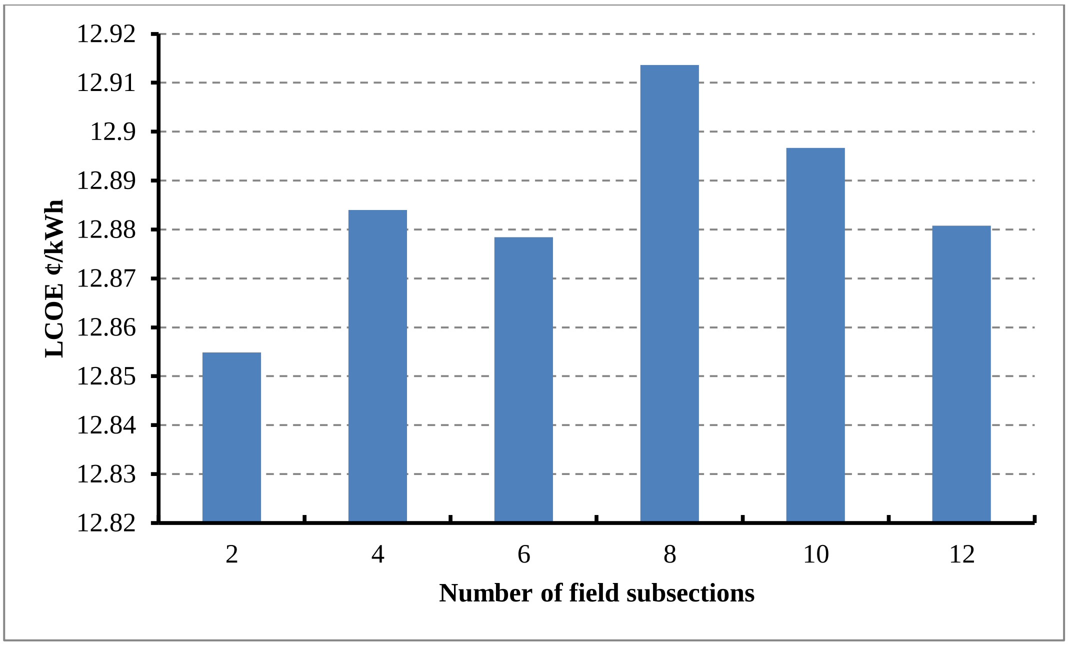


Figure 4.12: PPA price in the first year vs. number of field subsections

To further ascertain the accuracy of the selected number of subsections, the same test was conducted after entering all the financial data for in final design, as will be elucidated later. Simulation was then carried out from the parametrics page, showing that the lowest PPA was obtained for two subsections of solar field. Figure 4.13 illustrates a possible subsections grouping arrangements of a solar field. It shows that subsections can be arranged in two, four or six groups with the arrangement of Figure 4.13 a) being selected for this design.

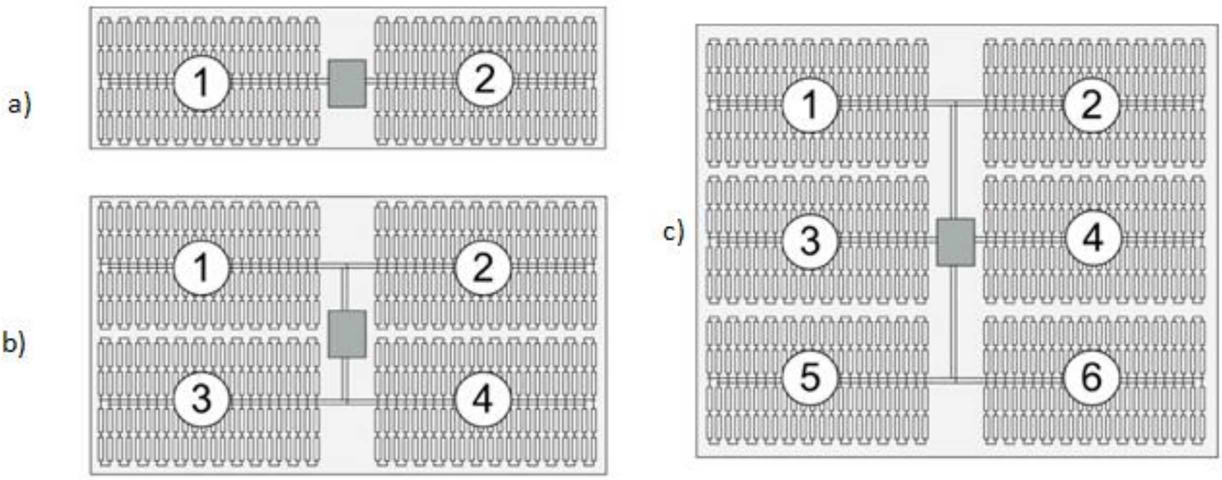


Figure 4.13: Field Subsections configurations a) two subsections, b) four subsections c) six subsections (Wagner and Gilman, 2011)

In the solar field page, the number of SCA/HCE assemblies need to be optimised through manual processes. Simulations were performed to determine the optimal number of SCA/HCE assemblies depending on the number of subsections in the field. Results of the test shows that 2 subsections lead to the lowest PPA price.

While the loop should contain 6 SCA/HCE assemblies. The number of assemblies was determined through an optimisation process based on the energy produced, and the PPA price, in terms of the highest energy produced and the lowest costs of the 6 SCA/HCE assemblies.

Freeze protection temperature should be sufficient to prevent freezing. Protection freeze temperature was set to 250°C. This value was selected, because it is above the minimum HTF operating temperature but also below HTF maximum operating temperature.

Table 4.1 gives a brief account of the inputs of the solar field page.

Table 4.1: SAM performance input solar field page for Wadi Aldawasir

Solar Field	**Solar Multiple (SM) (Opt. 1)**	**1.25**
	Irradiation at design	800 W/m^2
	Field HTF fluid	Hitec Solar Salt
	Design loop inlet temperature	293°C
	Design loop outlet temperature	550°C
	Minimum single loop flow rate	1.75 kg/s
	Maximum single loop flow rate	12.8 kg/s
	Minimum header velocity	0.7m/s
	maximum header velocity	1.2 m/s
	Number of Field subsection	2
	Number of SCA/HCE per loop	6

- **Solar Collector Assemblies (SCAs)**

In the collectors page, the CSPP collectors need to be defined. The physical trough model’s collector library contains a set of collector parameters for several commercially-available collectors. Siemens SunField 6 collectors were selected. SAM software automatically applies collector design characteristics from its database. These parameters were kept unchanged in the design, because they are collector specific. Among others, they comprise reflective aperture area, aperture width, total assembly length, number of modules for each assembly, and piping distance between assemblies.

One reason for selecting this type lies in the distinctive characteristics, such as tracking error, compared to other types found in the program library. In addition, the company's strong presence exemplified in current energy projects in KSA, in terms of construction and the supply of parts for the projects of this sector. This should enhance the price competitiveness and understanding of the Saudi domestic market, and in turn productivity and quality.

- **Receivers and Heat Collection Elements (HCEs)**

The second step is to configure the receiver components. Initially, the Siemens UVAC 2010 receiver was selected. One of the reasons for its selection refers to what has already been mentioned earlier in the collectors section. Furthermore, because the choice of a single company for collectors and receivers is driven by the need to enhance the work quality and the positive effects during implementation.

In the physical section, actual geometry of the selected receiver can be further specified for customisation. In this case, geometries provided in the software were kept at the design stage to avoid cost implications, and for the reason that this design was used in other similar CSPPs with proven high efficiency. Receiver geometry includes absorber tube inner and outer diameter, glass envelope inner and outer diameter, absorber flow plug diameter, absorber material type and internal surface roughness. In addition, there are four variant options that were used for modelling the receiver. Different variants are used to differentiate receivers' physical deflections that appear over time. These deflections include broken glass, which will lead to loss of vacuum between absorber tube and glass increasing average heat losses. This eventually causes worse performance of the receivers. Since the case study considers brand new equipment, the first receiver variant includes perfect performance with variant weighting factor of 1. The fraction of the solar field comprising the active receiver variation is known as variant weighting fraction. The four variations should give a total of one for every type of receiver, but in this design the first variation will be 1 and the others will be zero-valued, because it is assumed that it is a new solar field and in brand new conditions. In addition, they should all be identical immediately after installation. Hence, the other variations numbered 2, 3 and 4 do not affect this design (NERL, 2011).

After choosing the type of receiver and adjusting the inputs as shown earlier, the value of SAM according to the heat loss at the design is 192 W/m.

Table 4.2 shows the short inputs of the solar field page.

Table 4.2: SAM performance input Receivers page for Wadi Aldawasir

Receivers (HCEs)	**Configuration name (Type 4)**	**Siemens UAVC 2010**
	variant weighing fraction Variations	1,0,0,0
	Heat loss at design	192 W/m

- **Power Cycle**

In the next stages, it is important to have the features for the power cycle defined. Comprising a power block as shown in figure 4.14, a typical steam Rankine cycle PP is used by the power cycle model to produce electric power from thermal energy provided through the solar field and optional thermal energy system.

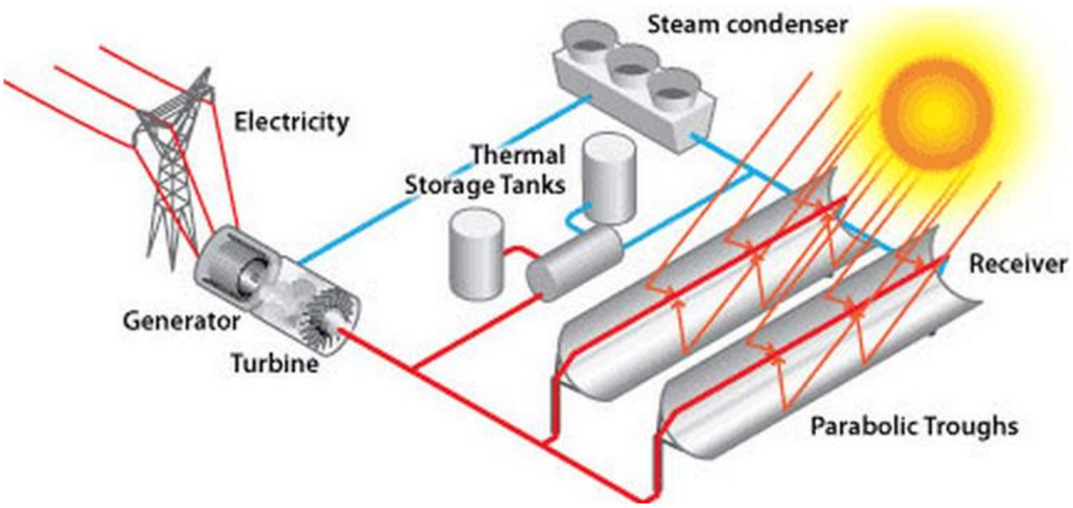


Figure 4.14: General layout for parabolic trough CSP plant

Subject to the wetness or dryness of the cooling, the energy cycle depends on an evaporative cooling system or an air-cooled system, respectively. Whenever the existing solar energy is not sufficient to run the power cycle at its projected load, the HTF is heated in a fossil-fired backup boiler prior to entering the power cycle. However, the lowest backup level in SAM has been chosen in the present design. The power cycle has the following main parameters:

- The design output of the power cycle is known as the design gross output (MWe), excluding parasitic losses. This value enables SAM to appraise system components (e.g. solar field area) when the size of the solar field is determined with the SM. Design gross output of 111 MWe was used in order to achieve 100 MW net output with 0.9 gross to net conversion factor. This factor takes into account system losses, which are inevitable. This study is based on studying the design and financial aspects for a station producing 100MW of solar energy, which is the reason for choosing this figure.

- The estimated gross to net conversion factor is known as the estimated calculation of the ratio of electric energy delivered to the grid to the gross output of the power cycle. It is used in SAM to decide the nameplate capacity of the power cycle allowing calculations linked to capacity, like the expected total cost per net capacity value on the trough system costs page, capacity-based incentives on the incentives page, and the capacity element shown in the findings. A value of 0.9 was decided for the power block design factor.

- In terms of the outcome of the design gross output and estimated gross to net conversion factor (Estimated Net Output at Design = Design Gross Output × Estimated Gross to Net Conversion Factor), the estimated net output design (nameplate) (MWe) is referred to as the nameplate capacity of the power cycle.

As indicated in Figure 4.15, during summer, the ambient temperature in Wadi Aldawasir reaches 46°C. Therefore, an ambient temperature of 48°C was established for the model, with an air-cooler condenser being consequently employed.

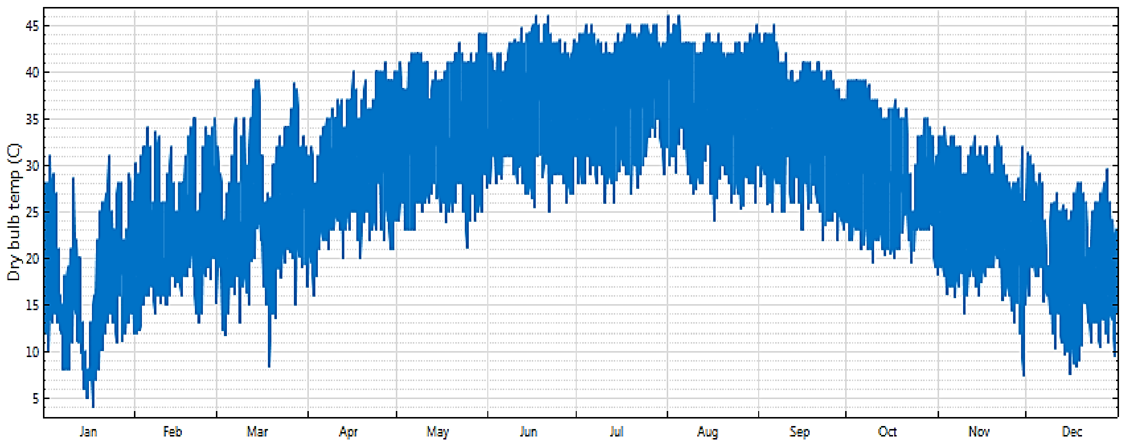


Figure 4.15: Ambient temperature at Wadi Aldawasir through the year

A good practice Initial temperature difference (ITD) was assumed to be 9^{o}C, and the difference between steam temperature at turbine outlet (condenser inlet) and ambient dry-bulb temperature are applicable solely in the case of the air-cooled condenser. That results in a condensed steam (condensate) temperature of 57°C. Figure 4.16 shows a layout of the CSPP with indicative HTF and steam/water temperatures.

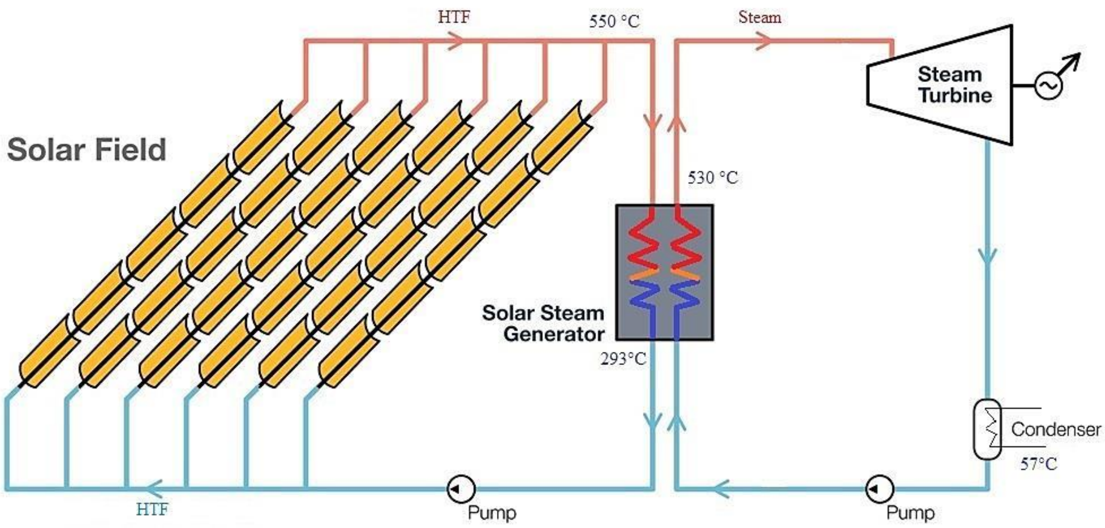


Figure 4.16: Indicative operating temperatures of the CSPP

The efficiency of the power cycle is also affected by the high ambient temperature and needs to be evaluated. In the absence of the detailed model, there are references that can be used as a rough estimate. This can be achieved by using a scale efficiency coefficient, taking a validated system performance which SAM uses 40.51% gross efficiency as a reference point. From table 4.1, the heat source (i.e., HTF design temperature) is 550^{o}C and with an ambient temperature of 57^{o}C, it results in a cycle Carnot efficiency of the power generation cycle of 59.90%. However, in practice it is assumed that the temperature gradient between the HTF and steam is about 20°C reducing the heat source temperature to 530^{o}C and in the process the cycle's Carnot efficiency to 58.90% (Wagner, 2014). the evaluation of the overall power generation of the system using SAM is obtained from the following:

$$\eta = 0.412 \frac{\eta_2|_{T=550}}{\eta_1|_{T=530}} = 0.4051 \qquad (4.2)$$

Table 4.3 gives the main parameters of the preliminary design of the power cycle.

Table 4.3: SAM performance input in power cycle page for Wadi Aldawasir

Power Cycle	**Capacity – Design gross output**	**111 MW**
	Conversion factor	0.9
	Estimated net output	100 MWe
	Rated cycle conversion efficiency	40. 51 %
	Auxiliary heater outlet set temperature	350 °C
	Ambient temperature at design	48 °C
	Condenser Type	Air-cooled

- **Thermal Storage**

It is important to delineate the features of thermal storage clearly. The storage of the heat derived from the solar field by a TES takes the form of a liquid medium. When there is little or no sunlight, the power block turbine can operate based on the heat from the storage system. Therefore, locations where power demand is highest after sunset could particularly benefit from a thermal storage system. The main advantage of incorporating thermal storage into a parabolic trough system is that accumulation of solar energy and power block operation could be kept separate. For instance, a system could produce electricity after sunset from the energy collected during the morning.

Direct and indirect storage systems are differentiated by the fact that the storage medium in the former is the actual HTF of the solar field, whereas in the latter it is a separate fluid, with heat exchangers mediating the transfer of heat from the HTF of the solar field to the storage fluid. One or multiple tank pairs, pumps for liquid circulation and design-specific heat exchangers are the main components of the thermal storage system. The hot and cold tanks that make up the tank pairs respectively store the heat from the solar field and the cooled storage medium following energy extraction by the power block (Gil et al., 2010a, Gil et al., 2010b).

The TES system is defined by the storage system variables. As such, the thermal storage dispatch control variables have to regulate the system transport of energy from the storage system, and also from a fossil-fired backup system, in case there is one.

The Full Load Hours of TES refers to the total number of hours of thermal energy provided for the design thermal input level of the power block. As for the optimal storage size of the system, it is decided on the basis of physical capacity. Such capacity is achieved by having the thermal input of the power cycle design multiplied by the number of hours of storage. This parameter can be optimised, thus enabling the study to explore a number of scenarios.

While maintaining the specifications and features in the thermal storage page, the appropriate design options for the number of storage hours required by the optimal design will be explained later.

4.5.2.2. Financial Input Parameters

This section provides a descriptive review of the financial implications in terms of costs and assumptions expected to set up the plant. In addition, it will address the required investment to establish a financial analysis covering the financial viability of the plant over a life time period of 25 years, coupled to its performance and productivity during the same period. The financial analysis is presented using similar procedure to that given in the input pages of financial analysis in the SAM program. The optimal financial results will be retained for final design. In conducing the financial analysis, a number of assumptions and good practice cost estimates from scholarly and published papers and guides were adopted. Some of the sources used in this analysis are listed in Table 4.4.Similarly, the project engineering and component costs as well as financial parameters including compatibility with the Saudi Arabia financial system (e.g., Zakat, subsidies for the energy sector, etc.) were fully checked for their validity.

Table 4.4: Financial previous efforts

Title	Author
Renewable Energy Technologies: Cost Analysis Series of Concentrating Solar Power	(IRENA, 2012)
Concentrating Solar Power – drivers and opportunities for cost-competitive electricity	(Hinkley et al., 2011)
Parabolic Trough Collector Cost Update for the System	(Kurup and Turchi,

Title	**Author**
Advisor Model (SAM)	2015b)
Current and Future Costs for Parabolic Trough and Power Tower Systems in the US Market	(Turchi et al., 2010)
Estimating the Performance and Economic Value of Multiple Concentrating Solar Power Technologies in a Production Cost Model	(Jorgenson et al., 2013)
Australian Companion Guide to SAM for Concentrating Solar Power	(Lovegrove et al., 2013)
Renewable Power Generation Costs in 2014	(IRENA, 2015)
Port Augusta Solar Thermal Generation Feasibility Study Stage 1 - Pre-feasibility Study	(PBA, 2014)
SunShot Vision Study: Concentrating Solar Power: Technologies, Cost, and Performance	(SunShot, 2012)
Concentrated Solar Power for Lebanon Techno-economic assessment	(UNDP, 2012)
System Advisor Model (SAM)	(SAM, 2014)
Solar Advisor Model User Guide for Version 2.0	(Gilman et al., 2008)
Line-Focus Solar Power Plant Cost Reduction Plan	(Kutscher et al., 2010)
Parabolic Trough Reference Plant for Cost Modeling with the Solar Advisor Model (SAM)	(Turchi, 2010)
Concentrating Solar Power Plants - Status and Costs	(Zhang and Langniss, 2010)
Numerical modeling of a hybrid parabolic trough Concentrating Solar Power Plant	(Sioumis, 2013)

- **System costs**

With regards to the project investment cost and annual operating costs stated in the project cash flow, they are decided by SAM from the variables on the trough system costs page. Similarly, the cost metrics stated in the metrics table are decided according to the variables on the results page.

According to different analysis requirements, capital costs can be allocated to various cost categories, which enables users to monitor different costs. This is because cash flow calculations are not influenced by the categories, but solely by the total installed cost value. For instance, the same outcome would be obtained if the cost of solar field design was allocated to the category of solar field cost, or to the category of engineer-procure-construct.

Description of the most important parameters is provided below.

- Site improvement cost, expressed as $/m^2, is calculated per square metre of the solar field area to include costs associated with site groundwork and additional equipment excluded from the solar field cost category. Thus, the site improvement cost has been established at 20 $/m^2 (Kurup and Turchi, 2015a).

- Representing cost per square metre of the solar field area, the solar field cost ($/m^2) includes costs associated with solar field set-up, such as labour and equipment. In this project, solar field cost has been established at 245 $/m^2.

- Representing cost per square metre of the solar field area, the HTF system ($/m^2) includes costs associated with set-up of HTF pumps and piping, such as labour and equipment. In this project, HTF system cost has been established at 75 $/m^2.

- In terms of the cost per thermal megawatt-hour of storage capacity, covering the expenditure associated with thermal storage system set-up is the storage cost ($/kWht), including labour and equipment. In this project, storage cost has been established at 80 $/m^2. However, this value will be neglected because the optimal design in this study will not include storage, as will be seen later.

- For the cost per electric megawatt of power block gross capacity, fossil backup system set-up fossil backup is included in the cost ($/kWe), such as labour and equipment. This cost is irrelevant in the present project, as no fossil backup will be used (Tanaka, 2010).

- In the case of the cost per electric megawatt of power block gross capacity, expenditure related to power block set-up is covered through the PP cost ($/kWe), including labour and equipment. In this project, PP cost has been established at 830 $/kWe.
- Any extra costs are covered by the balance of plant ($/kWe), representing cost per electric megawatt of power block gross capacity. In this project, the balance of plant cost has been established at 100 $/kWe.
- Anticipated unpredictability in direct cost estimates is covered by a contingency (%) factor, which represents a percentage of the total costs related to a number of factors, including storage, solar field, site improvement, fossil backup, PP, and HTF system. A 5% contingency factor is employed in this simulation. This value is sometimes referred to as an error value or tolerance value that may affect the total sum of the cost. It was decided that this cost should stand at 5%, which is the value to be taken into account for projects undertaken in some Arab countries, such as KSA.
- The Total Direct Cost ($) refers to the whole cost dedicated to developments, storage, PP, solar field, fossil backup, contingency plans and HTF system as calculated by SAM. An indirect cost is characterised by the fact that it is impossible to calculate with a particular equipment piece or set-up service. SAM calculated this cost, which was clear after selecting the optimal design with a net value of $317,354,304.00.
- The area necessary for the project and derived from the solar field of 526 acres created based on the case study modelling in the solar field page is known as the total land area.
- Nameplate refers to the nameplate capacity of the system from the power block or power cycle page. In the present project, its value is 100 MW.
- Project design and construction involve indirect capital costs, engineer-procure-construct (EPC) costs and owner costs. The sum of non-fixed and fixed costs represents the overall cost determined by SAM.

The following costs can also be integrated by the EPC and owner category, including permit costs, administrative or legal charges, and royalty payments. Other costs involve the consulting or interconnection costs, geotechnical and green surveys, records of spare parts, costs related to commission, in addition to the owner's engineering and project improvement operations. Although these costs have not been taken into account in this project, they actually account for 2-3% of the overall cost of the project. This cost had a zero hypothesis as the owner of the project and land owner refer to the same person; in this case, this would be a SEC, and there are no indirect costs, such as hiring the land or vehicles, etc. It was also included in the contingency and other plant-related costs.

- The sum of non-fixed and fixed costs, as well as the total land costs, which are calculated by SAM, denote the costs related to land acquisition. Since the area where the PP will be located is already under the ownership of SEC, a value of zero is attributed to this parameter.
- The total installed cost, or the net capital cost of the project, is calculated by SAM based on the sum of direct and indirect capital costs. SAM calculated this value, which stood at $ 317,354,304.00. Actually, this is the value obtained after selecting the optimal design of the plant, shown in the forthcoming analysis of the optimal design.
- In order to achieve the total installed cost per capacity, represented as $/Wdc or $/kW, the total installed cost is divided by total system rated or nameplate capacity. This value is not employed by SAM in cash flow calculations, serving merely as a reference. A calculation was conducted by SAM, with a value of $ 3,176.72/ kW.
- The costs incurred in a year due to equipment and services following system installation are known as operation and maintenance (O&M) costs. These costs can be entered into SAM in the form of variable by generation, fixed by capacity, and also fixed annual. Furthermore, the reporting of the O&M costs is included in the project cash flow. In this design, the variable by generation was adopted.
- The variable cost by generation ($/MWh) is defined as the variable annual cost equal to the total yearly electrical yield of the system in AC megawatt-hours. Based on the selected option, the annual energy output is the product of the estimated first year value of the performance model and the rate of degradation from the Lifetime page or of the annual schedule of costs. In this project, a value of 30 $/MWh has

been chosen. This cost was chosen based on the estimated cost of the O&M for 2015, as the mean cost for some current projects in other regions.

- **Life Time**

Energy performance degradation is exhibited by CSPPs over the entire life cycle and is around 0.5-1.0% per year. For this design, 1.0% was selected as the value of degradation in the annual energy output of the plant.

- **Financial Parameters**

This page focuses on the financial analysis to ascertain the feasibility of the project. The following is a brief explanation of the financial inputs used in the study.

In the following part, the financial parameters of the project are outlined. For every electricity unit produced by the system, the project receives a bid price in a PPA. The profitability of the project is assessed by the IRR, which represents the nominal discount rate associated with a NPV of zero.

SAM calculation determines whether an IRR target indicated by users is the basis of a PPA price or the other way around:

- Users can stipulate the IRR as an input if they select the IRR target option. Subsequently, a search algorithm is employed by SAM to identify the PPA price compatible with the target IRR.

  This is the method used in the financial analysis by installing the IRR. It is important to know that the IRR indicates the percentage of returns that investors can expect to obtain from their investment in the solar energy system. For instance, if the IRR is 13%, then investors will derive a yearly 13% profit on their investment. Price and Kearney (2003) estimated that IPP projects are associated with an IRR of 12-18% . Therefore, an IRR value of 13% was assumed as a reasonable percentage that could lead to achieving the expected price of the PPA, in addition to the fact that the SEC receives high government support to save energy for the local population as a higher priority than seeking to maximise its commercial gains. However, another review of IRR will be carried out later in this chapter to determine the percentage at which the project could be a profit or a loss. Another analysis will also include the LCOE and PPA.

- To determine the power purchase price in subsequent years, the PPA price in the first year is applied at an escalating rate. The inflation rate is not applied to the PPA price by SAM; instead, SAM makes the assumption that every year in the analysis interval is associated with the same price, if a PPA price escalation rate is not specified by users. In this case, a 2% escalation rate has been established.
- The number of years that the analysis spans is known as the analysis period, which usually corresponds to the lifetime of the project or investment. The number of years in the project cash flow is given by the analysis period. In the present case, a 25-year analysis period has been chosen.
- Usually underpinned by a price index, the yearly rate of cost change is known as the inflation rate. The dollar values stipulated by users on the system costs page for the first year form the basis on which SAM employs the inflation rate to determine costs in subsequent years in the project cash flow. In this case, a 2.1% inflation rate has been established.
- The measurement of the time value of money transferred as a yearly rate is carried out by the real discount rate, which is utilised by SAM first to decide the existing value from the initial year of the dollar sums in the project cash flow across the examination time, and second to determine annualised costs. In this study, a 7% annual value has been established SEC. The real discount rate input has a major impact on the financial model results of SAM. Therefore, users should choose the discount rate applied in analysis with great care, if they intend to employ such parameters as NPV, levelised cost, PPA price and IRR.
- The real discount rate and inflation rate are used by SAM in the calculation of the nominal discount. Thus, a value of 9.25 was obtained from the calculation Nominal Discount Rate = (1 + Real Discount Rate) × (1 + Inflation Rate) – 1.
- Annual Interest Rate was set at 2% .

- With regard to the section on the tax and insurance rate, 2.5% was added in taxes, which is the actual zakat money adopted in KSA. As for the insurance rate, a value of 0.5% was chosen as the annual value for construction.
- The value of debt was fixed at zero because the study is interested in the implementation of the project by the SEC, which would inject the full value of the project. The company has been offered tremendous government support, which is estimated at 100 billion interest-free loan, to be reimbursed over a period of 25 years, as previously stated in *Chapter 2*.
- A 4% annual depreciation was adopted under the assumption that the value of plant would be zero at the end of the 25th year. Thus, the net salvage value was also neglected.

System costs and financial parameters summary are shown in Table 4.5, which presents the feasibility study financial parameters. It should be noted that the price shown for storage in the table provides an explanatory account of the values used in the design, but after obtaining the optimal design TES = 0, the cost of storage is now equal to zero.

Table 4.5: SAM financial analysis input data

Page	Variable	Input Value
System Cost	Site Improvements	20.00 $/m^2
	Solar field	245$/m^2
	HTF System	75.00 $/m^2
	Storage	80 $/m^2
	Power Plant	830.00 $/kWe
	Balancing of plant	100.00 $/kWe
	O& M Variable Cost by generation	30.00 $/MWh
Life Time	Degradation rate	1 % per year
Financial Parameters	Minimum Required IRR	13 %
	Analysis period	25 Year
	PPA Escalation Rate	2 %
	Inflation Rate	2.1 %
	Real Discount Rate	7 %
	Federal Income Tax	2.5%
	State Income Tax	0 %
	Insurance Rate	0.5 %
	Debt percent	0 %
	Construction Period - Months	24
	Annual Interest Rate	2 %
Depreciation	Depreciation	4 % per year

4.5.3. System Design Optimisation

After adopting the inputs and values in the technical section and the financial section of the case study, a number of tests were carried out to achieve the most optimal and appropriate version for the accomplished design.

It has to be pointed out that core CSPP design is subject to multiple optimisations, since it is not possible to directly design the system including physical and financial parameters so that various metrics provide the most optimal values. This exercise shows changes of various metrics depending on the SM, TES values and number of field subsections. Each of these inputs affects overall physical design and eventual project profitability. It is important to mention that this section covers the most important metrics that can precisely show project feasibility and effectiveness. However, additional metrics can be obtained.

Figure 4.17 shows change of IRR value at the end of analysis period in relation to TES (h) and SM. It may be noted the highest IRR appears in the system with the lowest TES=0 and SM 1 or 1.25.

However, one must take into account that it is not possible to rely on SM = 1 for the reasons stated in terms of determining the optimal choice for SM. Thus, when TES = 0, the best value for IRR is when SM = 1.25.

Another value shown in the figure, TES=2 at SM=1.25 show a value slightly less than the value of TES=0 at the same SM. However, the highest value for IRR without storage is SM = 1.25, which is considered as more effective than achieving the target IRR value for a plant that has a thermal store, as this has further implications and costs.

In the case under study, the optimised SM is 1.25, which will reflect lower LCOE and lower total cost compared with high LCOE and total cost resulted from installing TES of just 2 hours.

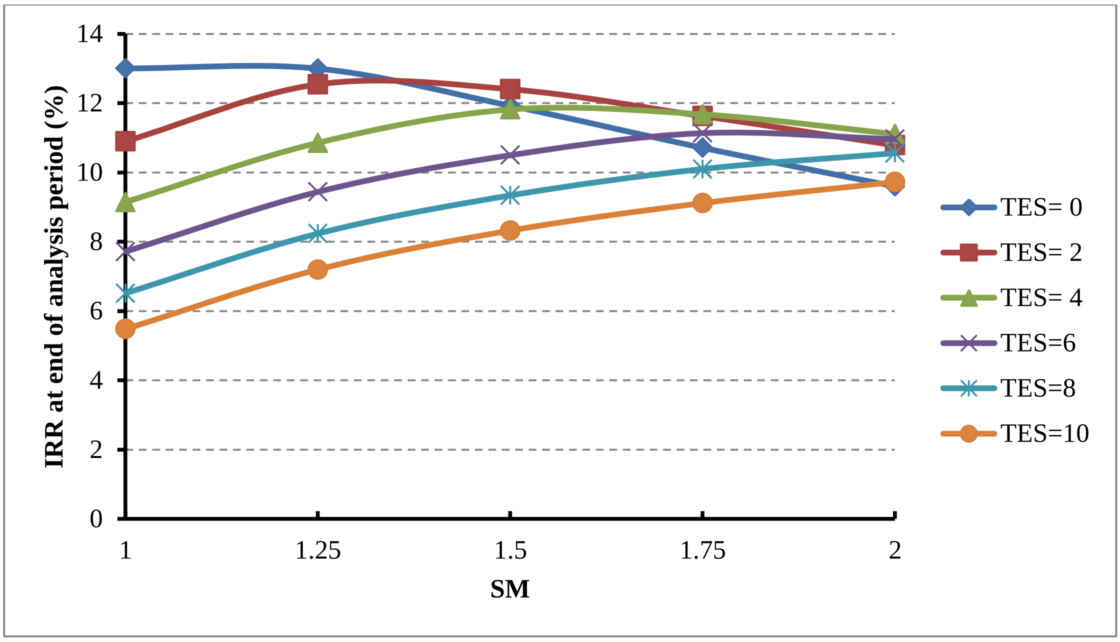


Figure 4.17: IRR at end of analysis period (%) vs. SM

Figure 4.18 below shows that IRR value is the highest for the system with zero hour storage and 2 subsections.

In spite of selecting the ideal number of subsections in the previous design stage, which was 2, the close percentages of the IRR at the various numbers of subsections shown in the following figure will not affect the choice of optimal number of subsection. This is because the construction of the plant at the best selected design with number of subsections = 2 benefits the dependence on a larger number.

It can also be noted from the figure below that both the percentage of IRR at TES = 2 and the percentage of the IRR at TES = 0 are slightly similar to each other. However, building the TES for two hours does not really represent a major contribution compared with the thermal store construction, and maintenance and operation costs, which will increase as opposed to a plant with no thermal storage. In addition, the power generated from the plant because of a two-hour storage will not have significant impact as in a six-hour storage, for example.

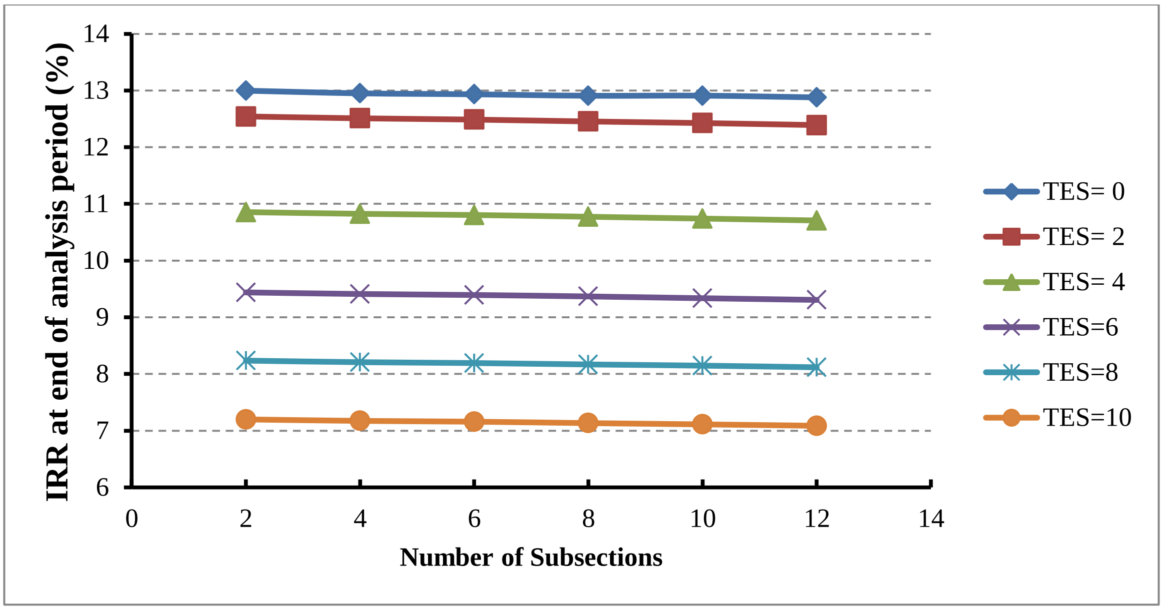


Figure 4.18: IRR at end of analysis period (%) vs. number of field subsections

However, looking at the costs, one can note that the lowest levelised costs appear for the system without thermal storage and SM of 1.25, as is shown in figure 4.19. It is important to mention that minimising costs during system operation would be preferable. Therefore, the solution with lower thermal storage capacity provides greater benefits. The values of LCOE between 15-17 ¢/Kwh for systems with TES = 2, 4, 6 and 8 at different SMs seems relatively similar to the value of LCOE at TES=0, but the value for IRR of these systems is lower, as illustrated in previous figures.

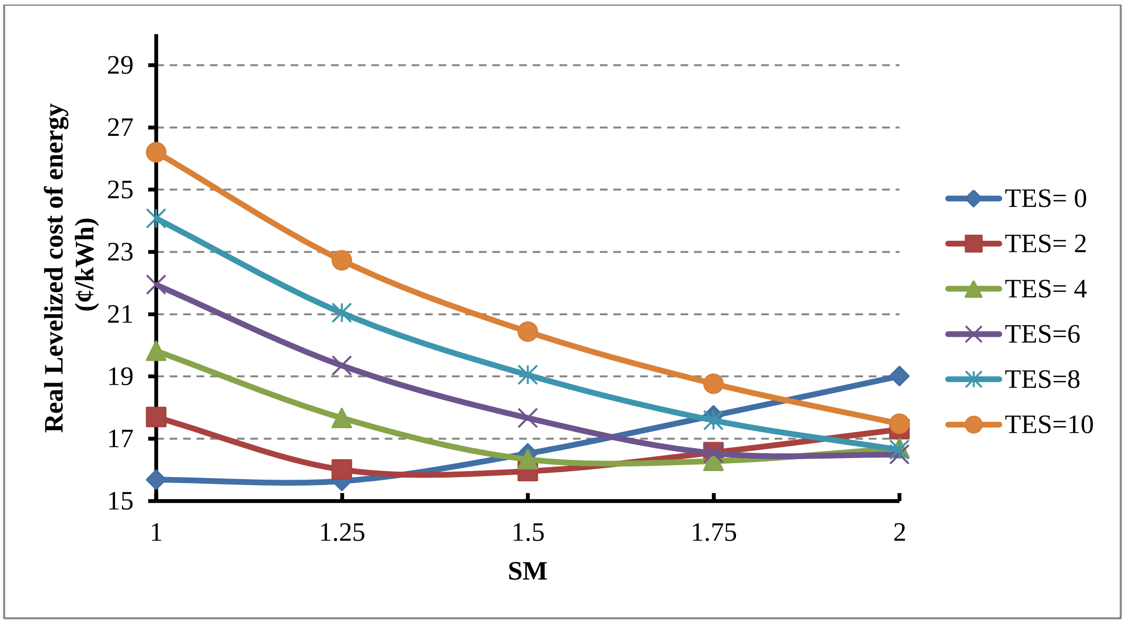


Figure 4.19: Levelised cost (real) (¢/kWh) vs. SM

In addition, if levelised costs are compared for arrangements with more subsystems, it can be seen that systems with less subsections and lower TES have less costs, which makes them more favourable than larger systems. Levelised real costs (¢/kWh) vs. system subsections are shown in Figure 4.20.

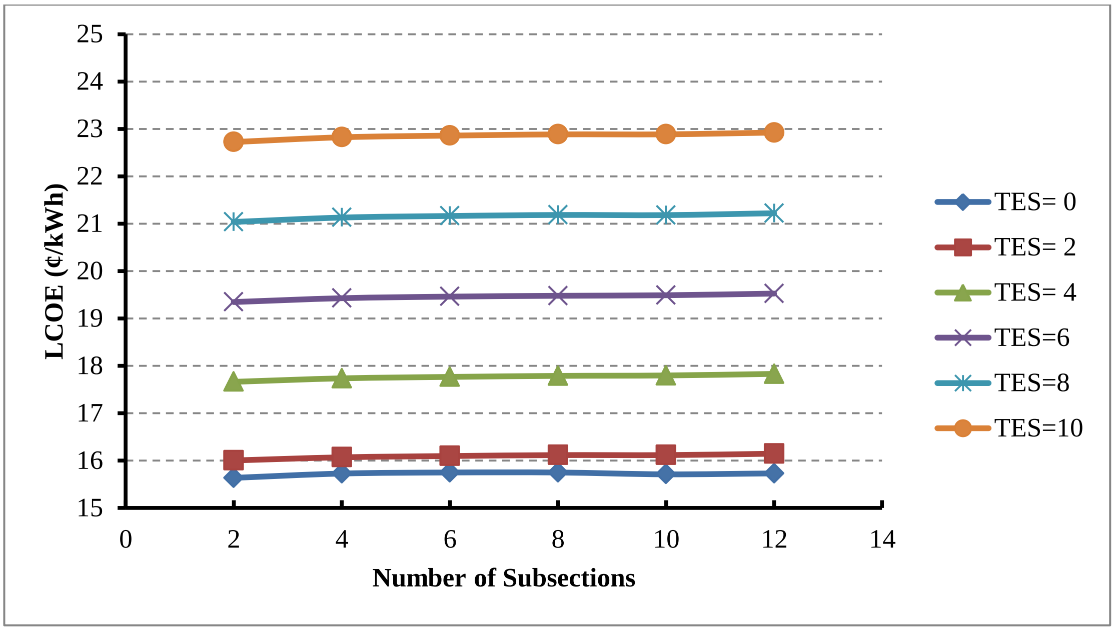


Figure 4.20: Levelised cost (real) (¢/kWh) vs. number of field subsections

On the other hand, a larger system with higher TES has a higher NPV ($) as can be seen in Figure 4.21. However, having higher TES will affect the LCOE. For example, if TES=10 with SM 1.25, LCOE will be around 22.88 c/kWh, which is very high compared with 15.63 c/kWh for the system without thermal storage, as seen in the previous figure.

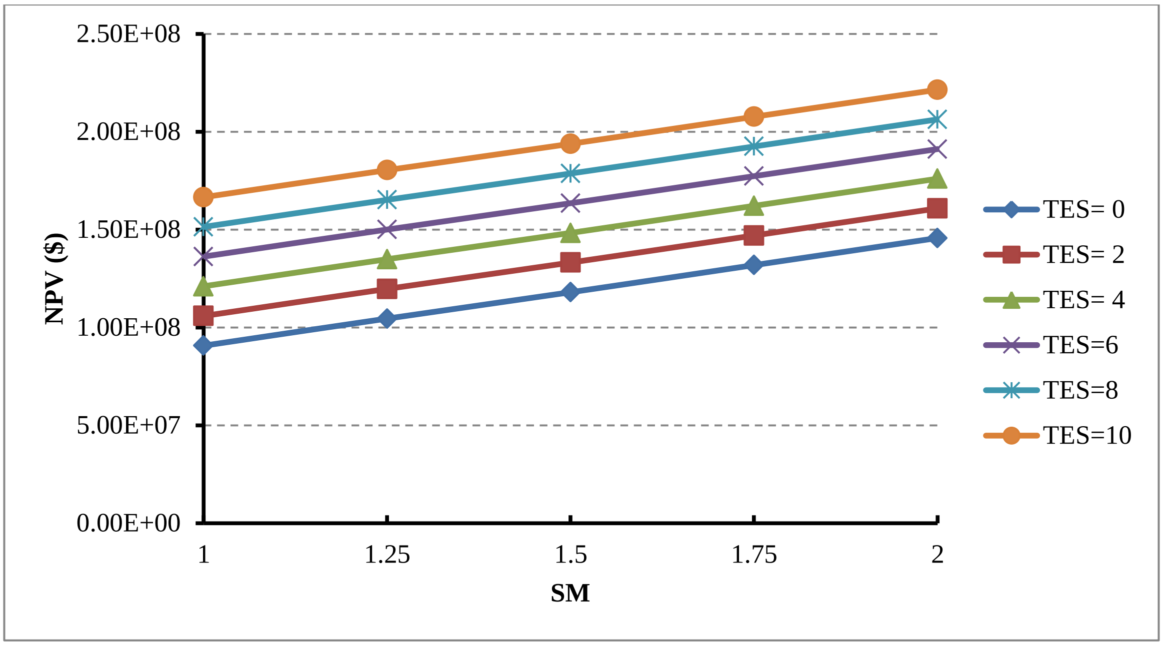


Figure 4.21: NPV ($) vs. TES (h)

Finally, it is very important to achieve competitive costs for energy production. From Figure 4.22 below, it may be noted that systems with smaller TES have significant advantage and that energy produced from these systems is comparable to energy produced from conventional energy sources. It may also be observed in the Figure below that the best minimum PPA value is when TES = 0, and SM is 1.25.

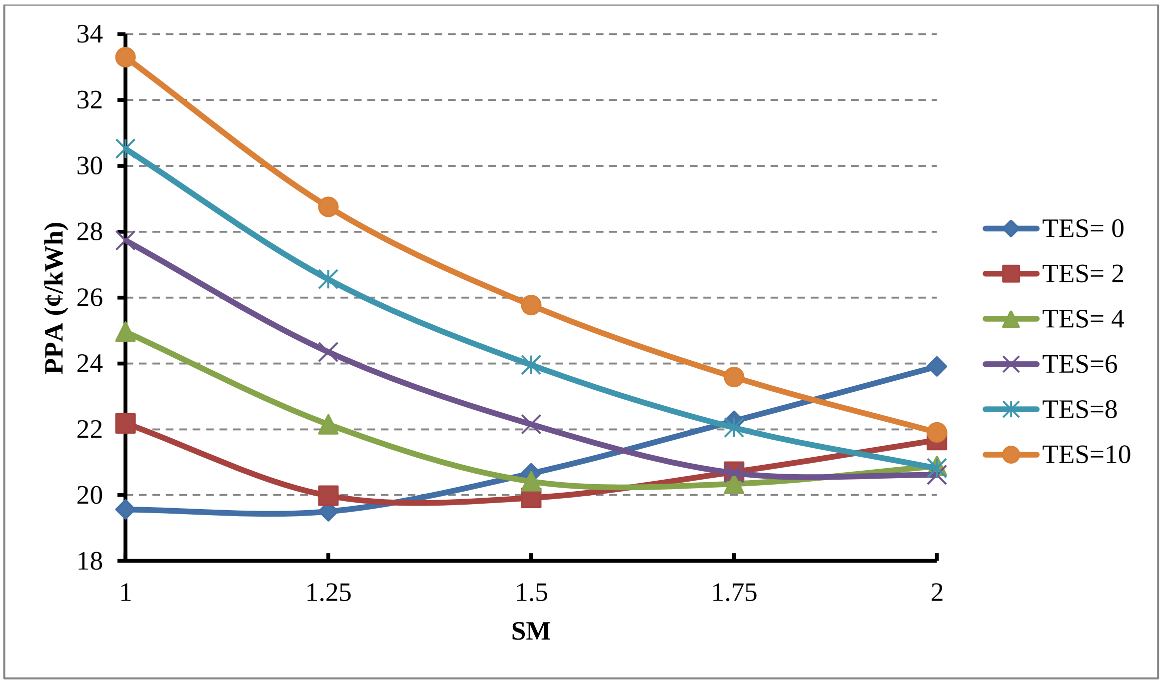


Figure 4.22: Levelised PPA price (real) (¢/kWh) vs. SM

After the previous analysis of the results, and from a financial point of view, it was shown that the best choice for the design is one without a thermal store. As proven in the design, the best financial performance in terms of the value of the PPA and the value of the LCOE stood at SM = 1.25 where the number of subsections = 2, which makes it the best option. However, the energy produced from the station has a major contribution in terms of production capacity at variable capacities in the presence or absence of thermal storage. Thus, an analysis was carried out as shown in Figure 4.23 showing how the annual energy-producing capacity can be affected at different storage capacities to enable the identification of the plant's behaviour in terms of production values at different store sizes. It was found that the production capacity could double when SM = 1.75 and SM = 2 when using large stores with capacities between 4 to 10 hours. Nonetheless, there would be a negative impact on the feasibility of the design, which could be reflected in an increase in the price of energy production and thus a surge in the selling price. However, it is worth mentioning that when the station has an SM = 1.25, it produces similar amounts of energy when using variable storage capacities, with a simple difference if carried out without storage, as illustrated in the previous analysis.

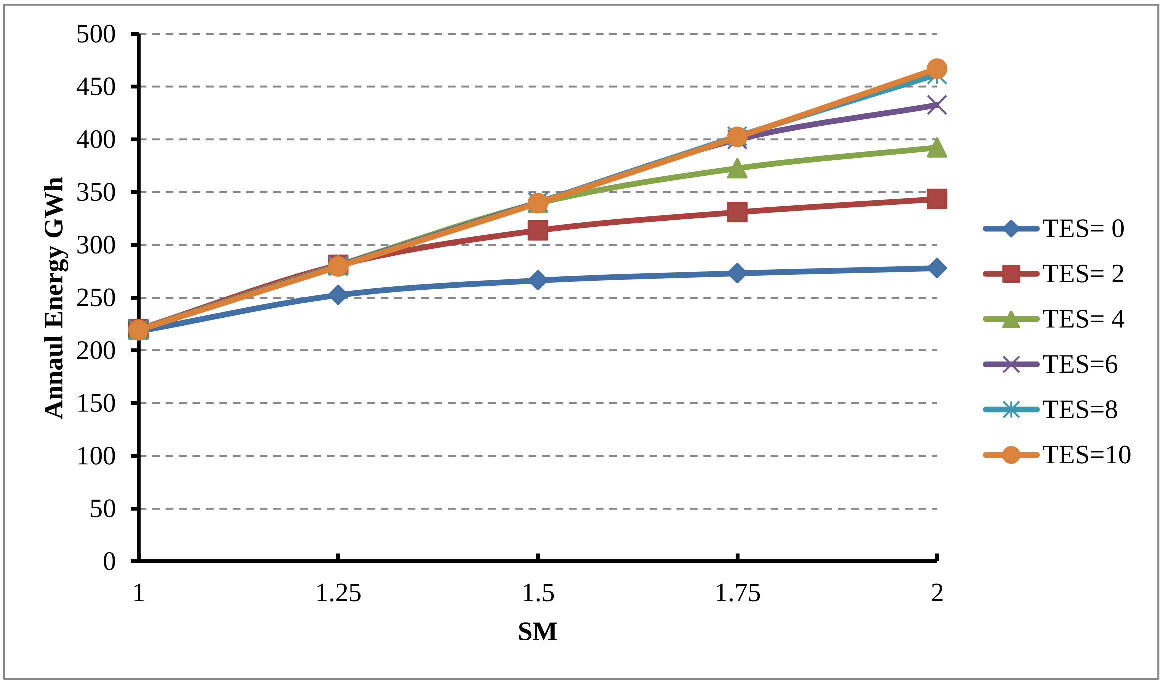


Figure 4.23: Levelised PPA price (real) (¢/kWh) vs. SM

All the above processes ensure that the most optimal design is selected, such that system costs can be minimised as well as PPA price, which should make this plant competitive in comparison with conventional energy sources. Therefore, SM of 1.25 and 2 solar field system subsections were selected for the system without thermal storage. It is believed that this direct system would operate in the most efficient and optimal way.

4.5.4. Simulation Results and Energy Yield for Optimised Design

Based on the specified technical parameters and the optimal design discussed earlier, the total aperture area of 585330 m² was obtained, and the predicted energy performance from the computer simulation is given in Figure 4.24. Simulation shows that the CSP plant will perform adequately all year round with a minimum monthly power generation capacity of about 13.1 GWh accruing on January with the peak power generation occurring in May with a total capacity of 27.90 GWh.

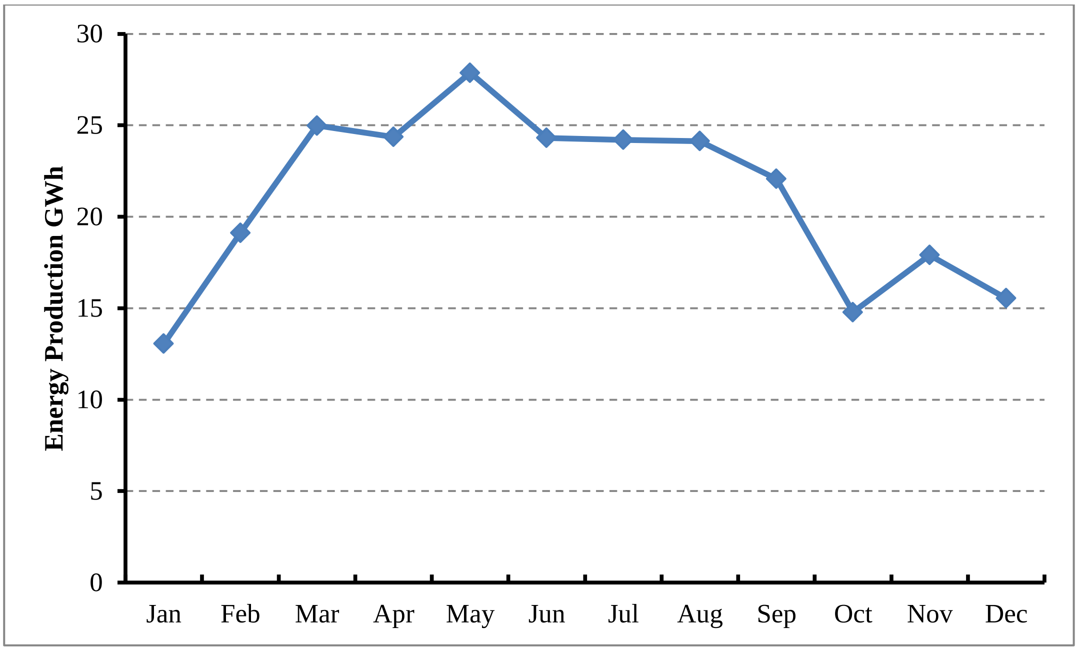


Figure 4.24: Monthly power generation at Wadi Aldawasir CSPP

Evaluated at around 252 GWh, the annual total power generation capacity would take up approximately 19% of power generation from the current Juba PP functioning on fossil fuel. The production of electricity from solar energy at this plant has a total thermal efficiency of around 28.8%.

It can also be observed in Figure 4.25 that the energy produced annually from the plant is on the decrease with a rate of 1% a year, which corresponds with the declining and degradation rate of the plant systems that were assumed in the design in relation to the efficiency of the plant for a period of 25 years.

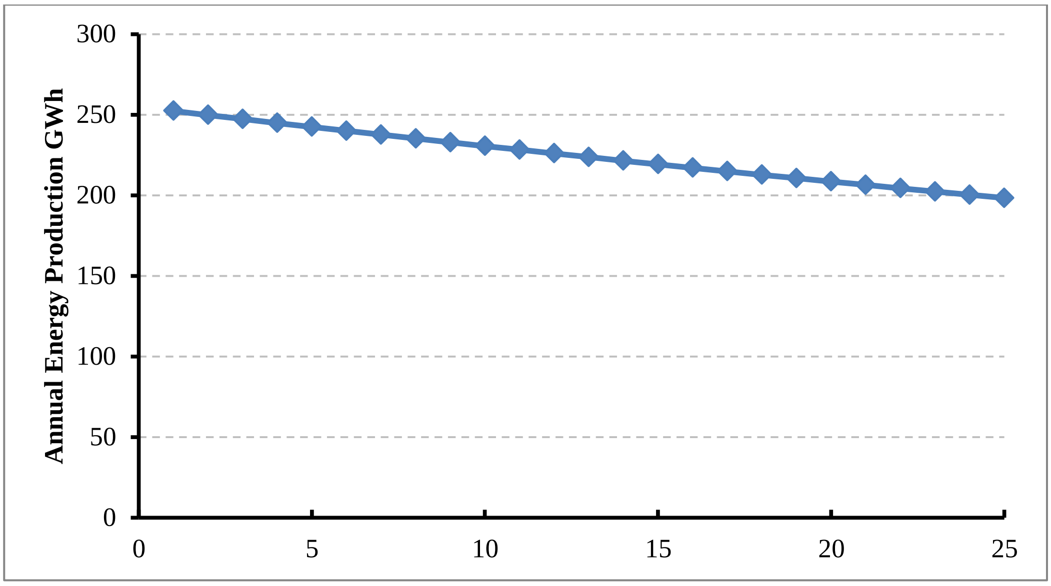


Figure 4.25: Yearly energy yield over 25 years at Wadi Aldawasir CSPP

Results obtained from the SAM software computer model on the project cost effectiveness are presented in Table 4.6. In this table, the solar PP is seen to have a nominal LCOE of around 18.76 c/kWh, which is competitive with unsubsidised electricity generation from fossil fuel power plants. More discussions about the results will be presented in the discussion section.

Table 4.6: SAM results

Metric	Base
Annual Energy	252. 362GWh
Cross to net conversion	84%
Capacity factor	28.8 %
PPA price (Year 1)	16.22 ¢/kWh
PPA price escalation	2.00 %
Levelised PPA price (nominal)	23.40 ¢/kWh
Levelised COE (nominal)	18.76 ¢/kWh
Net present value (NPV)	$104,499,888
Internal rate of return (IRR)	13.00 %
Year IRR is achieved	25
IRR at end of analysis period	13.00 %
Net capital cost	$ 317,354,304
Equity	$ 317,354,304
Total Land Area (km^2)	2.13 km^2

Both real and nominal LCOE values are determined by SAM for every financing option. The difference between the two values is that the former is a fixed dollar, inflation-adjusted value, while the latter is a current dollar value.

Analysis dictates whether real or nominal LCOE should be used. Long-term analysis covering numerous inflation years over the lifetime of the project is more compatible with real LCOE, whereas short-term analysis benefits more from nominal LCOE (SAM, 2014).

Therefore, as illustrated in Figure 4.26, the Real LCOE is at 15.63 ¢ / kWh and the value of PPA stands at 18.75 ¢ / kWh, which is a value that takes into account the impacts of the financial analysis, including inflation rates, for the whole duration (25 years).

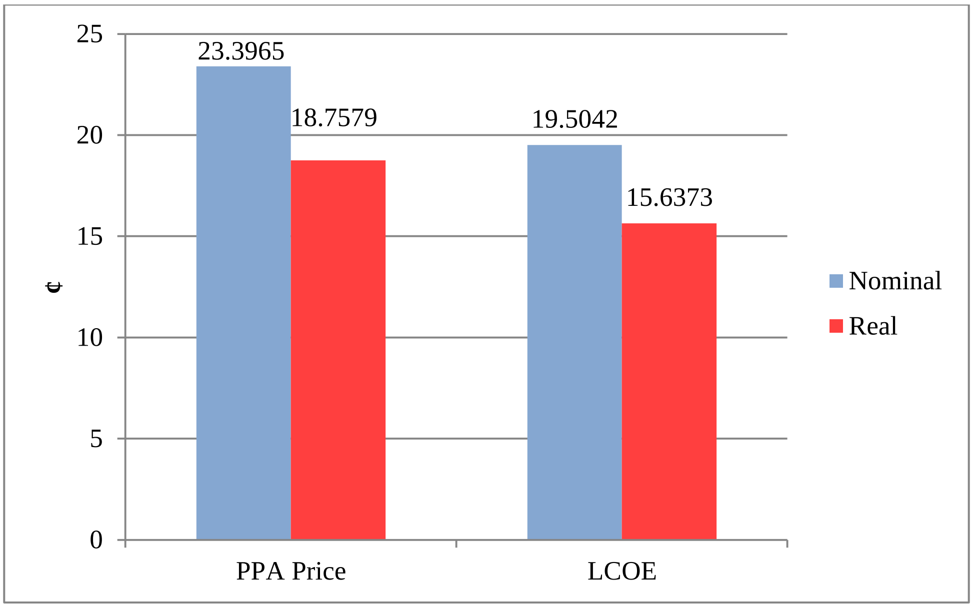


Figure 4.26: Nominal and real PPA price and LCOE

Given the aforementioned prices, the study proved that the project is in profit, when the IRR is equal to 13% at which the value of NPV is equal to zero.

However, other tests were carried out to determine the percentage of IRR at which the project would break even or less; i.e. not making profit or operating at a loss. Considering a price of 15.63 ¢ / kWh for LCOE, and a lower price for PPA, would lead to a loss. The LCOE price was used as a reference when conducting the analysis. As shown in Figure 4.27, the findings showed that with any IRR percentage at 9.2, the value of LCOE is equal to the price of the PPA, which renders the project unfeasible.

Achieving less than 9.2 may inevitably also mean that the project would be at a loss and that it would be even less feasible when the percentage continues to decline. The impact of the PPA and IRR prices for this project will be discussed later, taking into account the situation of the energy industry in KSA and government support for the sector.

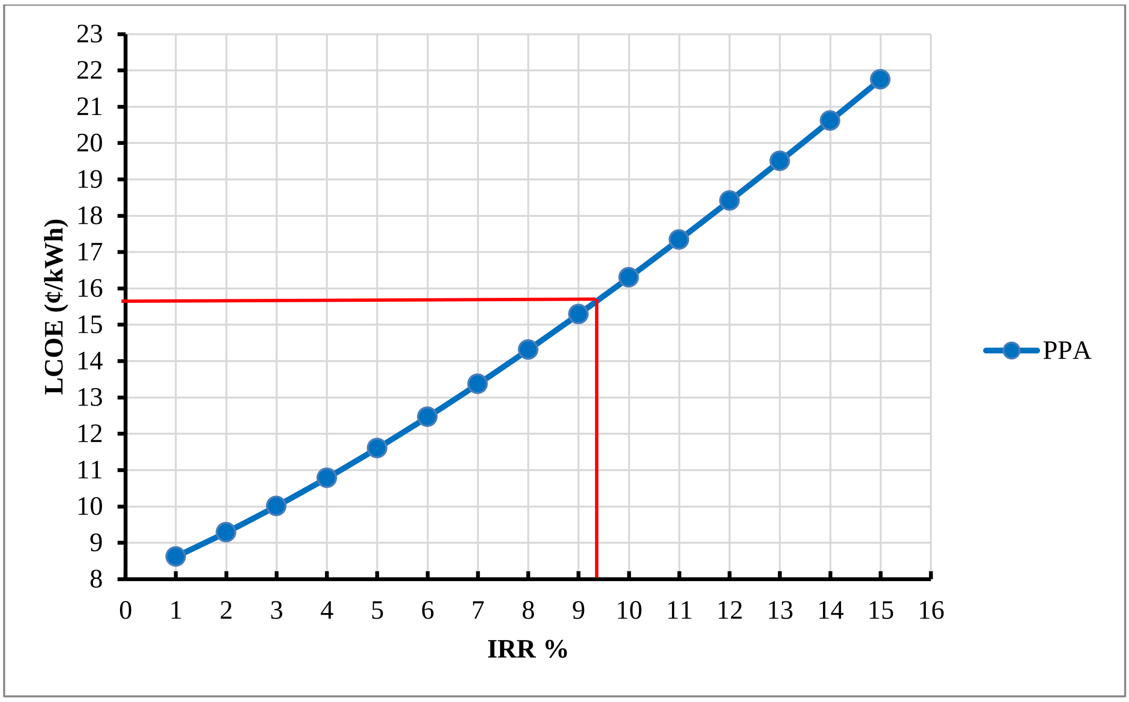


Figure 4.27: Profitable IRR% with PPA vs LCOE

These costs of the plant are distributed, as illustrated in Figure 4.28, over six main sections, with the solar field as the highest at a rate of 45% of the value of the plant. This indicates that in CSP power plants, technology is seen as the most important aspect, and the costliest in terms of providing free fuel for the solar plant, because the solar field represents fuel as in fossil fuel power plants. This also applies to HTF, with its cost ratio of the net cost of the plant amounting to approximately 14%.

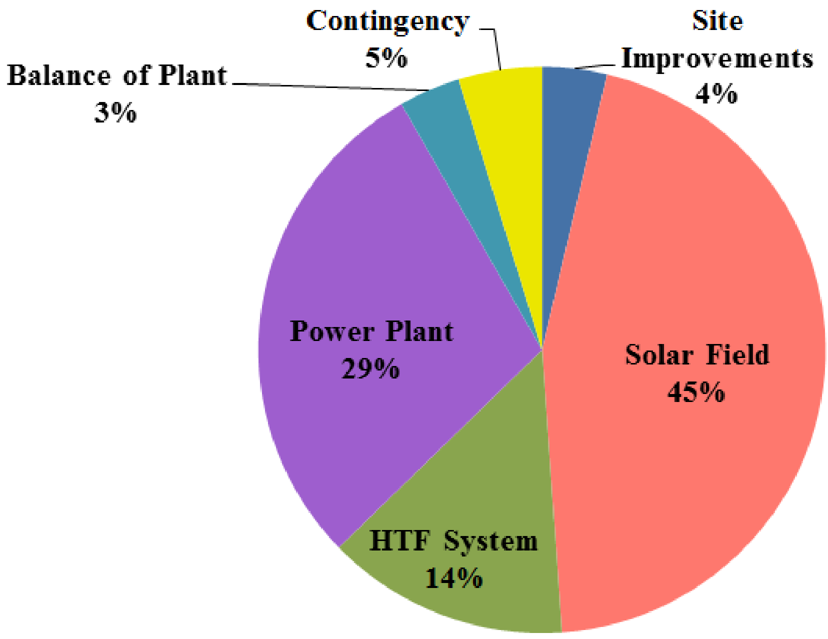


Figure 4.28: Cost breakdown for the proposed CSPP at Wadi Aldawasir

Project total revenue throughout the complete CSPP life cycle is presented in Figure 4.29. It can be noted that total revenue equals $ 64 Mil in the final year of operation. As expected, revenue increases from the initial years in the operation until CSPP reaches the end of its life cycle.

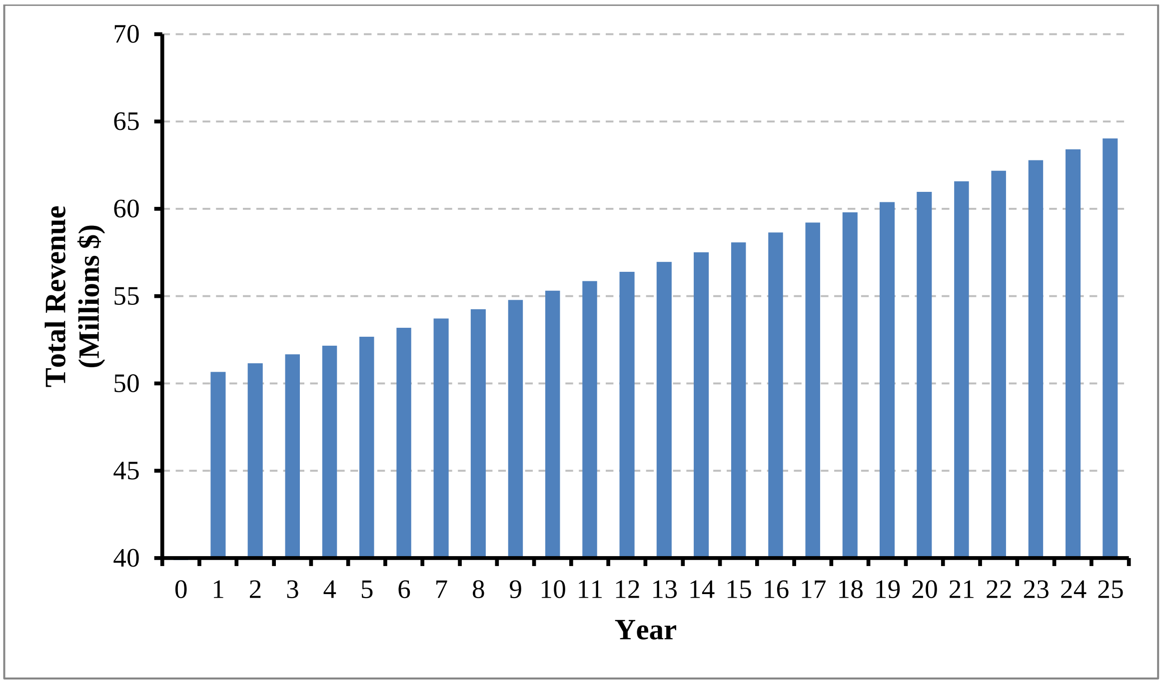


Figure 4.29: Total revenue at Wadi Aldawasir CSPP

Post-tax cumulative IRR (%) is shown in Figure 4.30. IRR is a measure of the project profitability, and it can be seen that the target 13% IRR is reached after 7 years in operation. IRR at the end of service equals 13%.

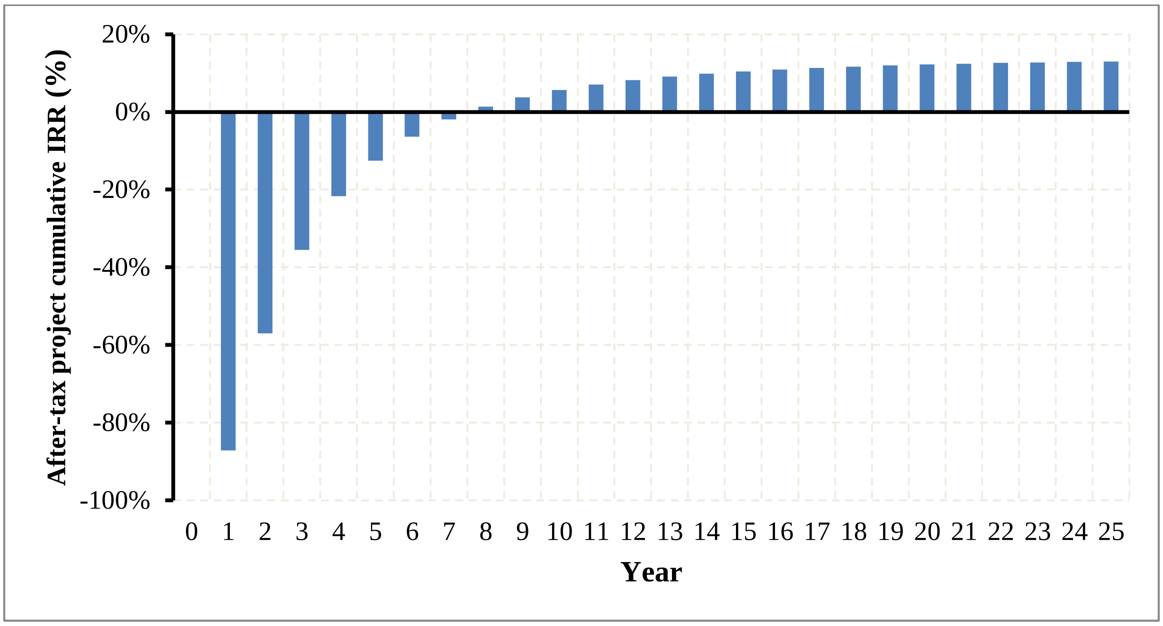


Figure 4.30: Post-tax project cumulative IRR (%) at Wadi Aldawasir CSPP

Project cash flow is shown in Figure 4.31. It can be seen that cash flow steadily increases from the initial year in operation until the CSPP is decommissioned. Negative cash flow is only seen in the first year of operation.

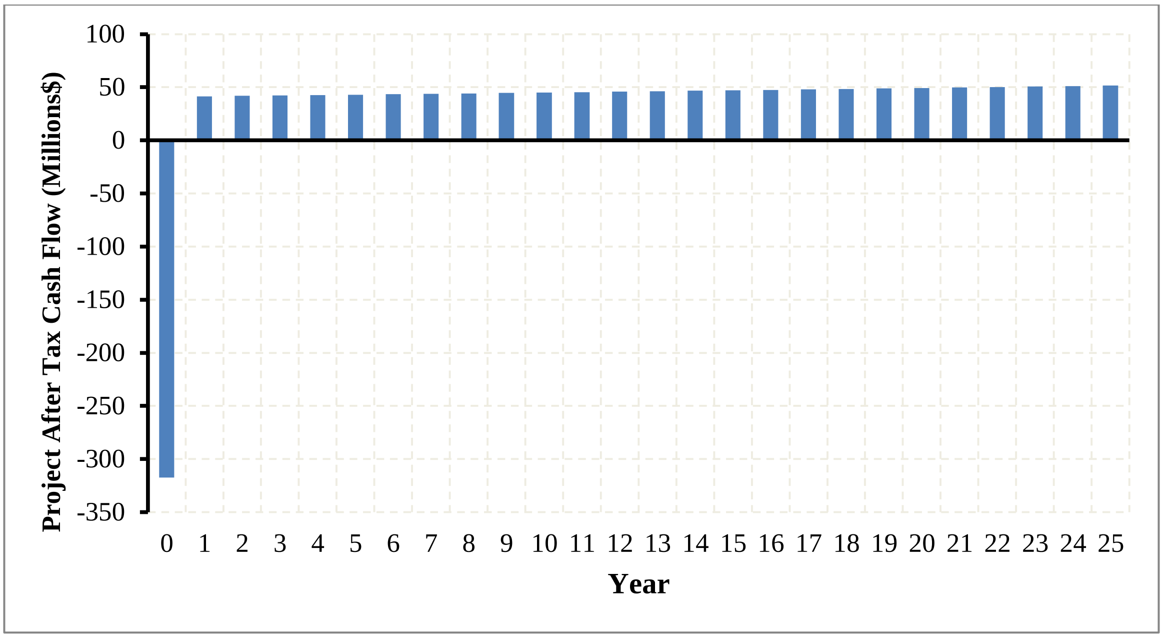


Figure 4.31: Post-Tax project returns cash total ($) at Wadi Aldawasir CSPP

Post-tax project returns are shown in Figure 4.32. It may be noted that the project operates with a loss in its initial year, while returns rise in subsequent years of operation.

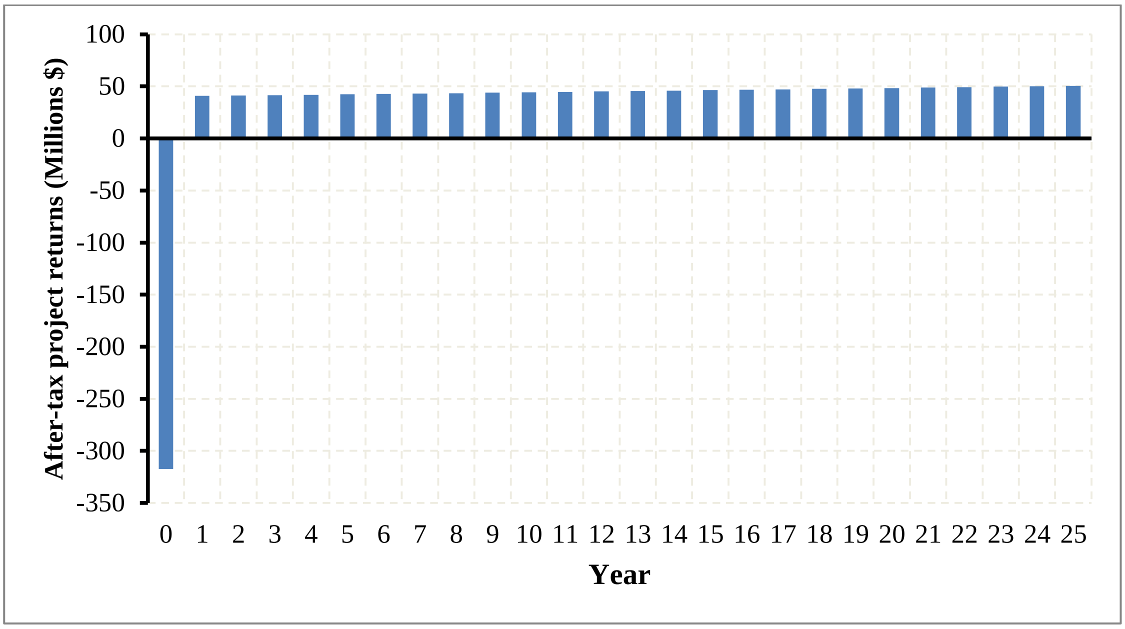


Figure 4.32: Post-tax project returns ($) at Wadi Aldawasir CSPP

Project NPV ($) is shown in Figure 4.33. NPV reaches balance after 12 years of operation, after which it becomes positive, which is a promising trend for the feasibility of the plant.

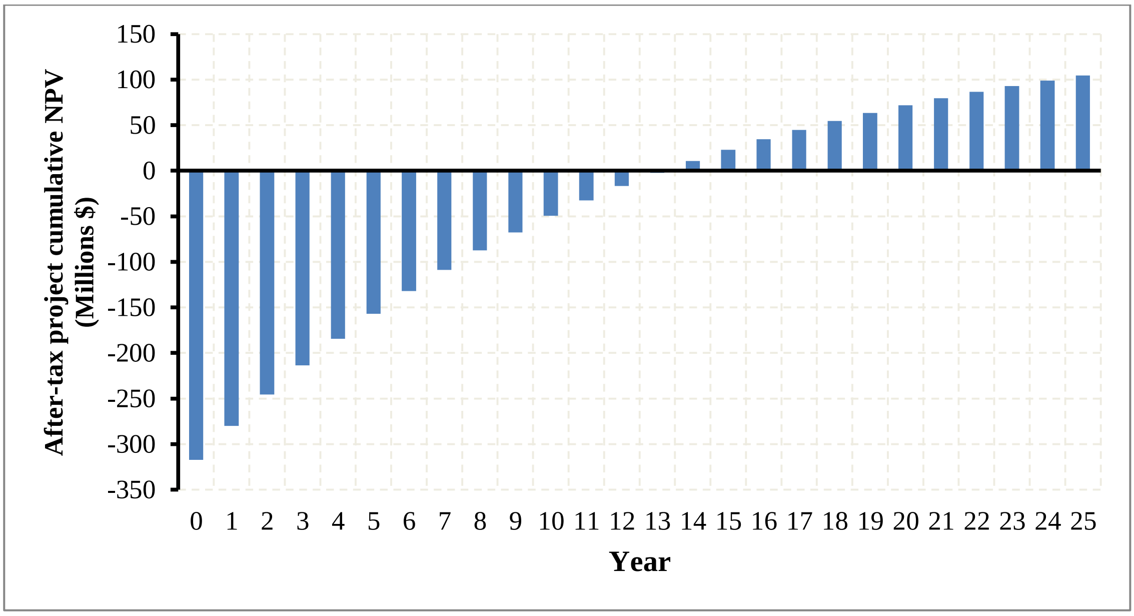


Figure 4.33: Post-tax project cumulative NPV ($) at Wadi Aldawasir CSPP

4.6. RETScreen Software Analysis

After using SAM in the study and analysis of the PP, as well as achieving results, another analysis was undertaken on the same plant. The same data and results adopted and obtained previously are referred back to using the RETScreen program, which, in turn, will give fresh readings due to the different methods in terms of entering the data and producing the relevant results. It should be pointed out that an analysis of emissions and risk was performed using this program, as it was not provided by SAM. It is then be followed by an analysis of the pages available in the program, as well as an illustration of inputs and how they are incorporated in every page.

- **Climate data**

The required data was entered in the first page of the program, as shown in Figure 4.34, including most importantly the choice of the type of power for the project. Solar thermal power was selected because the RETSCreen program studies and analyses the situation in general, and does not have an option to specify the type of technology to be used, be it parabolic trough or otherwise. Method 2 was also chosen to analyse and study the situation in the five pages provided by the program, instead of method 1, which gives a very brief review of the five pages of the study. One of the most important inputs in the first page is determining the location of the plant; and for this, the city of Sulayel was selected for being very close to the plant site, as stated in *Chapter 3*. The weather data was downloaded from the program database, as can be seen in Figure 4.34.

Comprehensive climate information for several locations can be derived from the RETScreen software. The NASA Prediction of Worldwide Energy Resource (POWER) project has been initiated by the Langley Research Centre at NASA and CanmetENERGY and is the source of the climate data for CSPP simulation.

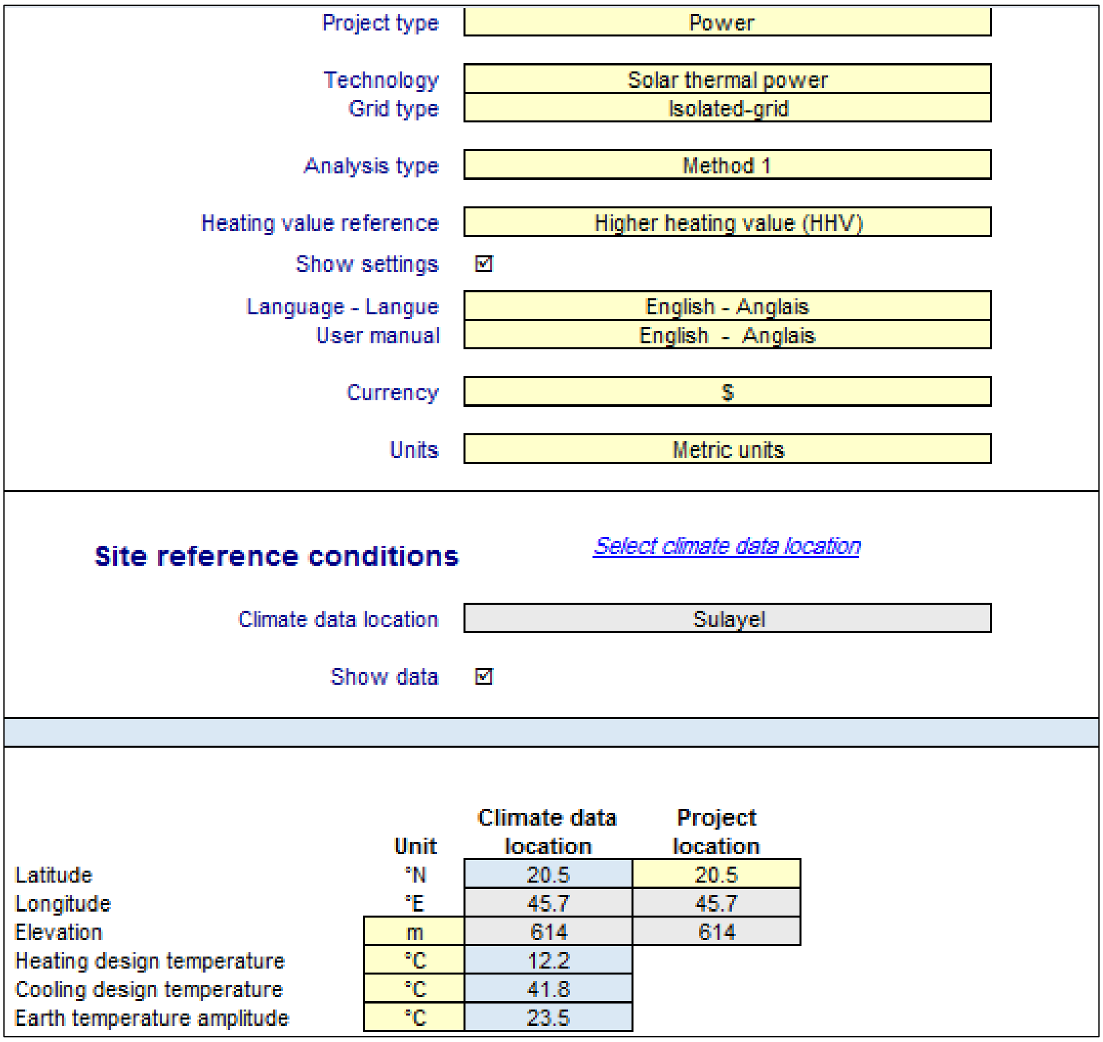


Figure 4.34: Start page and weather data in Wadi Aldawasir

- **Energy model**

The same model underpinned by solar thermal power technology is supplied by RETScreen for all CSP technologies in relation to CSPP modelling, without any arrangements for a possible coupled storage system. Power stations with single source or multiple sources, isolated or linked to the grid with or without internal load, are available for users to choose from.

In the context of CSPP modelling, installed power (power capacity) and the capacity factor (CF) are used to determine the estimated output of the plant. The CF represents the ratio of the average annual plant-generated power to its rated power capacity. As such, the interplay between the climate information associated with a particular location and the output of a CSPP is not managed directly by the software. Furthermore, user assistance takes the form of the mere supply of a 20-70% CF rate. Additional facets of possible discrepancies between CSPPs are treated similarly.

In this design, the same value of CF achieved in the previous results through the SAM program is supposed to be used, which is 28.8; however, it cannot be relied upon, because RETScreen does not take into account the degradation of the system over the 25-year period. In order to calculate this, the power plant's mean energy produced annually has been accounted for during the whole period by depending on the values shown in Figure 4.25 previously, with the average annual value of the energy produced standing at 244 GWh. Therefore, the CF has been computed and a value of 25.57 reached, which will be used in the analysis. The electricity export rate was also entered at 187.5 $ / MWh, which is the PPA real value achieved through the SAM program.

Figure 4.35 shows the design page for the Energy Model.

The RETScreen energy model sheet is shown in Figure 4.35. It may be noted that annual delivered energy is about 244 GW. This is an average of the annual energy produced by the system over 25 years in GWh.

RETScreen Energy Model - Power project				
Proposed case power system				
Technology		Solar thermal power		
Solar thermal power				
Power capacity	kW	100,000		
Manufacturer		Abengoa Solar		
Model		PS10		
Capacity factor	%	25.6%		
Electricity exported to grid	MWh	223,993		
Electricity export rate	$/MWh	187.50	$/kWh	0.188
		Complete Cost Analysis sheet		

Figure 4.35: Energy model worksheet

- **Cost Analysis**

The next step is to define overall project costs.

The analysis was based on two main sections; namely the initial costs and annual costs. It adopted the value of the direct capital cost of the plant obtained from the SAM program. A value of 5% was also taken into account for contingency. As for the section on annual costs, the cost of O & M was estimated at $ 30 per MWh for the entire annual volume of energy produced (252.362 MWh) and without declining production, because it is known that this cost relatively increases with increasing life of the plant. The cost of insurance was estimated at 0.5% of the full cost of the plant, and was entered into the program as a cut off value of $ 1.58836 million, in addition to 5% contingency for annual expenses in order for the financial analysis to be more conservative.

RETScreen automatically calculates overall system costs by summarising initial costs at $ 317,354,100 and annual costs at $ 9,617,175. Since SAM and RETScreen have different calculation methodologies, it is important to mention that not all input parameters are labelled in the same way. However, it is important to set them in a way that they provide accurate final figures as has been done in this modelling.

The costs analysis sheet is shown in Figure 4.36.

Initial costs (credits)	Unit	Quantity	Unit cost	Amount	Relative costs
Feasibility study					
Wadi Aldawasir	cost	1		$ -	
Subtotal:				$ -	0.0%
Development					
Development	cost	1		$ -	
Subtotal:				$ -	0.0%
Engineering					
Engineering	cost	1		$ -	
Subtotal:				$ -	0.0%
Power system					
Solar thermal power	kW	100,000.00	$ 3,022	$ 302,242,000	
Road construction	km	1		$ -	
Transmission line	km	0	$ -	$ -	
Substation	project	0	$ -	$ -	
Energy efficiency measures	project	0		$ -	
equipment	cost	1		$ -	
thermal storage		0		$ -	
Subtotal:				$ 302,242,000	95.2%
Balance of system & miscellaneous					
Spare parts	%	0.0%		$ -	
Transportation	project	0		$ -	
Training & commissioning	p-d	0		$ -	
	cost			$ -	
Contingencies	%	5.0%	$ 302,242,000	$ 15,112,100	
Interest during construction		12 month(s)	$ 317,354,100	$ -	
Subtotal:				$ 15,112,100	4.8%
Total initial costs				$ 317,354,100	100.0%

Annual costs (credits)	Unit	Quantity	Unit cost	Amount
O&M				
Parts & labour	project	1	$ 1,588,360	$ 1,588,360
User-defined	cost	252,362	$ 30	$ 7,570,855
Contingencies	%	5.0%	$ 9,159,215	$ 457,961
Subtotal:				$ 9,617,175

Figure 4.36: RETScreen cost analysis

It may be noted that using the above listed input parameters, overall project costs are slightly similar to the system cost obtained from SAM, because similar costs with different calculation behaviours are relied upon in the two software programs.

- **Emission Analysis**

One of the major analyses in this case study is the analysis of emissions. The latter are calculated using the RETScreen program, which gives results directly affecting the environment. Since protection of the environment and reduction of emissions are among the main reasons for using solar plants, identifying a framework on the benefits that will be gained for the design upon a study of the plant will lead to a deeper analysis of the positive effects on the environment through the adoption of this study.

RETScreen software provides a very convenient way to complete emissions analysis. Method 1 is used for this purpose and the base case electricity system for KSA was selected from the list of available countries. The GHG emission factor for all types of fuel was automatically set to 0.737 tCO_2/MWh. Results indicate for the base case electricity system using 100% fuel mix, electricity production of 223.993 MWh will generate 183,371 tCO2 while from the CSPP, it is equivalent to 18,337 tCO2 taking into account the transmission and distribution (T&D) losses at 10%. Therefore, reduction of 165,034 tCO2 will accrue when the CSPP is considered as an alternative to the fossil fuel one. This is equivalent to a reduction of 30,226 cars and trucks. The RETScreen emission analysis sheet is shown in Figure 4.37.

Base case electricity system (Baseline)

Country - region		GHG emission factor (excl. T&D) tCO2/MWh	T&D losses %	GHG emission factor tCO2/MWh
Saudi Arabia	All types	0.737	10.0%	0.819

☐ Baseline changes during project life

Base case system GHG summary (Baseline)

Fuel type	Fuel mix %	Fuel consumption MWh	GHG emission factor tCO2/MWh	GHG emission tCO2
Electricity	100.0%	223,993	0.819	183,371.6
Total	100.0%	223,993	0.819	183,371.6

Proposed case system GHG summary (Power project)

Fuel type	Fuel mix %		T&D losses	Fuel consumption MWh	GHG emission factor tCO2/MWh	GHG emission tCO2
Solar	100.0%			223,993	0.000	0.0
Total	100.0%			223,993	0.000	0.0
Electricity exported to grid	MWh	223,993	10.0%	22,399	0.819	18,337.2
					Total	18,337.2

GHG emission reduction summary

	Base case GHG emission tCO2	Proposed case GHG emission tCO2	Gross annual GHG emission reduction tCO2	GHG credits transaction fee %	Net annual GHG emission reduction tCO2
Power project	183,371.6	18,337.2	165,034.4	0%	165,034.4

Net annual GHG emission reduction 165,034 tCO2 is equivalent to 30,226 Cars & light trucks not used

Complete Financial Analysis sheet

Figure 4.37: RETScreen emission analysis

- **Financial Analysis**

The financial sheet in RETScreen allows selection of key financial indicators that define commercial feasibility of the project. A summary of financial parameters is provided in Table 4.7 below.

RETScreen as a software does not provide an automatic optimisation process to reach a desired project objective. Instead, this process needs to be done manually by changing a few input parameters until the objective is reached. The objective was to reach simple payback after 25years, while other costs were kept constant.

The financial analysis adopted the same values assumed in the financial analysis using the SAM program. The same values were assumed and entered based on what had illustrated early in SAM section. It should be noted that the insurance rate had already been calculated in the cost analysis page.

Table 4.7: RETScreen Financial input parameters

Page	Variable	Input Value
Financial Analysis	Minimum Required IRR	Will be calculated
	Analysis period	25 Year
	PPA Escalation Rate	2 %
	Inflation Rate	2.1 %
	Real Discount Rate	7 %
	Federal Income Tax	2.5%
	State Income Tax	0 %
	Insurance Rate	0.5 %
	Debt percent	0 %
	Construction Period - Months	24
	Annual Interest Rate	2 %
	Depreciation	4 % per year
	Degradation rate	Not measured

The financial analysis worksheet is provided in Figure 4.38.

Financial parameters		
General		
Fuel cost escalation rate	%	2.0%
Inflation rate	%	2.1%
Discount rate	%	7.0%
Project life	yr	25
Finance		
Incentives and grants	$	0
Debt ratio	%	0.0%
Income tax analysis	☑	
Effective income tax rate	%	2.5%
Loss carryforward?		No
Depreciation method		Straight-line
Depreciation tax basis	%	4.0%
Depreciation period	yr	25
Tax holiday available?	yes/no	No
Annual income		
Electricity export income		
Electricity exported to grid	MWh	223,993
Electricity export rate	$/MWh	187.50
Electricity export income	$	41,998,725
Electricity export escalation rate	%	2.0%

Project costs and savings/income summary			
Initial costs			
Power system	95.2%	$	302,242,000
Balance of system & misc.	4.8%	$	15,112,100
Total initial costs	**100.0%**	**$**	**317,354,100**
Annual costs and debt payments			
O&M		$	9,617,175
Fuel cost - proposed case		$	0
Total annual costs		**$**	**9,617,175**
Periodic costs (credits)			
Annual savings and income			
Fuel cost - base case		$	0
Electricity export income		$	41,998,725
Total annual savings and income		**$**	**41,998,725**

Figure 4.38: RETScreen financial analysis

Based on the previous financial assumptions, the program updated the evident results in Figure 4.39. It is noted that the energy production cost was calculated at $ 145.43 / MWh, which translates into an IRR at 11.2%. Thus, meeting the payback period in the tenth year with an NPV of almost $ 130 million. The results showed little difference compared to those achieved using the SAM software. As a result, the major findings will be discussed according to each program separately and the reasons for the differences and similarities in order to gain clear insights into the most likely results to be adopted.

Financial viability		
Pre-tax IRR - equity	%	11.2%
Pre-tax IRR - assets	%	11.2%
After-tax IRR - equity	%	10.9%
After-tax IRR - assets	%	10.9%
Simple payback	yr	9.8
Equity payback	yr	9.1
Net Present Value (NPV)	$	130,780,908
Annual life cycle savings	$/yr	11,222,377
Benefit-Cost (B-C) ratio		1.41
Energy production cost	$/MWh	145.43
GHG reduction cost	$/tCO2	(68)

Figure 4.39: Financial viability

The following figure 4.40 provides a brief descriptive graph of the cumulative cash flows of the proposed plant.

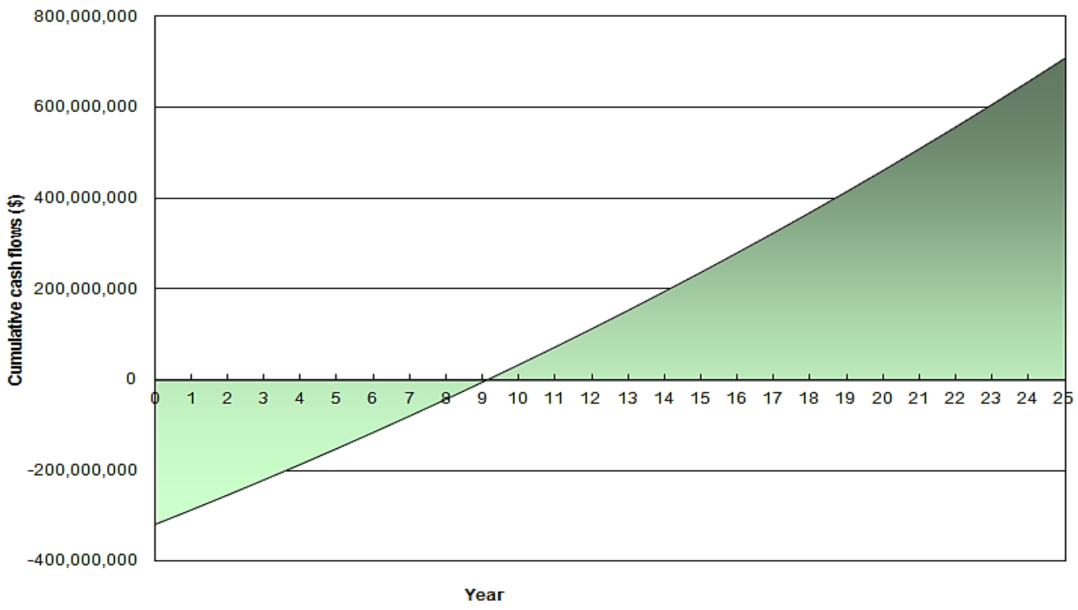


Figure 4.40: Cumulative cash flow of the proposed CSPP

4.7. Results Comparison of SAM and RETScreen Analysis

Table 4.8 shows the most important results obtained through the two programs that should contribute to a better description of the feasibility of the project and analysis of the identified findings.

Table 4.8: Results comparison

Software	SAM	RETScreen
Annual Energy (GWh)	252.362	223.993 (Average over 25 years)
Capacity factor	28.8 %	25.6 % (Average over 25 years)
PPA price (¢/kWh)	18.7579	18.7579
LCOE (¢/kWh)	15.6373	14.543
IRR (%)	13 %	11.2%
Payback period	13	9.1
Net capital cost (m$)	317,354,304	317,354,304
Net present value (m$)	104,499,888	130,780,908

The energy produced from the PP, which was calculated through the SAM program is arguably equal to the result achieved using the RETScreen program, taking into account the mean CF of 25.6 for the plant over a period of 25 years. This is a positive indicator allowing the adoption of the SAM results, because they simulate the behaviour of the energy produced from the station during its years in operation, while taking into account the rate of degradation in the system, when carrying out the financial analysis.

The PPA in the SAM results were obtained from the technical and financial design of the PP; however, the results achieved using the RETSCreen program were analysed and studied from a purely financial point of view. As such, it was thought useful to refer directly to the results emanating from the SAM and entering them into the RETScreen program in order to confirm them or gain fresh results for the financial analysis and feasibility of the project, especially the price of the LCOE.

It is clear that the LCOE results in the SAM program are higher than the results of the RETScreen, which may impact on the results of the financial analysis in terms of profits, IRR, payback period, and NPV.

Some of the interesting results identified using RETScreen program include IRR at 11.2, simple payback at 9.8, and NPV at 130 $ million, which appear to be more useful than the results obtained using the SAM program. However, when taking into account the feasibility factors, it is certainly the case that the conservative results achieved by the SAM program will be more useful and dependable. Especially since they have taken into account accurate details of technical and financial specifications of the plant in a way that simulates the behaviour of the PP almost as in reality.

According to the abovementioned results, the results identified using SAM will be adopted given their realism, as emphasised in the financial analysis using the RETScreen program as a verification tool. While there were similarities as shown in the findings, one should take into account the reasons cited for the slight differences. As identified in the analysis, the results obtained using RETScreen refer to the environmental analysis, which is considered a positive feature that was missing in the SAM program among other significant results.

It is important to mention that due to differences in software tools results cannot be exactly the same. This particularly refers to models RETScreen modelling capabilities for coupled CSP technologies. On the other hand SAM software provides full set of options to properly calculate energy production, CF and associated costs. It can be concluded that SAM software tool would be the preferred choice for CSPP technology simulation.

4.8. Discussion

This study covered the Wadi Aldawasir location in KSA. The area is supplied by Juba PP having a generation capacity of 400MW. The plant consumes 5,265,185 barrels of crude oil annually at a cost of 26.6 $/m3. The scope here is to investigate the feasibility of using CSP plant with a capacity of 100 MW for future expansion, to meet the population growth and economic development of the area, using parabolic trough solar thermal technology for power generation.

This area is a strong candidate for CSP plant, because it lies on the solar belt as shown in figure 4.5 where the GHI = 2433 Kwh/m2/yr. and the average annual direct normal irradiance = 2754 Kwh/m2/yr, which is considered to be very high solar radiation.

Molten salt was chosen to be the Heat transfer fluid (HTF) for the system, because it has a higher operating temperature than oil, costs less than oil, and has greater energy density. More importantly is that direct thermal storage uses the same type of molten salt. However, later, the simulation and optimisation result recommended no energy storage, because the average sunshine hours in the day is higher than 11.5 hour for the whole year, as shown in Figures 4.41 and 4.42. These figures show that the shortest day is December 21 with 10:53 hours of daylight, while the longest day is June 20 with 13:22 hours of daylight. The earliest sunrise is at 5:18 am on June 9 and the latest sunset is at 6:44 pm on July 2. The latest sunrise is at 6:38 am on January 16, while the earliest sunset is at 5:17 pm on November 26 (Weatherspark, 2015). Therefore, the average working hours = 11.5 for all seasons, and accordingly, the plant is working for 48% of the time.

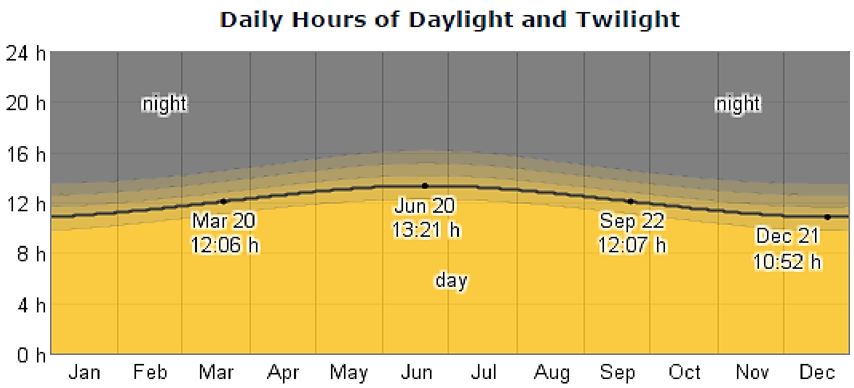


Figure 4.41: The length of the day over the course of the year for Wadi Aldawasir

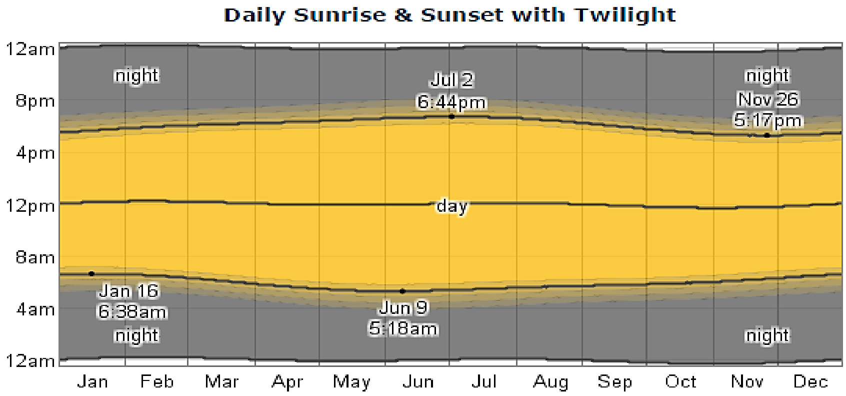


Figure 4.42: Daily sunrise and sunset for the whole year at Wadi Aldawasir

Results show that the total land area for the solar field = 2.13 Km2 , around 0.6 Km2 of them are the total aperture area, number of loops = 179. Hence, each loop will occupy an area of 3,270 m2. Figure 4.43 presents a satellite image for the site, and the availability of land for the project. Indeed, there is still enough empty land to accommodate future expansion.

Figure 4.43: Satellite image for the site and the availability of land for the solar plant

Main relevant aspects of the case study results will be discussed in the following sections

4.8.1. Discussion on Technical Feasibility

With a total aperture area of 585,330 m² and an optimal selected SM of 1.25, the solar plant could generate 252.362 GWh of energy per year. This high value is due to the correspondingly high DHI in the environs of Wadi Aldawasir. Indeed, KSA lies within a region of high solar resource. With proper exploitation of this resource, KSA could become a major exporter of solar energy and technology. The new CSPP may be combined with an existing fossil fuel plant, with potential cost reductions.

This additional 252.362 GWh annually from the parabolic trough CSPP would boost generation capacity in Juba plant power from 2752.0 GWh to 3004.362 GWh during daylight hours. Expanding Juba PP generation using a CSPP will allow meeting future population growth and economic development, while reducing GHG emissions. Currently, Juba plant is a grid-isolated oil-fired PP with a 400 MW generation capacity. This integration of a solar power plant with another PP is termed Integrated Solar Combined Cycle (ISCC). This recent hybrid technology enables increased generation capacity and reduction of fossil fuel use. It also enables faster plant starting times and reduced gas consumption during start up operating conditions. The Archimedes solar power plant in Italy is the first ISCC plant in the world, starting operation in 2010. Table 4.9 shows the list of existing ISCC plants in operation around the globe. ISCC is an integrating method used by countries with viable DHI to increase power generation, and remain environmentally friendly. The data is sourced from NREL database (NREL, 2015).

Table 4.9: Existing ISCC plants currently in operation round the globe

Name	Country	Capacity (MW)	Start year	Elect Gen/yr	Cost (million)	Fossil Type	Period
Solacor 2	Spain	50	2012	98000	€153	Biomass (2x22MWt)	25
ISCC Demonstration project	Canada	1.1	2014		$9	Natural gas	
Colorado Integrated	USA	2.0	2010		$4.5	Coal plant	

Name	Country	Capacity (MW)	Start year	Elect Gen/yr	Cost (million)	Fossil Type	Period
Solar Project							
ISCC Kuraymat	Egypt	20	2013	34000		fossil fuel	25
ISCC Hassi R'mel	Algeria	20	2011		€315	fossil fuel	
Martin Next Generation Solar Energy Center (MNGSEC)	USA	75	2010	155000	$476	fossil fuel	
Shams 1	United Arab Emirates	100	2013	210000	$600	Natural gas	25
Solar Electric Generating Station II (SEGS II)	USA	33	1985				
Agua Prieta II	Mexico	14	2014	34000		fossil fuel	
ISCC Ain Beni Mathar	Morocco	20	2010	55000		fossil fuel	25

LCOE is a constant unit price ($/MWh) for comparing and analysing the costs and viability of power plants. It could be used to compare different capital expenditure paths, differing annual costs and different net outputs. The value of money today does not have the same economic value as next year or in 30 years. In order to properly add costs that occur at different points in time, these are converted into "present value" terms, using "discounting." This ensures that inflation and other factors are captured in feasibility studies. One of the key considerations in selecting energy generation technology apart from its carbon footprint is its economic impact. With a high investment cost, CSPPs require detailed financial feasibility analysis to inform their development to large commercial-scale in KSA. Wherever an appropriate location is selected, CSPPs will be an economically viable option for electricity generation. One of the most important aspects utilised in deciding the feasibility and cost-effectiveness of the PP is LCOE. In the differences of the configuration of CSPPs, one can note that

LCOE is a much more effective signifier of true cost than installed cost. As for the CF (or load factor), it can vary over a wide variety for CSPPs. There are variously sized generators for plants with identical parts of solar field, and yearly energy yields. These generators may have been reliant on whether or not they have energy storage, which renders LCOE a crucial factor in feasibility literature (Lovegrove et al., 2013, Kost et al., 2013).

On the other hand, a fairly low LCOE signifies that electricity is being generated in a cost effective way, with possible greater yields for the investing authority. For optimal performance of the Juba solar plant, the LCOE value is 15.6 cents, and has the potential of being as low as conventional energy cost. An optimal levelised PPA price of 18.7579 ¢/kWh is selected to give a good return of investment for SEC. The PPA is a financial contract, in which one party develops, owns, operates, and maintains the PP, and another party agrees to purchase the electricity generated. This agreement permits the customer to receive a stable and lower cost electricity. On the other hand, the solar energy provider receives stable income from the sale of electricity generation. Table 4.10 shows the US average levelised costs ($/MWh) for plants entering service. Conventional energy generation plant currently offer cheaper levelised capital cost, because most renewable energy generation technologies are still in their infancy, with more research and development required to mature them. It is good to note that the total system LCOE cost of conventional plant does not capture the impact of waste and the cost of disposal. Although data is not available, factoring waste from conventional energy generation plants will increase the total system LCOE, making it greater than for renewable energy generation plants. The data are average values with a variation of about 20% (EIA, 2015a). The US currently has one of the largest investment programmes in solar energy generation. This is frequently used as reference in comparison of power plants by other countries. The data from Table 4.10 is used for comparison as most power plants will have similar capital costs (EIA, 2015b).

Table 4.10: US average levelised costs ($/MWh) for plants entering service

Plant type	CF (%)	Levelised capital cost	Fixed O&M	Variable O&M (including fuel)	Transmission investment	Total system LCOE
Conventional Coal	85	60.4	4.2	29.4	1.2	95.1
Advanced Coal	85	76.9	6.9	30.7	1.2	115.7
Advanced Coal with CCS	85	97.3	9.8	36.1	1.2	144.4
Natural Gas-fired						
➢ Conventional Combined Cycle	87	14.4	1.7	57.8	1.2	75.2
➢ Advanced Combined Cycle	87	15.9	2.0	53.6	1.2	72.6
➢ Advanced CC with CCS	87	30.1	4.2	64.7	1.2	100.2
➢ Conventional Combustion Turbine	30	40.7	2.8	94.6	3.5	141.5
➢ Advanced Combustion Turbine	30	27.8	2.7	79.6	3.5	113.5
Advanced Nuclear	90	70.1	11.8	12.2	1.1	95.2
Geothermal	92	34.1	12.3	0.0	1.4	47.8
Biomass	83	47.1	14.5	37.6	1.2	100.5
Wind	36	57.7	12.8	0.0	3.1	73.6
Wind – Offshore	38	168.6	22.5	0.0	5.8	196.9
Solar Photo voltaic	25	109.8	11.4	0.0	4.1	125.3
Solar Thermal	20	191.6	42.1	0.0	6.0	239.7
Hydroelectric	54	70.7	3.9	7.0	2.0	83.5

The simulation result shows a gross to net conversion of 84 % (0.84) from the gross generation of 111MW. The energy losses during the conversion accounts for the reduction of about 16%. The high performance of the solar plant will be dependent on certain key factors in order to maintain the 100MW power generation. Inevitable losses arise within a parabolic trough plant from geometric, optical and thermal factors. Sandstorm events need to be managed properly to maintain power generation levels. This is unique to solar fields situated in a desert region.

4.8.2. Power Plant Availability

PP availability refers to the amount of time that a plant is able to generate electricity over a specified period with respect to the amount of time in the period. In circumstances where partial capacity is available, such as using a parabolic trough system without thermal storage, PP availability is estimated based on the feasible period of operation, i.e. daylight hours. PP availability is different from the CF, and is always more than the CF over the same period. This difference between plant availability and CF depends on the utilisation of the PP. PP availability varies depending on plant operation, design and energy source. The actual CF depends on the PP availability factor, since the CF captures the period and the percentage of the existing output over a timescale of one year and its output if it had been functioning at nominal power for the whole year. From the simulation result, the CF is 28.8%, which lies in the interquartile range of most parabolic trough systems, as shown in table 4.11 (IRENA, 2012). At present, the capacity factors of parabolic trough plants are approximately in the region of 23-28% without taking storage into account. According to NREL (2011), when it comes to parabolic trough solar systems, they are usually available for 98%. It is worth mentioning that typical values for CF, according to the US Energy Information Administration (EIA), are nuclear 90.3%, coal 63.8%, natural gas 42.5%, hydroelectricity worldwide average 44%, renewables (wind/solar/biomass) 33.9%, wind farms 20-40%, CSP solar with storage and natural gas backup in Spain 63%, PV solar in Arizona 19%, PV solar in Massachusetts 13-15%, and oil 7.8%. Some of the examples for CSP plant, such as the CSP solar in California, the CF is 33%, and so for this solar field, 28.8%, is acceptable.

Table 4.11: Capacity factors of parabolic trough solar systems

Location	Heat transfer fluid	SM	Storage (hrs)	CFs (%)	Cost (USD/KWe)
USA	Synthetic oil	1.3	0	26	4600
USA	Synthetic oil	1.3	0	23	7144
USA	Synthetic oil	2	6	41	8000
USA	Synthetic oil	2	6.3	48	9810
USA	Synthetic oil	2	6	43	7732
USA	Molten Salt	2.8	4.5	50	7380
USA		2.5	9	56	7550
USA		3	13.4	67	9140

Juba PP has the potential of easy expansion to meet future energy demands, while utilising clean renewable energy. Future addition of TES will increase the CF and the total annual energy of the PP. Increasing SM from 1.25 to 2.00 or even 3.00 could double or triple the energy generation. From Table 4.11, having SM=3.00, and a thermal storage system of 9 hours, will increase the CF to 67% and would potentially increase the annual solar energy generation to about 625GWh. As the technology matures with more research being conducted to reduce cost and increase efficiency, the annual generation based on the suggested values could be higher, and cost lower than conventional energy generation technology. This shows that parabolic trough solar systems have promising potential to meet future energy demands.

4.8.3. Discussion on Financial Feasibility

Only depending on the resource, technological and project-related costs, and government backup and endorsement that the Juba solar power project can be financially profitable. In relation to the present technology cost and research, it has been shown that only solar power plant projects are situated in the regions that have DNI values greater than 2200 KWh/m²/year are likely to be viable. Juba solar field has a DNI value of more than 2400 KWh/m²/year. This makes it a viable option to explore the feasibility of using solar energy generation technologies in the KSA to meet energy demands. Juba solar power plant is under consideration for development by SEC, which is the KSA government agency tasked with electricity generation. The plant has a low cost to taxes (2.5%), no land cost, no debt, and no loan repayment with interest. This greatly enhances the viability of the PP development by giving 100% equity to SEC. With a total capital cost of $320 million and IRR of 13%, the profit over the life expectancy of the plant is very promising. A guaranteed PPA with its escalation make developing and operating the solar plant viable. As stated by Sargent et al. (2003), there are three categories making up the CSPPs costing, including investment costs, which are also referred to as capital cost and operation and maintenance costs (O&M), as well as financing costs. Approximately between $ 4500/kW and $ 7150/kW is presently the estimated investment cost for parabolic trough solar power plants without storage. As for CSPPs with TES, they are likely to be considerably more costly, even though they permit higher capacity factors, the changing of production to when there is no sunshine and/or the capacity to maximise production at the times when demand is at its highest.

The LCOE for this study is simulated and optimised to be 15.6 cent/Kwh. In comparison, LCOE for a diesel generator in unsubsidised electricity generation is [29-33] cent/Kwh, assuming that diesel cost = 4 $/gallon (LAZARD, 2014). Therefore, this value of LCOE, 15.6 cent/Kwh, is competitive with the worldwide average for unsubsidised fossil fuel PP. However, diesel cost in KSA is very cheap, and subsidised by the government. In fact, it is considered the second cheapest country for diesel prices worldwide, where in December 2015, price was 0.3 $/gallon, compared to 4 $/gallon in countries like UK, Sweden, Denmark, Italy and other countries (GPP, 2015).

For a comparison of LCOE using various energy resources for the data of 2013, a study was carried out in KSA. As shown in the findings, LCOE for power produced utilising a wind-electric conversion system accounted for 9.2 cent/Kwh for a non-taxpaying public utility. It also amounted to 10.9 cent/Kwh for a taxpaying private independent power producer (IPP). As for LCOE for power produced by diesel, it accounted for 10.8 cent/Kwh for a non-taxpaying public utility, while it was 11.7 cent/Kwh for a taxpaying IPP. LCOE for power generated by a PV-electric system is 27.9 cent/Kwh for a public utility that pays no tax, and 32.8 cent/Kwh for an IPP that pays tax. LCOE for power generated by a hybrid diesel generation plus wind electric conversion system is 11.0 cent/Kwh for a public utility that pays no tax, and 12.4 cent/Kwh for an IPP that pays tax (Bawah et al., 2013).

The national energy strategy for KSA seeks to reach (23-30) % of energy being produced by renewables by 2032. The contribution of CSP systems would be (11.7-

17.2)% of the total energy produced by 2032, equivalent to (75-110) TWh/y = 25 GW. So the plant meet the scope and the purpose of the national energy strategy in spite of high LCOE compared to a diesel generator (AlGhabban, 2013).

4.8.4. Socio-Economic Impact

The KSA's unemployment rate is currently 11.7% with over 600,000 unemployed persons. Building the solar plant will provide greater local employment opportunities during construction and during the operating lifespan of the plant. This will also create opportunity in improving the skill set of local inhabitants of Wadi Aldawasir through training and capacity building for employment in the project, as it will contribute in growing the technical advancement of the populace. Over 1000 direct and indirect jobs could be created during the construction phase and during operation. Renewable energy is more labour-intensive compared to fossil fuel technologies, which are typically mechanised.

Solar technologies will give rise to spin-off companies, which will also stimulate local economy through creation of businesses during the implementation stages of the project to provide goods and services for the project both during construction and operations. Vast barren land will be useful for the building of solar fields.

4.8.5. Discussion on Environmental Impact

The globe is currently facing environmental problems due to the impact of burning fossil fuels and nuclear elements, which has resulted in acidification of the eco system, global climate change and accumulation of radioactive waste. The power sector globally accounts for about 40% of carbon emission, and the demand for more electrical energy is rising due to growth in population and development. Encouraging the use of renewable energy resources will help in fighting climate change and preserving the earth for future generations. Using solar energy generation technology, there will be no carbon emissions, which is currently a global threat to livelihood and existence of man. RETs generate clean energy, which means no GHGs, no toxic waste, and no environmentally devastating accidents. Individual countries' carbon footprint differ substantially, and carbon foot print of KSA is used to estimate the environmental benefit of using solar energy in Wadi Aldawasir instead of using fossil fuel in meeting rising demand. The emission of $kgCO_2$ per unit energy is calculated and compared to a conventional electric system. The emission factor or the energy mix in KSA has a carbon footprint of 0.754 kgCO_2 per kWh (IG, 2015). In order to quantify the amount of carbon emissions saved annually when using parabolic trough solar plant, the carbon emsssion factor for elelctricty generation mix in KSA of 0.754 kgCO_2/kWh was used in the simulation. Therefore, the Juba solar plant with annual power generation of 252 GWh will save about 190,000 tons of carbon dioxide in emission. If renewable energy is not used in meeting future energy demands, the carbon footprint will increase. Indeed, electricity consumption in KSA is going to increase due to projected temperature rises from global warming and the associated increasing demand for space cooling.

4.9. Summary

This section focuses on analysing a case study for the CSPP in Wadi Aldawasir region in KSA. In this region, a parabolic trough solar thermal technology for power generation is planned. This should provide the electrical energy required by the region for coming expansions, and reduce the dependence on fuel for energy production. Two types of analysis were carried out for this purpose. The first focused on providing a detailed description for the regional location with a feasibility assessment. In addition, the SAM software was used to undertake the technical design and plant optimisation. What has been done can be summarised in the following:

- An analysis and assessment of the site's Solar Field was performed using the Weather Data analysis that contained the DNI and GHI and DHI received by the site at different times of the year and analysed over different yearly and monthly intervals. This analysis gave a clear picture of the data included in the site's climatic file, which covered the DNI, dry bulb and dew point temperatures, relative humidity, barometric pressure and wind speed.
- Carrying out a simulation and design of the plant, as well as expanding and detailing the description of the technical and financial disruptions, and the reasons for their selection. In fact, these inputs have been covered in terms of the technical aspect (location and the solar field) by addressing the most optimal SM for the plant, as well as the choice of the HTF type, determining the

subsections and the number of the CSA/HCA. Also covered were the data related to the collectors, receivers and power block.

- The various thermal storage capacities were analysed to reach the optimum number of hours for the design, which has reflected positively on the technical and financial design of the station, with the optimal design of the station being without thermal storage.
- The financial parameters and system costs have been studied and analysed to be suitable for the analysis period, which covers the period of operating the plant (25 years), with a rate of decline amounting to 1% per annum.
- Conducting an extensive analysis of the behaviour of the plant at different speeds of the TES and the SM, as well as the number of subsection, where the plant's optimal results reached zero, 1.25 and 2 hours, respectively.
- The energy produced from the plant on a yearly basis is estimated at 252.362 GW, while LCOE is calculated at 15.63 ¢ / kWh. A financial analysis was conducted to confirm the results and the cost for each part of the main parts of the plant.

Subsequently, a financial analysis and evaluation of the plant was undertaken using the RETScreen program as a measure to confirm the results that had been obtained from the SAM program and its relevant equations. The results of the two programs were then compared, after which the results of the SAM program were adopted, along with an explanation of the reasons for choosing such results. The positive effects on the environment were also analysed, in addition to calculating the amount of harmful emissions discharged by the plant, with the design confirming that the station would provide annual emission savings of approximately 165,034 tCO_2.

After obtaining the design results and dimensions of the plant, the results were discussed from several angles in terms of the technical and financial feasibility, as well as the viewpoint of the availability of plant and the socio-economic and environmental impacts of the plant.

CHAPTER 5

SHUAIBAH POWER GENERATION GRID

5.1. Introduction

This chapter presents a case study of solar thermal tower technology for power generation in Shuaibah in KSA. This technology is proven to provide economically viable energy output. The proposed Shuaibah CSPP is a case study to investigate use of CSP to provide electricity as part of future capacity expansion plans. The case study seeks to establish whether the proposed technology is both economically feasible and technically efficient in producing electrical power in the Shuaibah region.

In addition, the technology may be combined with existing power generation infrastructure, particularly the thermal block of an existing fossil-fuelled plant. This is based on the belief that savings could be secured by combining the thermal blocks of existing plant and newly constructed CSPP. Finally, solar thermal tower technology sustains high temperatures without degrading system performance.

Relevant data relating to site climate conditions, and technical and financial parameters, were gathered, as key inputs to the CSPP design and evaluation of project feasibility. This is needed prior to execution of any such project. For the purposes of evaluating both financial and technical feasibility, data was separated into two sets. On one hand, the climate conditions, site location, and the main components of the plant were analysed. On the other, SAM and RETScreen were employed to design and model the proposed CSPP. Site climate, plant component data, etc. was fed into the programs, which provided outputs in terms of energy flows, GHG emissions, risk analysis, and CSPP sustainability. This is all presented in the chapter.

5.2. Shuaibah

Shuaibah is a small disused historic seaport located on the western coast of KSA on the Red Sea, situated at latitude 20 37' 22.84''N and longitude 39 33' 44.02''E (Figure 5.1). It is one of the most important economic centres in KSA, and home to the largest power and water desalination plants in the Middle East. Shuaibah is situated 110 km south of

Jeddah city, and shares similar solar radiation characteristics. Therefore, Jeddah solar data were selected to calibrate ground measurements with the satellite data, as was investigated in this work

Figure 5.1: Shuaibah city

The Shuaibah industrial PP complex consists of three major power and water desalination plants. The combined capacity makes it the global leading producer of power and potable water. SEC, Saline Water Conversion Company (SWCC) and Shuaibah Water & Electricity Company (SWEC) are the joint owners of the complex (Figure 5.2). Therefore, the location is of great economic importance for future government investment.

A Combined cycle gas turbine (CCGT) power and desalination complex runs on fuel oil. Shuaibah power and desalination plant is the third largest integrated water and PP, and is among the most expensive fossil fuel power plants in the world. It is also the largest desalination plant at global level, with a daily capacity of 1,030,000 m^3. The Shuaibah plant was been built and expanded to meet the high water and electricity demand in Makkah, Jeddah, Taif and Al-Baha. This demand is a result of the high population growth in these cities, which led to huge pressure on the existing PP (IWPP, 2013). SEC owns Shuaibah PP, which provides power to the KSA Western Province, including Jeddah, Makkah and Taif. It has a generation capacity of 5,538 MW using 14 steam turbines on a total area of the PP of 8.140 km^2 (Figure 5.2). The efficiency of each turbine varies from 38.48 % to 42.04 %, while unit capacity varies from 393 MW to 397 MW.

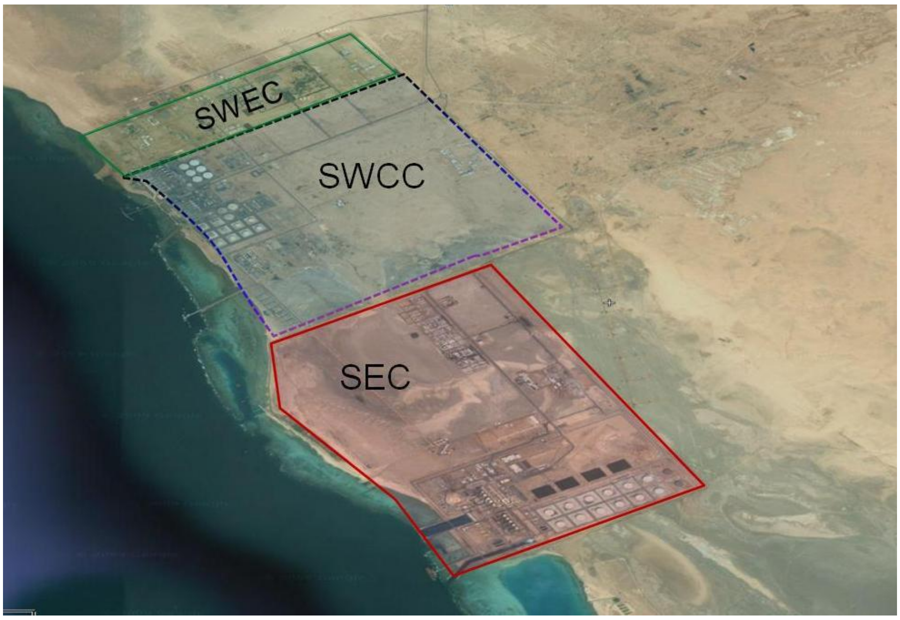


Figure 5.2: Aerial map of Shuaibah Power and Water complex

In 2014, the plant used 41,326,852 barrels of crude oil at a cost of 26.6 $\$/m^3$ and 11,242,393 barrels of heavy fuel oil costing 13 $\$/m^3$ supplied by Saudi Aramco tankers. Power generated in the power station is distributed to users through the national grid at 380 kV voltage, as shown in Figure 5.3 below. The plant also has a desalination facility using steam to heat seawater for the distillers to provide salt-free water for cooling the plant condensers, and for drinking water.

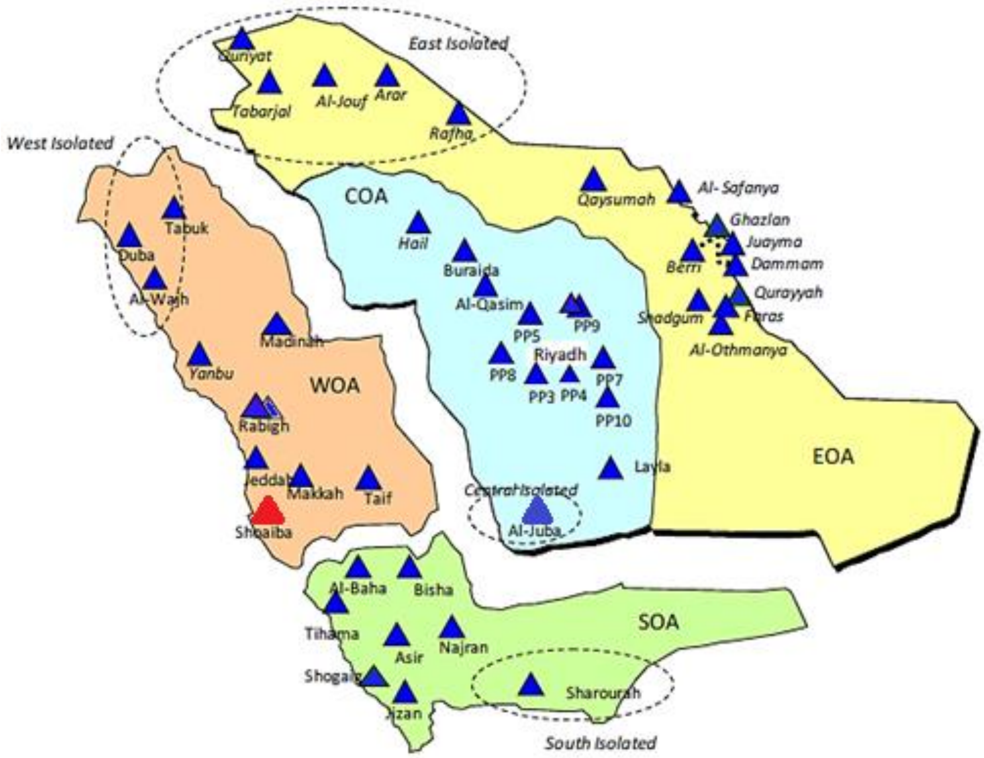


Figure 5.3: Saudi power transmission network

Population growth and economic development in KSA have put stress on the Saudi power generation sector. There are expansion plans for existing power infrastructure, mainly for power plants. However, this work will investigate the feasibility of using CSPPs for future expansion, in order to address government commitments to reduce fossil fuel consumption, and provide a proposal for the use of the abundant solar energy in KSA.

The present case study examines the design of solar thermal tower technology, and analyses how practical it is for the Shuaibah site.

5.3. Energy Demand Profile at Shuaibah

Extensive data on energy demand at Shuaibah PP was provided by SEC. This gives monthly maximum loads monitored during 2012 (Figure 5.4). It can be seen that maximum load was 5601 MW in July 2012, while the minimum load recorded did not drop below 3400 MW. Annual plant power generation is 34,852.316 GWh (Data-Collection-Trip, 2012).

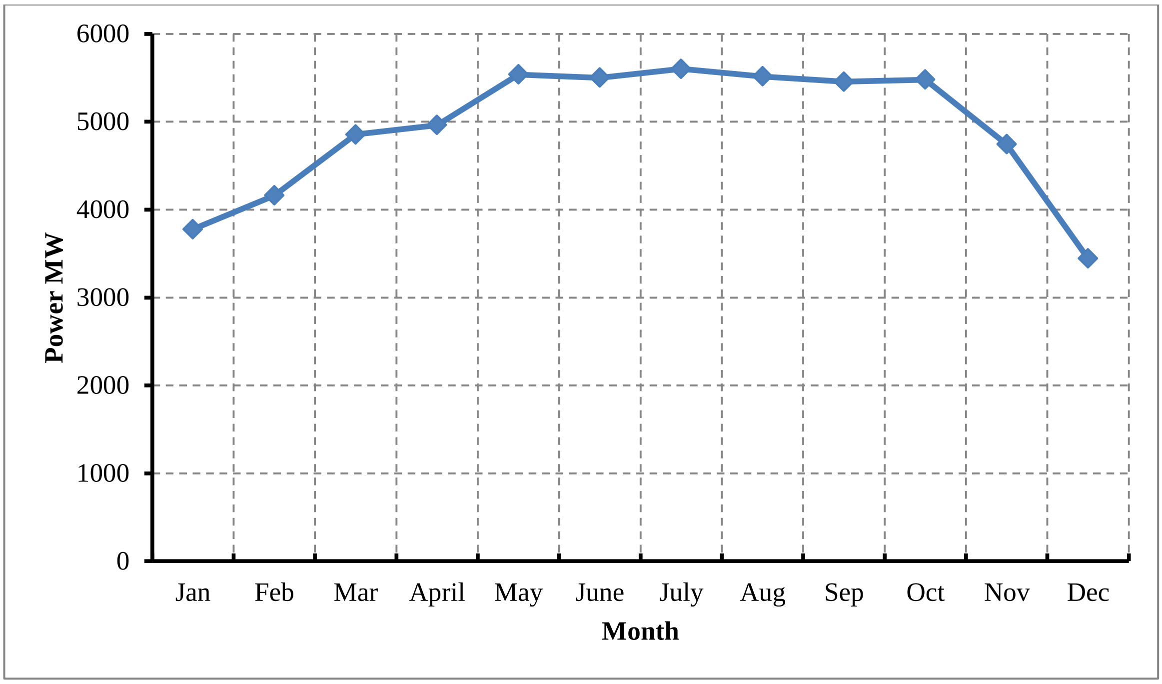


Figure 5.4: Shuaibah PP - Monthly Peak Load (MW) for 2012 (Data-Collection-Trip, 2012)

5.4. Design and Feasibility of CSP Integration into The National Grid

This section presents the key part of this work, relating to CSPP modelling and simulation following the NREL approach. The evaluation of available solar resource was based principally on the DNI measurements for the area. In this instance, solar thermal tower technology was applied as a mature technology, and another possibility, alongside parabolic trough CSP technology, given the ready availability of extensive land.

The reason why the present case study employed tower technology is that the previous case study on Wadi Aldawasir (*Chapter 4*) used parabolic trough CSP technology. Evaluated for the Shuaibah location, tower technology will form the basis for the investigation of the CSPP. The technical practicality of solar thermal tower plants for power generation projects has already been demonstrated, and the commercial viability of the CSP technology has been confirmed as well (Zhang et al., 2010). This is a major factor in selecting the technology for this site. The main objective is to simulate a CSP plant that is customised for this region's context, and to evaluate the proposed CSPP performance. Economic modelling and financial analyses are also one of the main aims of this chapter. The cost of the CSPP and the LCOE are also assessed and presented.

5.4.1. Site Specification

- Shuaibah PP is fossil fuelled, and has strong infrastructure and facilities, with available investment for CSP technology.
- Availability of the current plant data and support for expansion plans using renewables.
- Solar resource assessment for the site is promising, where DNI is higher than 2000 kWh/m^2.
- Natural land conditions are appropriate for constructing a CSPP with availability of vast areas of lands around the current PP, as shown in figure 5.5. This will play a very important role in reducing the initial cost of preparing the land for plant construction.
- The plant location is accessible, and the site is grid connected.

Figure 5.5: Site of proposed CSP tower plant in Shuaibah

5.4.2. Solar Irradiation at The Site

DNI information has been gathered and appraised to explore the compatibility of CSP with the mini-grid system. Satellite data were the source of this information, having been verified with ground-measured data from the Saudi Renewable Energy and entered into SAM (Simulation, 2012, Atlas, 2015). GHI and average annual DNI at the location were calculated to be 2264.7 kWh/m^2/year and 2345.4 kWh/m^2/year, respectively. These values confirm that a CSPP can be established at the chosen location. Furthermore, the favourable direct solar irradiation at the location is highlighted by the satellite image of DNI of KSA (Figure 5.6).

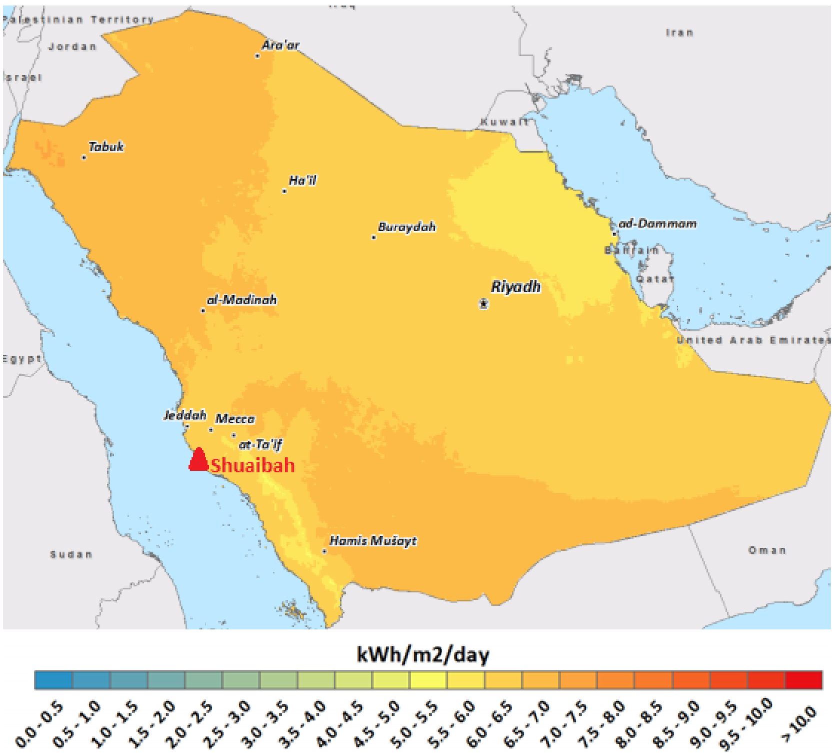


Figure 5.6: Annual average daily DNI map for KSA (1990-2013) (KACARE, year)

Figure 5.7 illustrates the overall quantity of global, direct and diffuse solar radiation that is received each year on a horizontal surface at the chosen site. As can be seen, during the hours 08:30 to 16.30, DNI exceeds 500 W/m^2, which means that the system could operate for eight hours every day, thus satisfying the demanded load peak. The GHI varies from hour to hour for all months of the year in Shuaibah, as shown in Figure 5.8. It may be noted that the maximum value is recorded during the summer months due to the high amount of sunlight received at the Earth's surface. Minimum values are obtained during winter months, especially during December and January, when the

Earth's surface receives less sunlight. From figure 5.8, it can be seen that the maximum GHI obtained during May reached 1,000 W/m^2, while the minimum value of 700 W/m^2 is obtained in December.

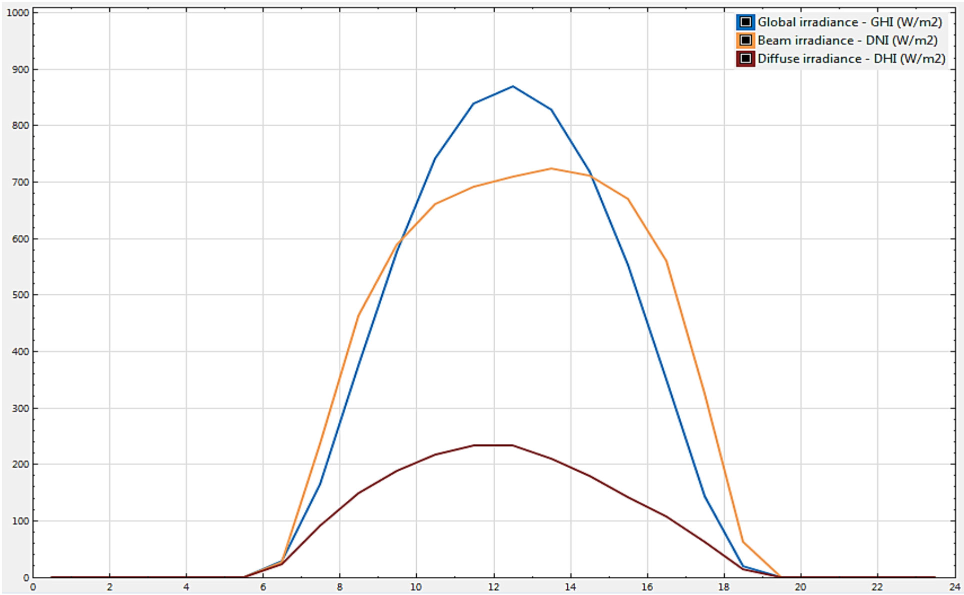


Figure 5.7: Annual Global Horizontal, Beam and diffuse horizontal Irradiation at Shuaibah

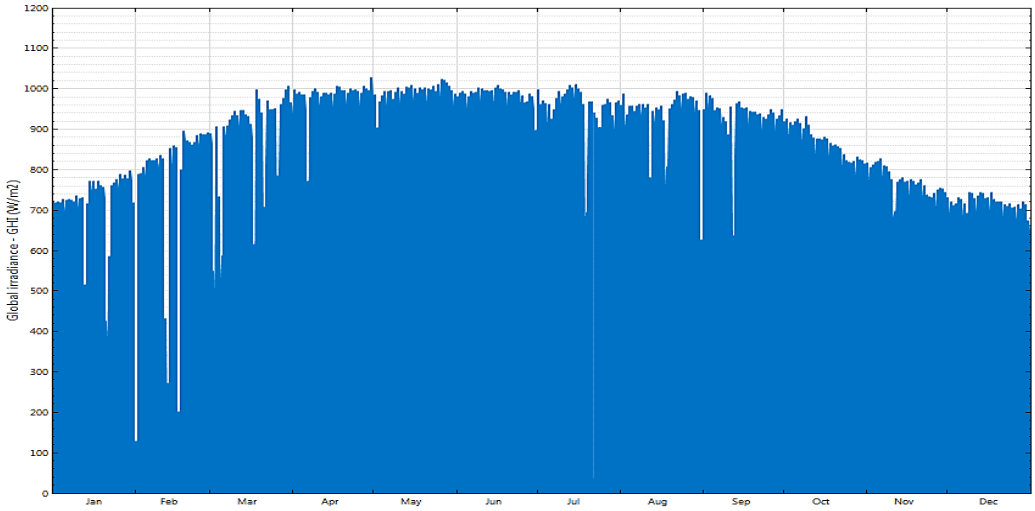


Figure 5.8: GHI at Shuaibah

The amount of solar radiation received is shown in Figure 5.9 for Shuaibah. It can be noted that this value is roughly constant all over the year with a decrease in July and August. The maximum reaches a value of 1,000 W/m^2 in March, while the minimum value is about 700 W/m^2 and is recorded in October.

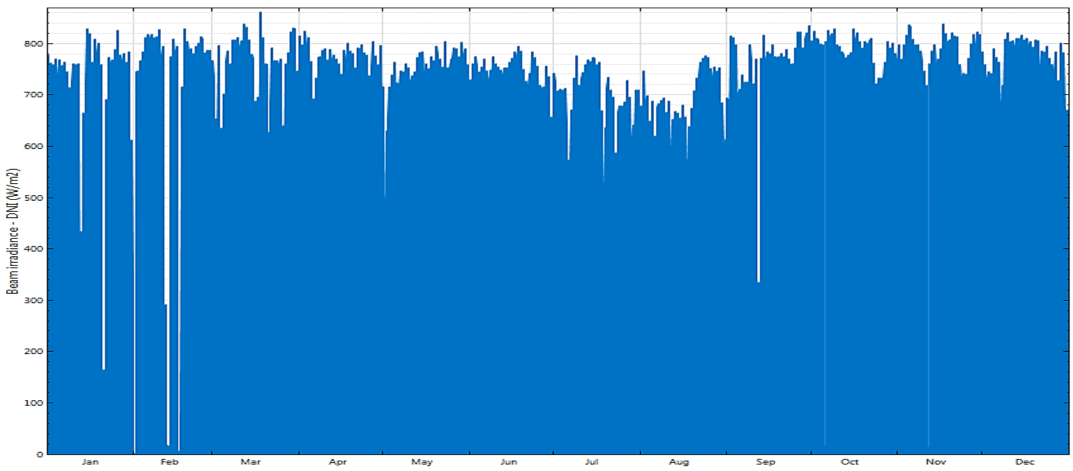


Figure 5.9: Beam normal irradiation at Shuaibah

5.5. Simulation of The Proposed CSPP Using SAM Software

The effective use of the SAM software in the simulation of existing CSPPs as well as the reliable modelling results it produced in the earlier case study warranted its use for modelling and evaluation of feasibility (Janjai et al., 2011). This software facilitates the calculation of energy generation and financial parameters, thus providing an overview of the performance of the CSPP. Screen shots from SAM of the Shuaibah CSP power plant design are given in Appendices (A.2).

Modelling was performed using the data gathered for the site and the technology, as well as assumptions made for the CSPP. The simulation software, SAM and RETScreen, requires the CSPP parameters relating to finance and technology, including various efficiencies, solar potential, financial rates of discount, etc. This enabled plant performance to be quantified along with the main feasibility indicators.

5.5.1. Radiation Input Data

The use of solar thermal tower technology for electricity production at Shuaibah is justified by the fact that it has an average solar potential on a flat surface of about 2,200 kWh/m^2 per year, and receives high levels of solar radiation in April and September.

Solar radiation data, monthly average DNI, was obtained from ground measurement, and then converted into EPW format for input into SAM. Radiation data gathered by satellites was calibrated against the ground data for a period of 15 years (1998 – 2013). SAM demands detailed climate data, such as prevailing wind speed, DNI, barometric pressure, relative humidity, and dry-bulb and dew point temperatures (Gilman, 2014).

5.5.2. SAM Model Input Parameters

The case study draws on the EPW climate file for Shuaibah and system requirements derived from NREL and SolarPACES, while financial assumptions have been formulated based on the Saudi financial system. The case study and overall plant design is based on the following premises:

i. The options of in SAM software of PPA single owner and molten salt CSP power tower were chosen for this case study.

ii. The CSP will operate as an independent power producer, because SEC is a state monopoly that controls the electricity industry. It also seeks to pursue state policies and strategies in terms of the provision of electricity services from a range of energy sources. In so doing, the company receives significant government support.

The key steps in designing the CSPP followed the same order of pages within the software. They are arranged generally as follows:

SAM software simulation processes can be summarised as follows:

i. Location, Sources
ii. Heliostat Field
iii. Tower and Receiver
iv. Power Cycle
v. Thermal storage
vi. System costs
vii. Life time
viii. Financial parameters
ix. Optimise SM and TES capacity scenarios
x. Generating and showing the simulation results for the optimal design

5.5.2.1. Technical Input Parameters

When designing a tower-like plant, many important aspects should be taken into account for an optimal and effective design. One of these features is the design point, representing the data on the environment-related issues on which the design of the plant is based. In this design, the main data pertains to the geographical and climatic factors of the Shuaibah site. The most important of these data is DNI, which falls on the heliostat field.

The power output of the heliostat field is another key aspect, where the solar energy reflected by the heliostat is utilised to run the power block. Accordingly, the design of the heliostat field is one of those aspects that is addressed in this section, to achieve an optimal CSPP design.

The receiver thermal power output, which is dependent on the energy reflected by the heliostats, represents a major feature in the design. At the receiver, the average temperature of the Heat transfer fluid (HTF), namely molten salt, is raised, and sent to the power cycle at high temperatures. The thermal energy required for the power cycle is extracted from the HTF. Again, this aspect is addressed to achieve the most optimal and appropriate version.

In addition, the effect of the SM on the plant is studied, to select the optimal value that provides maximum energy from the field to be exploited to achieve financial feasibility for the design. This is because an increase or decrease in the SM can have obvious implications on the design of the CSP tower, and equally on the financial analysis.

The number of optimal storage hours that are parallel with the optimal value of the SM is one of the most important factors to be taken into account in the design. Analysing variables at the various storage hours will also confirm the safety and validity of the design chosen for the plant and yield positive effects on the economic feasibility. Conducting a feasibility and economic analysis will reflect how implementable this design is, as well as shed light on the design’s benefits and drawbacks from an economic point of view. The following is a detailed review of these important aspects:

- **Location, sources and weather data**

The initial step for CSPP location is the use of appropriate climate data. The location and resource parameters existing in the SAM database can be selected from the location and resource tab in the software. Since climate data for Shuaibah are unavailable in the SAM database, they have been derived from the EPW data format for the neighbouring city of Jeddah, which has a climate similar to Shuaibah. Acquired straight from satellite data, the information was automatically entered in the software, as previously indicated.

After downloading the weather data file into SAM, the program analysed it and showed the geographical and climatic data. One of the most important data is the direct normal beam, which is the most important element in the design of the CSPPs, as shown in Figure 5.10.

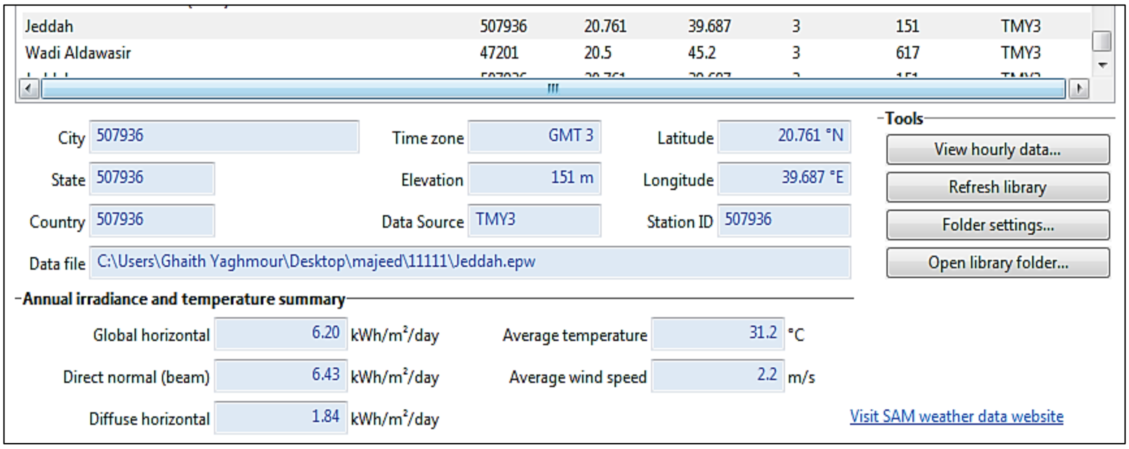


Figure 5.10: Location and resource data

- **Heliostat Field**

The second page, related to the Heliostat field, contains one of the most important components of the plant, which is the heliostat field layout. The Heliostat Field page displays the location of the heliostats in the solar field. Indeed, their geometry and optical features are indicated by the variables included in the Heliostat Field page. The designs for a power tower system differ from both parabolic trough and dish system designs in that they are not underpinned by modular designs of separate elements but must be optimised in terms of tower height, receiver geometry, and heliostat arrangement around the receiver as a whole system.

The heliostat field layout can be outlined in two ways. One is by introducing existing ready field layout parameters, or by establishing the ideal layout with the optimising wizard in SAM.

In this design, the second method was adopted due to the lack of a specific area or previous design on which this design can build on to test the plant's energy outputs and prices. In fact, the current estimates a capacity of 100 MW for the overall design and analysis of the plant. Therefore, the parameters of the design of the heliostats and other aspects will have to be determined first.

The selection of values for the many input parameters necessary for defining the power tower solar field and receiver is made easier by the power tower optimisation wizard. It is of essential importance to reduce the project total cost through optimising the size of the heliostat field, as this alone accounts for 30-40% of the overall installation cost of a power tower project.

A series of optimal system parameter values are the target of the optimisation wizard. In this regard, a system is considered optimal if it produces a minimal LCOE. It is also important to observe that optimisation and simulation are distinct processes. Upon activation, the wizard attaches optimal values to certain input variables in the SAM input pages.

Installed via the PTGen program, the DELSOL3 code from Sandia National Laboratories represents the code on which the wizard is based (SAM, 2014).

The thermal rating of the receiver is determined by the optimisation wizard with the SM multiplied by the nameplate electric capacity of the power cycle divided by the conversion efficiency of the rated cycle, which can both be found on the Power Cycle page.

To determine optimal values for the below variables on the Tower and Receiver page, the wizard conducts a search within the established ranges. Once this search is concluded, optimal values are attached to the variables by SAM.

i. Diameter of receiver
ii. Height of receiver, measured as a function of the ratio of receiver height to diameter

iii. In the case of the direct steam tower model, the receiver height is the sum-total of boiler, superheater and reheater heights.

iv. Height of tower

Values from the wizard are also attributed by SAM to the variables on the Heliostat Field page:

i. Radial step size for layout

ii. Overall reflective area

iii. Heliostat number

iv. Heliostat number for a radial zone in the field layout table

The values below from the input pages are employed unchanged by the optimisation wizard.

The variables derived from the Heliostat Field page are:

i. Width of heliostat

ii. Height of heliostat

iii. Reflective area to profile ratio

iv. Mirror reflectivity and soiling

v. Circular heliostats

vi. Maximum distance from tower

vii. Minimum distance from tower

viii. Image error

ix. Radial zone number

x. Azimuthal zone number

xi. Coating absorptivity

xii. Maximum receiver flux

However, before using this feature, the optimal design for the plant should be selected. This is discussed in the subsequent analysis in this section. Once the optimal design and the chosen specifications of the plant, as well as the design data and other required financial inputs have been determined, the optimising wizard feature is used to determine heliostat layout and geometry. It should be pointed out that the optimised wizard mechanism is used after providing the following information, which is done after selecting the optimal option.

1. Identifying the plant capacity from the power cycle page in the program and adjusting any related data so that the estimated net plant output is 100 MWe, in keeping with the required design for the plant. This page is discussed later in the chapter.
2. Entering the data on costs and financial analysis.
3. Determining the optimal SM from the tower and receiver page, as elucidated later.
4. Determining the number of storage hours from the thermal storage page, which is also addressed later.
5. Entering the irradiation at design as a design point for the heliostat field.

It is important to adjust the value of irradiation at design, as a design component of the solar field. A total value of 780 W / m² was adopted based on the analysis of the energy falling on the site every year. The actual values of DNI were higher than this figure for most of the year, as illustrated in Figure 5.9.

Table 5.1 provides a short description of the inputs in the solar field final page for the adopted design, which was reached after choosing TES = 6 and SM = 1.75 as the design best option, as is presented in a later analysis.

Table 5.1: SAM performance input solar field page for Shuaibah

Heliostat Field	**Optimisation algorithm**	**BOBYQA**
	Irradiation at design	780W/m^2
	Heliostat focusing method	Ideal
	Heliostat canting method	On-Axis

The optimal number of storage hours for the design was determined from the thermal storage page. This was 6 hours based on the analyses performed in the selection of this value, as is explained later. Subsequently, the best value for the SM was 1.75 as calculated from the tower and receiver page. This is also based on the conducted analyses that are explained further in the discussion. It was deemed important to generate heliostat layout and optimise solar field geometry for optimal values of the results of the heliostat field. As illustrated in Figure 5.11, the heliostat layout results showed that the ideal heliostat number was 7879. Hence, the location of each heliostat was determined on the site, as well as the tower dimensions with height = 203.139 m; receiver height = 18.4603m; and receiver diameter = 15.6572 m. As can be shown in Figure 5.12, these results are adjusted automatically in the pages of the tower and receiver. This is explained later.

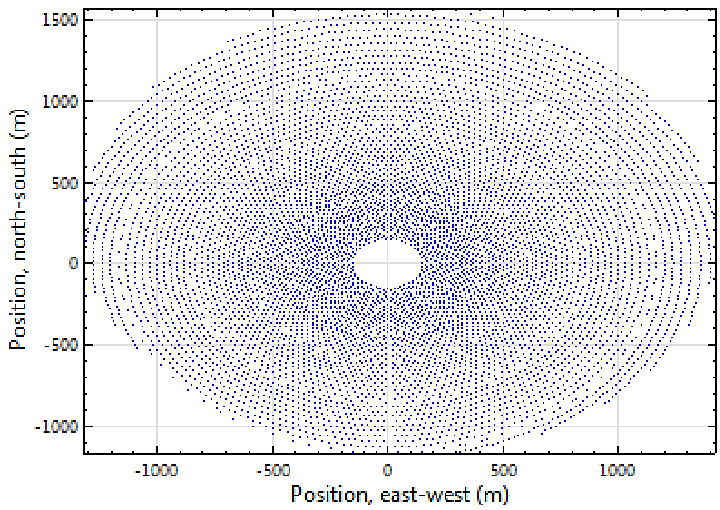


Figure 5.11: Heliostat layout

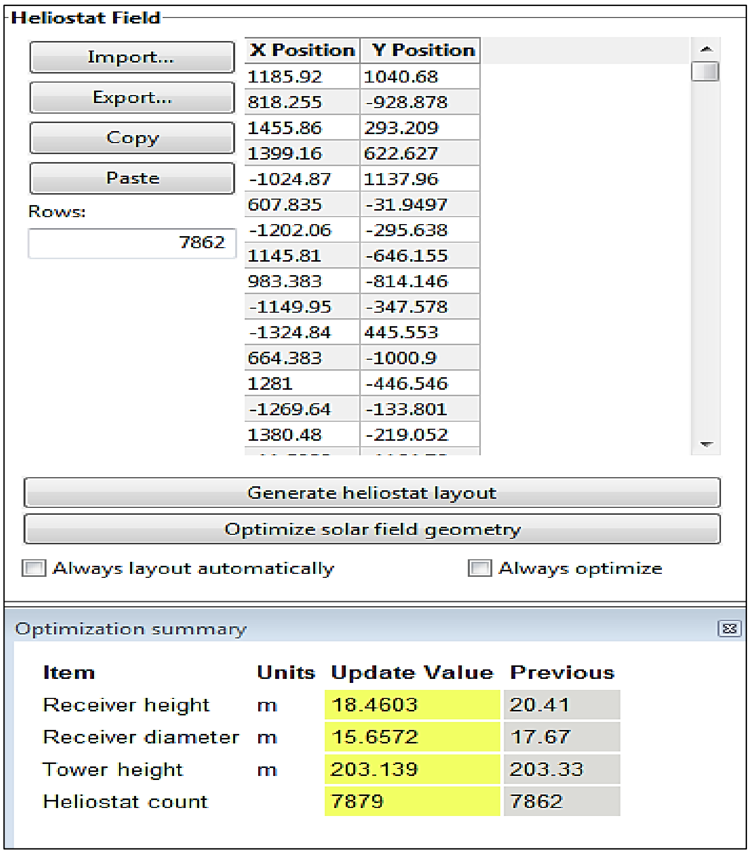


Figure 5.12: Optimisation summary

- **Tower and Receiver**

The geometry of the heat collection system is defined by the variables included in the Tower and Receiver page. By measuring the receiver's thermal performance based on semi-empirical heat transfer and thermodynamic relationships, the receiver model can achieve the representation of various different geometries, while staying within the specifications of an assumed reference system (SAM, 2014).

A number of hypotheses regarding system geometry for external receivers and the height of the tower are formulated by the model. The optimising wizard from the heliostat page provides the following system geometry:

i. Multiple panels make up the receiver.

ii. Every receiver panel comprises a series of aligned tubes in thermal contact sharing the HTF header.

iii. The panels have vertical tubing and a serpentine movement pattern characterises the flow of heat transfer fluid through every consecutive panel (upwards in one panel and downwards in the next one).

iv. The variables of panel number, receiver diameter and tube outer diameter dictate the number of tubes that each panel has.

The heat transfer fluid, otherwise known as the working fluid, is compatible with two types of solar salt. The reason for choosing salt, consisting of 60% sodium nitrate and 40% potassium nitrate, is that it has proven efficiency, and is employed in other plants.

As shown by the schematic representations on the Receiver/Tower page, a number of options for the HTF flow patterns through the receiver are permitted by SAM, such as full circle round the receiver, split path round the receiver, and split pass with single cross-over. The trajectory of the fluid as it goes through the receiver is determined by the flow pattern variable. The panel number has to be a multiple of two in the case of flow pattern options 1-4 (Figure 5.13). Therefore, Flow pattern No1, which is split pass with a single cross-over, with number of panels = 20 was used in the modelling.

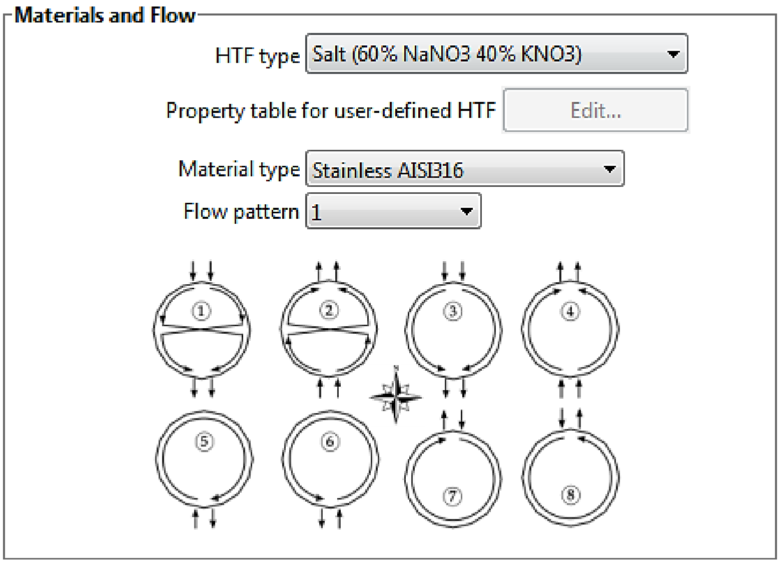


Figure 5.13: Material and flow of proposed tower CCPP

The second important step in the tower and receiver page is to determine the SM.

The ratio of the design thermal outputs of the receiver and power block gives the SM. Its value should be one or near one in the case of systems without storage (ref).

Optimisation of the solar field size can be undertaken with the LCOE or the PPA and IRR, as they cover the quantity of system-produced electricity, the costs of project set-up, and system operation and maintenance costs.

Determining the storage hours can also have a direct impact on the SM. As such, it is taken into account during the implementation of the test by adding it as a variable, since there is an ideal SM for each different set of storage hours. The SM is determined after analysing the various scenarios and selecting the optimal design. The next step would be to enter its value in this page, which in turn would affect the process of the optimisation wizard, as stated earlier. The optimal design results obtained for the plant refer to the adoption of a SM = 1.75, as will also be clearly shown in the selection procedure later in this chapter.

- **Power Cycle**

In this design a CSPP of 100 MW power output was considered. Using SAM's modelling guidelines for the conversion of mechanical power at the turbine shaft to electrical power output a factor of a 0.87 was used. this requires a gross mechanical power output of 115 MWe. Figure 5.14 shows a schematic of the concept of the

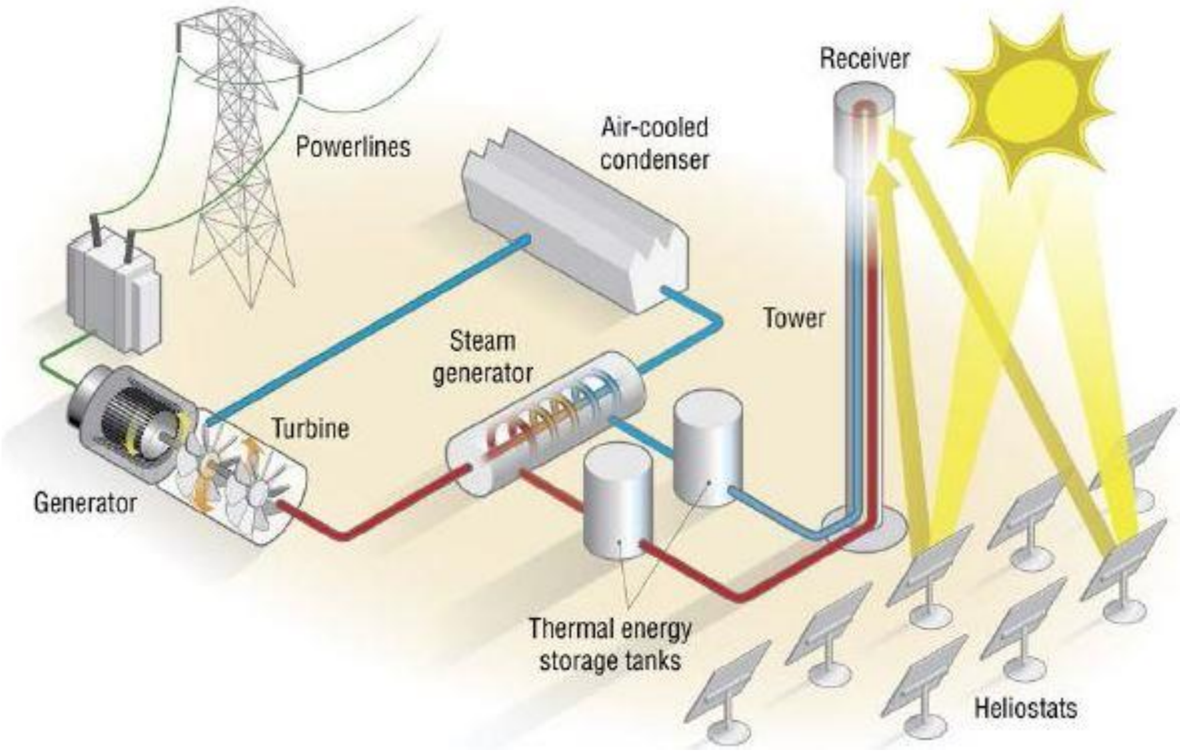


Figure 5.14: General layout for Tower CSP plant

As indicated in Figure 5.15, during summer, the ambient temperature in Shuaibah reaches 46°C. therefore, an ambient temperature of 48°C was established for the model, with an air-cooler condenser being consequently employed.

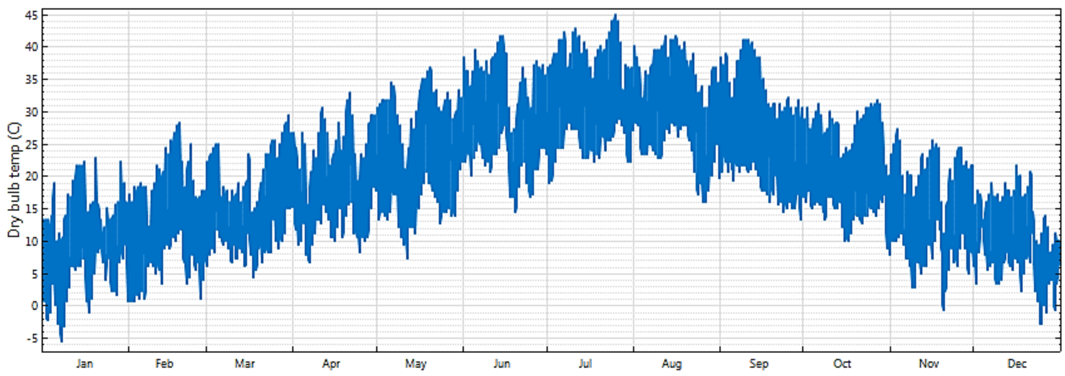


Figure 5.15: Ambient temperature at Shuaibah through the year

In the CSP with solar tower the Initial Temperature Difference (ITD) was assumed to be around 16°C, as used in SAM. The dry bulb temperature of the air cooled condenser was taken from the loaction's prevailing weather conditions of 48°C, leading to a steam-condensing temperature of 64°C. the working fluid and HTF temperature profiles are given in Figure 5.16.

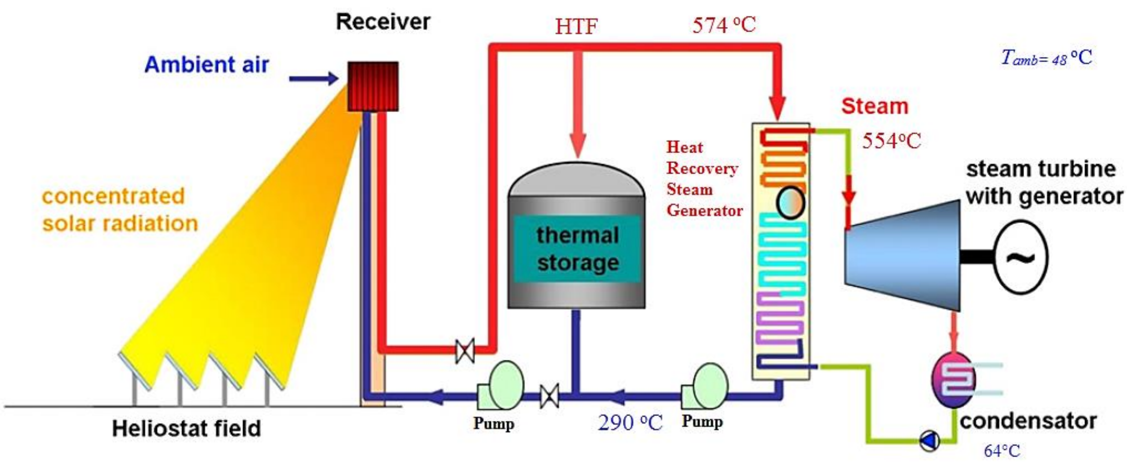


Figure 5.16: Temperature profiles of the CSP solar tower system

Having no specific model in place, one can refer to a number of references to be utilised as a rough estimate, which can be gained through the use of a scale efficiency coefficient, taking a validated system performance where SAM utilises 40.51% gross efficiency as a reference point. In respect to the HTF design temperature, it estimated to be in the range of 574°C, and given an ambient temperature of 48°C, the condenser temperature is 64°C, it leads to a cycle Carnot efficiency of 60.2%. In practical terms, however, it is expected that the temperature gradient between the HTF and steam could be in the region of 20°C, which is likely to reduce the heat source temperature to 554°C and in turn lowers the thermodynamic cycle's Carnot efficiency to 59.24%. SAM uses a correction factor to take into account the drop in temperature between the HTF and steam using the following relationship.

$$\eta = 0.412\frac{\eta_2|_{T=574}}{\eta_1|_{T=554}} = 0.4051 \qquad (5.1)$$

Table 5.2 gives a brief description of the inputs from the power cycle page, while the rest of the readings were ignored, because this is a preliminary study and not an analytical study of an existing system.

Table 5.2: SAM performance input in power cycle page for Shuaibah

Power Cycle	**Capacity – Design gross output**	**115 MW**
	Conversion factor	0.87
	Estimated net output	100 MWe
	Rated cycle conversion efficiency	40. 54 %
	Ambient temperature at design	48 °C
	Condenser Type	Air-cooled

- **Thermal Storage**

Next, thermal storage characteristics need to be defined.

A storage tank geometry is employed by the power tower storage model. Therefore, it is necessary to indicate HTF volume, tank loss coefficients, and tank temperatures. The reason for the calculation of the storage tank geometry by SAM is to ensure that the power block is adequately provisioned with energy by the storage system. This is dictated by the block's design thermal input capacity for the time indicated by the variable Full Load TES Hours. The specifications and features are maintained in the thermal storage page, because the program will calculate the necessary dimensions and provide an optimal design for the thermal storage after determining the number of hours required. The number of hours for the store is determined and entered in this page after obtaining the optimal option. The number of hours will also have an effect on the optimised wizard feature stated previously.

According to the results of the analysis to select the optimal design, it was shown that the optimal design would be a 6 hours thermal storage for the plant. As such, the number of storage hours was entered after conducting the analysis, which is presented in detail later.

5.5.2.2. Financial Input Parameters

In this section, the financial parameters are explained, especially the costs and estimates expected in establishing the proposed plant. In so doing, it takes into account the required values to undertake a financial analysis regarding the financial behaviour of the plant over a period of 25 years, in parallel with its performance and productivity during the same period. In terms of the values that are achieved at the end of the analysis, the results are presented for the optimal design from a financial perspective. The analysis is presented using similar steps as those undertaken in the pages of input financial analysis in the SAM program.

The prices and financial assumptions stated in this section and which are concerned with the design of CSP adopting Tower technology in Shuaibah have been gathered and selected as a result of the various efforts and research studies related to the financial costs and activities for existing and prospective thermal plants on the same technology. Illustrated in Table 5.3 are some of these studies and reports with their respective references, in addition to the reports and studies that have already been addressed in *Chapter Four*. Regarding the selected prices, they have been ascertained and matched to what has been stated in these studies, while also ensuring they conform to the financial system in Saudi Arabia, especially in the case of Zakat, in addition to taking into account the state support received by the energy sector. The adopted prices were fairly sensible in order to achieve practical and documentable results, especially those of LCOE.

Table 5.3: Financial previous efforts

Title	Author
Power Tower Technology Roadmap and Cost Reduction Plan	(Kolb et al., 2011)
Progress Towards Cost-Competitive Solar Power Tower Plants	(Santelmann et al., 2014)

- **System costs**

- Site improvement costs are set to 20$/m^2. This cost was chosen based on costs references mentioned earlier, as well as on the estimates obtained from the SEC on the cost of levelling the lands that had a similar type to the flat Shuaibah land, as illustrated in Figure 5.5.

- Covering costs associated with heliostat set-up, including heliostat components, field wiring, drives, labour and equipment, the heliostat field cost represents the cost per square metre of total reflective area indicated in the Heliostat Field page. In this case, the heliostat field cost was established at 200 $/m^2.

- Balance of plant cost was set to 350 $/kWe.

- PP cost was set to 1140 $/kWe.

- Storage cost was set to 30 $/ kWht.
- The fixed cost covering expenditure related to tower construction, materials and labour is known as the fixed tower cost ($). This represents the multiplier in the equation of tower cost scaling.

$$C_{TT} = C_{FT} e^{\lambda_T H_T} \quad 5.2$$

Where, C_{TT} is the total tower cost, C_{FT} is the fixed tower costs, H_T is the tower height and λ_T is the tower cost scaling exponent. The tower cost is used in SAM for optimisation calculation. The total cost of the tower depends on its height which is estimated using a cost scaling exponent, λ_T. For instance, the fixed tower cost was set at $ 3,000,000, while tower cost scaling exponent was set at 0.0113.

- Covering expenses associated with receiver set-up, including equipment and labour, the receiver reference cost ($) represents the cost per receiver reference area and is calculated through the following equation:

$$C_R = C_{RR}(\frac{A_R}{A_{RR}})^{\lambda_R} \qquad 5.3$$

Where C_R is the receiver cost, C_{RR} the receiver reference cost, A_R receiver area, A_{RR} the receiver reference area, and λ_R is receiver cost scaling exponent. In this modelling the receiver reference cost and the cost scaling exponent were set at 110,000,000 $ and 0.0113 respectively.

- This simulation assumes 5% contingency factor. This value is referred to as an error value that may affect the total sum of the cost. It was determined that this cost should stand at 5%, which is the value to be taken into consideration for projects carried out in a number of Arab countries, including KSA.
- The total direct cost ($) refers to the whole cost of location enhancements, storage system, balance of plant, heliostat field, power block, fixed solar field, total receiver, total tower and contingency. SAM calculated this cost, which was clear after choosing the optimal design with a net value of $ 605,182,336.

- Total land area was generated from the case study modelling in the solar field page, which is 1,491 acres.

- In terms of the nameplate, it is the nameplate capacity of the system from the power block or power cycle page, amounting to100 MW in this instance.

- The indirect capital cost: was hypothesised to be zero, as the owner of the project and land are the same entity. In such a case, it would be a SEC, and there are no indirect costs, such as leasing the land or vehicles, etc. It was also included in the contingency and other plant-related costs.

- Total Land Costs with value of 0 was used, because the PP is to be constructed on land already owned by SEC.

The total installed cost, SAM calculated this value, stood at $ 605.182.336.00. In fact, this is the value achieved after choosing the optimal design for the plant, as shown in the ensuing analysis of the optimal design.

- Total installed cost per capacity ($/kW), as calculated by SAM, with the value standing at $ 6,048.80 /kW.

Operation and Maintenance (O&M) costs: in this design, the variable by generation was adopted. Variable Cost by Generation Value of 30$/MWh was used.

- **Life Time**

Energy performance deterioration is exhibited by CSPPs over the entire life cycle and is around 0.5-1.0% per year. In respect of this design, 1.0% was chosen as the value of degradation in the annual energy output of the plant.

- **Financial Parameters**

This page sheds light on the financial analysis in its review of the project feasibility. In the following section, a brief explanation of the financial inputs used in the study is provided.

In the following part, the financial parameters of the project are outlined. For every electricity unit produced by the system, the project receives a bid price in a PPA.

SAM calculation determines whether an IRR target indicated by users is the basis of a PPA price or the other way around:

Users can stipulate the IRR as an input if they select the IRR target option. Subsequently, a search algorithm is employed by SAM to identify the PPA price compatible with the target IRR. This is the technique adopted in the financial analysis employing IRR. As such, the IRR value was set to 13%, as a realistic percentage that could lead to attaining the expected price of the PPA. In addition, SEC receives significant government support to save energy for the Saudi citizens as a higher priority than seeking to increase its business profit. However, another analysis of IRR will be carried out later in this chapter to decide the percentage at which the project could be at a profit or loss. Another analysis includes LCOE and PPA.

- An escalation rate of 2 % was used.
- Analysis period of 25 years was selected for this case study.
- Inflation rate of 2.1 % was used.
- Real Discount Rate Value of 7 % per year was used. SAM's financial model results are very sensitive to the real discount rate input. If the user plans to use metrics like the NPV, levelised cost and PPA price, and IRR, he should carefully consider the discount rate used in analysis.
- Annual Interest Rate was set at 2%.
- In respect to the section on tax and insurance rate, up to the value of 2.5% was added in taxes, as this is the standard zakat rate to be paid by in a compulsory religious contribution to charitable purposes in KSA. In terms of the insurance rate, a value of 0.5% was selected as the value of construction per year.
- The value of debt was fixed at zero, since the study is focused on the implementation of the project by the SEC, with the latter providing the full value of the project. The company has been provided with unlimited government support.
- A total value of 4% annual depreciation was applied under the assumption that the value of plant would be zero at the end of the 25th year. As a result, the net salvage value was also neglected.

A summary of system costs and financial parameters are presented in Table 5.4, which shows the feasibility study financial parameters.

Table 5.4: SAM financial analysis input data

Page	Variable	Input Value
System Cost	Site Improvements	20 $/m2
	Heliostat field	200 $/m^2
	Balancing of plant	350 $/kWe
	Power Plant	1,140 $/kWe
	Storage	30 $/m^2
	Fixed tower Cost	3,000,000 $
	Tower cost scaling exponent	0.0113
	Receiver reference cost	110,000,000 $
	Receiver cost scaling exponent	0.7
	O&M Variable Cost by generation	30.00 $/MWh
Life Time	Degradation rate	1 % per year
Financial Parameters	Minimum Required IRR	13 %
	Analysis period	25 Year
	PPA Escalation Rate	2 %
	Inflation Rate	2.1 %
	Real Discount Rate	7 %
	Federal Income Tax	2.5%
	State Income Tax	0 %
	Insurance Rate	0.5 %
	Debt percent	0 %
	Construction Period - Months	24
	Annual Interest Rate	2 %
Depreciation	Depreciation	4 % per year

5.5.3. System Design Optimisation

After adopting the inputs and values in the power cycle, system cost, lifetime, financial parameters, and depreciation pages related to the case study, a number of tests were carried out to study the plant's reaction to variables that are related to the number of hours of the thermal storage and SM. According to these analyses, the most optimal and appropriate version for the accomplished design is achieved.

Because designing the system with optimal values for the different metrics is impossible, the core CSPP design has to be optimised several times. The effect of SM and TES values on different metrics is clearly indicated by this analysis. This means that the physical design and project profitability are also affected. The present section addresses only those metrics that are indicative of how feasible and effective the project is, but it is possible to include other metrics as well.

The number of hours of the TES and SM contribute largely to the plant's behaviour at the various values and the changing capacities, which can have an impact on all of the generated energy and the feasibility of the plant. Therefore, it is necessary to conduct an extensive analysis explaining this reaction to the variables, and its impact in the selection of the optimal design of the TES and SM variables, as well as its effects on the viability of the plant and the optimal amount of generated energy to achieve the ideal option. This analysis has a direct correlation on the financial analysis, with the PPA, LCOE and NPV having a close association with the behaviour of the plant during the various TES and SM design conditions. In addition, the CF contributes to achieving a clearer picture when choosing the most optimal design. As such, this analysis is carried out at different TES values ranging between 0 and 10, with a two-hour difference between each one of them. However, the SM values will range between 1 and 3, with 0.25 difference.

The first analysis shows the relationship between the PPA at different TES and SM capacities. It should be noted that this analysis seeks to achieve the lowest possible PPA with these variables. As shown in Figure 5.17, findings proved that the lowest value of PPA is achieved at four TES variables, which are 4, 6, 8 and 10 at the SM values of 1.5, 1.75, 2 and 2.25, respectively. Here, the value of the PPA is close and at its lowest. However, the exact values proved that with TES = 6 when SM = 1.75, this achieves the lowest value of PPA, which was 20.61 ¢/ kWh.

Results also showed that there is an ideal SM for each different TES. As shown in the Figure, the optimal SM when TES = 4 is 1.5, and when TES = 6, the optimal SM is 1.75. It also turned out that any increase in the value of ideal SM for each different capacity will affect the price of PPA, with its value increasing every time the SM exceeds its optimal value for TES.

Despite achieving a TES = 6 and an SM = 1.75 as the lowest value of PPA, the analysis is expanded as a result of convergence in the value of the PPA at variable capacities of the TES and SM. In addition, other analyses were carried out to verify the optimal TES, as well as the value of its optimal SM.

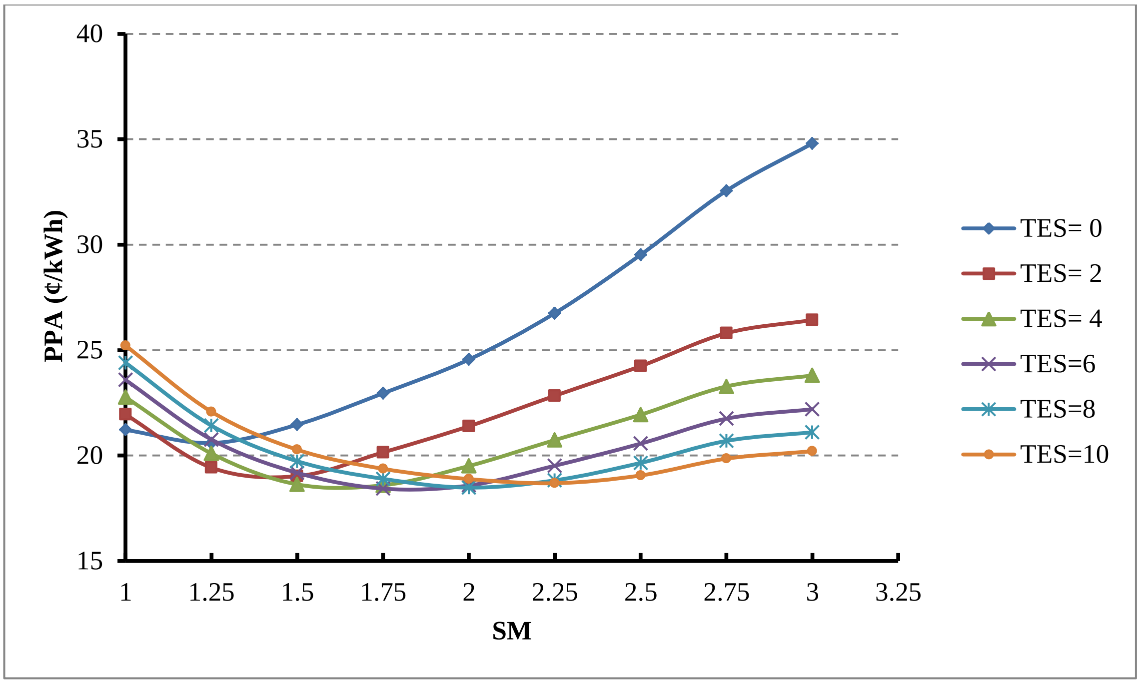


Figure 5.17: Levelised PPA price (real) (¢/kWh) vs. SM

The relationship between TES and SM justifies the effect on LCOE price. As a result, an analysis was undertaken showing the relationship between these variables to identify the financial response of the plant when exposed to these variables. Analysis has shown that the lowest LCOE occurs when the storage capacity of the plant rises in parallel with the increase in the optimal SM value for each storage option. However, as can be seen from Figure 5.18, LCOE values that have achieved less than 17 ¢/ KWh with the optimal values for the MS related to the various storage capacities will also be important, while taking into account that these are competitive prices. It has also been shown that LCOE decreases gradually. Hence, it may be stated that with the increase in TES, there is an increase equally in the optimal value of SM. Therefore, the value of LCOE decreased at TES = 10 and SM = 2.25, compared to the lowest LCOE storage capacities with TES = 8 and TES = 6, but values remained rather close. However, an increase in TES and in SM, respectively, will have other financial implications that is discussed later.

Based on the previous two analyses, it can be said that three TES values between 6 and 10 hours at different values of the SM between 1.75 and 2.25 compete according to the previous results, in spite of achieving less PPA at TES = 6 and SM = 1.75. The exception to the design options is where TES = 0, 2, and 4 due to the increase in LCOE and PPA, as shown in the previous analyses. This has a negative impact on the economic feasibility and plant optimal design.

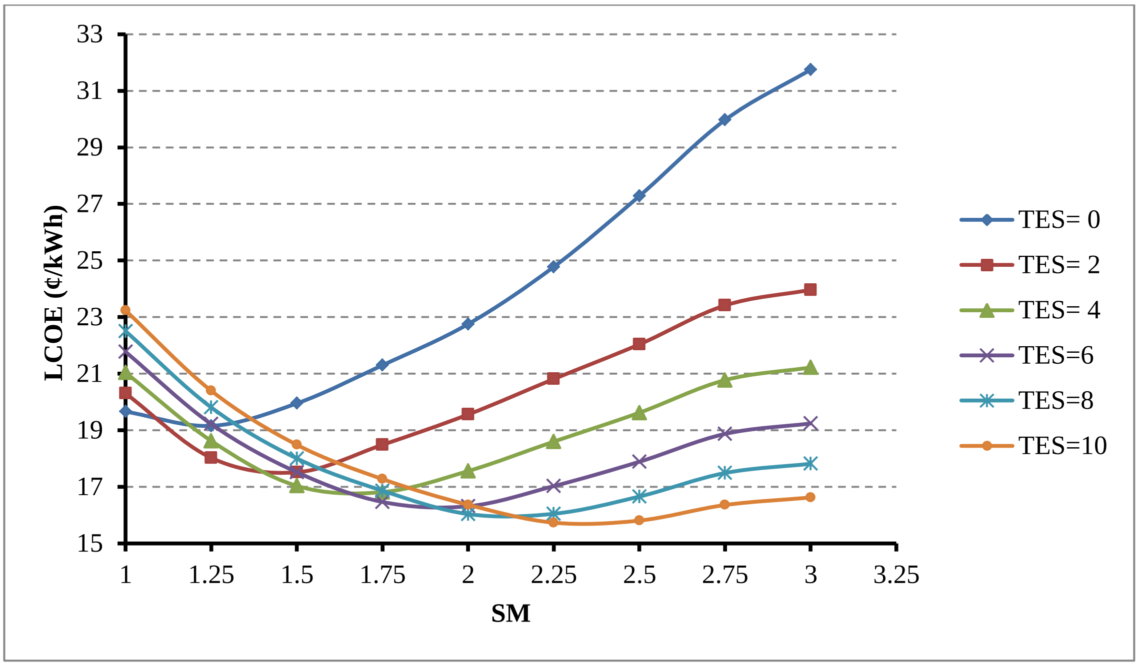


Figure 5.18: Levelised cost (real) (¢/kWh) vs. SM

Figure 5.19 shows the change of IRR value at the end of the analysis period in relation to TES (h) and SM.

An analysis was performed to assess the effect of different capacities of thermal stores and SM on the percentage of IRR, whereby variables would be evaluated to determine their impact on different storage capacities at which the highest IRR percentage could be achieved. The storage capacity achieving the highest IRR will have a positive impact in terms of the selection of the optimal SM related to that capacity. As suggested in Figure 5.19, the highest IRR is achieved when the TES = 6 and SM = 1.75, despite the fact that the IRR values at other different store capacities between 4 and 10 at 1.5 to 2.25, respectively have achieved relatively higher IRR ratios.

Previous analytical perspectives on the results showed that with TES = 6 and SM = 1.75, they could achieve better competitive values compared to other systems with similar results.

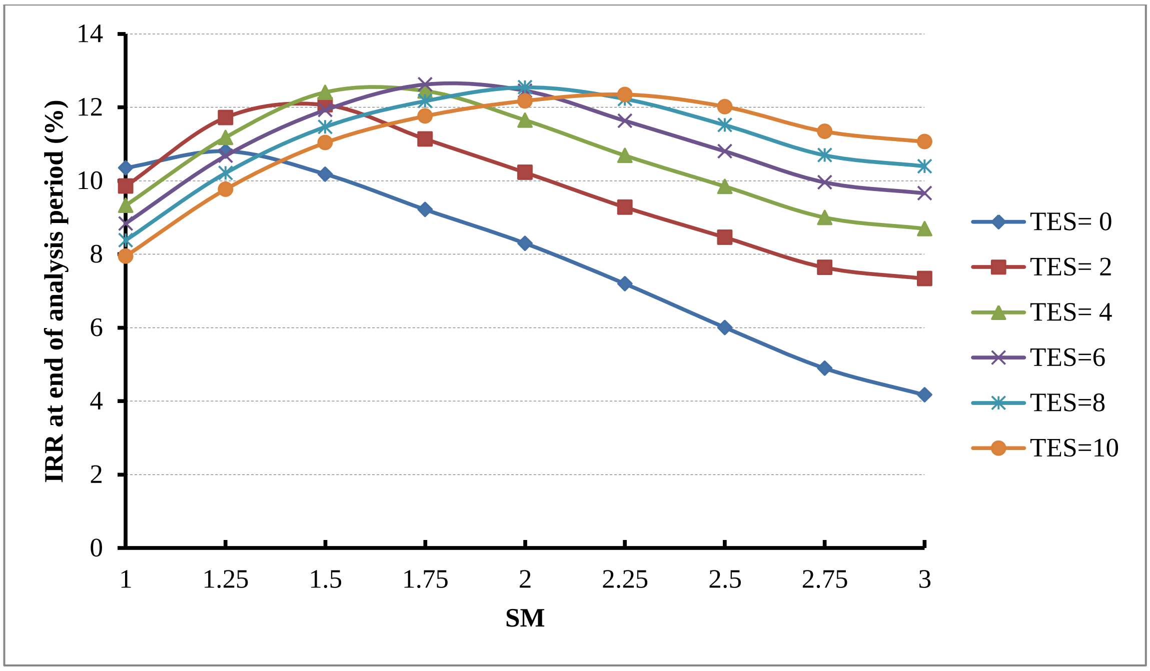


Figure 5.19:IRR at end of analysis period (%) vs. SM

From the economic analysis the IRR optimal values is dependent on the selected thermal storage capacity of the system at different level of SM, as shown in Figure 5.20. for the current design specification, the most advantageous IRR value for the investors is 12.62% which corresponds to an SM of 1.75. This makes it the perfect choice for the design of the plant and reflects positively on the technical and financial performance of the plant.

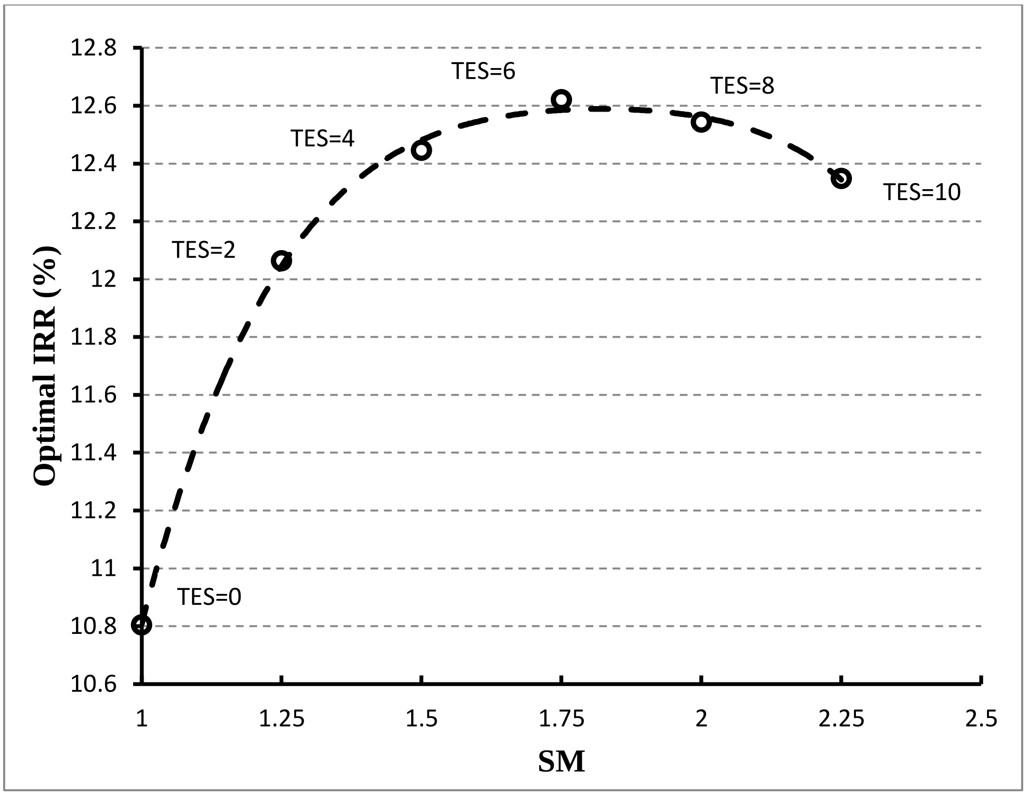


Figure 5.20: Optimal IRR (%) of each TES capacity (h)

Following the previous analyses, it is also important to review the plant's behaviour in terms of the amount of energy produced in order to determine the appropriate TES, especially after identifying MS = 1.75 as an optimal option in the previous analyses. As shown in Figure 5.21, there is a relationship between the CF and different variables for the energy stores and SM of the proposed plant. In general, the results indicate that the CF for any TES increases whenever there is an increase in the rational and appropriate SM for the same capacity. However, in terms of CF when SM = 1.75 and when TES = 6, it is very close to the case of TES = 8 and TES = 10. These similarities in results lead us to reflect seriously on the previous results, and take them into account when deciding on the best thermal store drawn from these analyses. Therefore, the choice of TES = 8 or 10 at the same SM = 1.75 will yield an increase in the cost and a higher PPA and LCOE when compared to selecting TES = 6 at the same value of the SM.

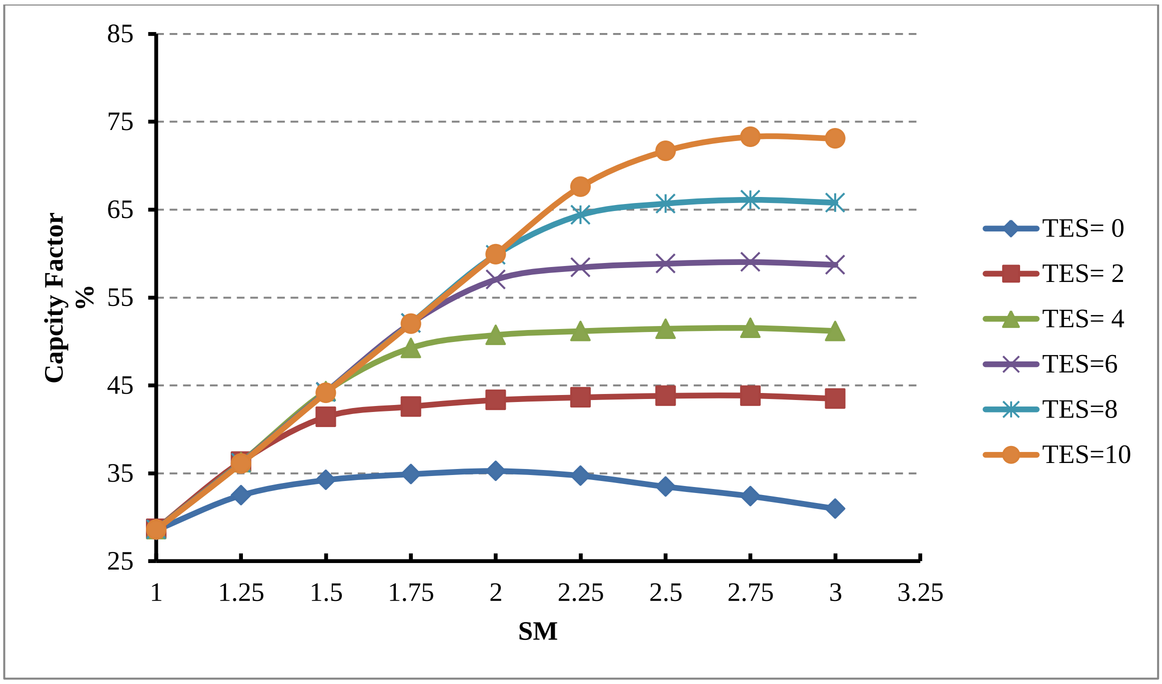


Figure 5.21: Levelised PPA price (real) (¢/kWh) vs. SM

Another analysis was performed to clarify the relationship of plant variables to the value of the NPV. Results, as indicated in figure 5.22, have shown an increase in the value of NPV when there is an increase in the thermal store, and according to the optimal SM appropriate for each value of storage capacity. Therefore, the value of NPV at TES = 8 and 10 was higher compared to TES = 6. However, taking into account the feasibility of the previous analyses results, and their impact in terms of the PPA, LCOE and the IRR, it may be said that NPV is not a suitable indicator to judge whether TES = 8 or TES = 10 achieve the best feasibility. This is because price competitiveness is an important factor in terms of the feasibility of the plant, and the ability to market its product. As a result, an increase in the value of the NPV is not a definite indicator of whether the design is profitable and feasible or not. On the other hand, IRR is considered the most important indicator, whenever NPV values are all equal.

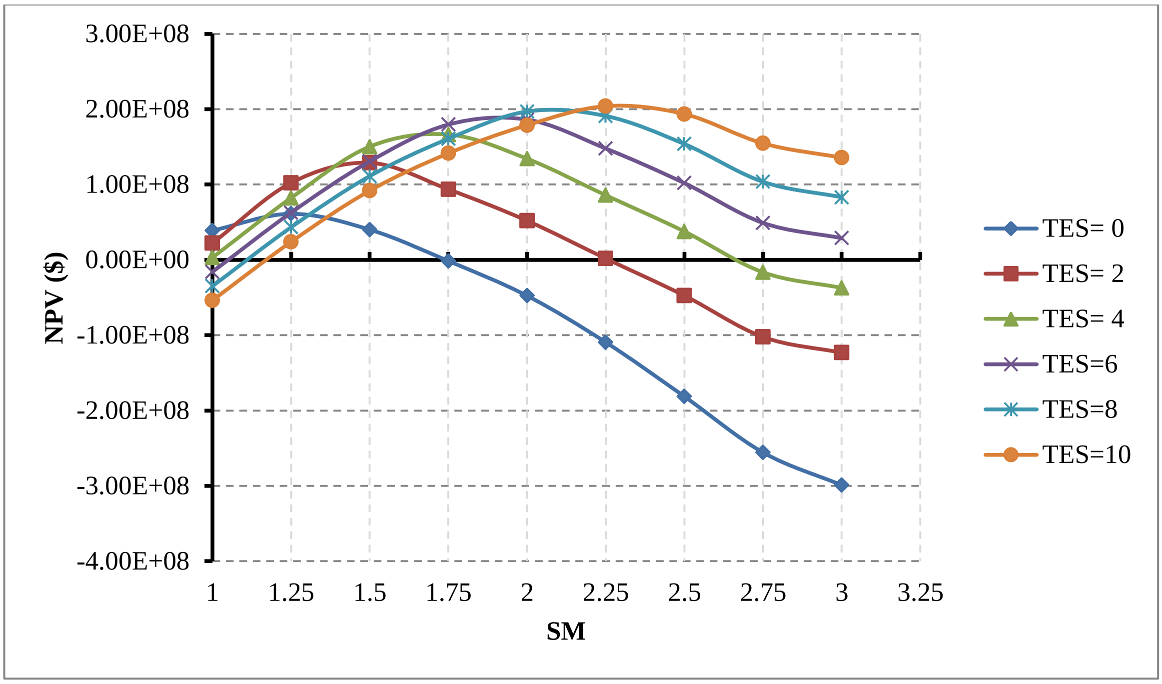


Figure 5.22: NPV ($) vs. TES (h)

Results demonstrated that when TES = 6 and SM = 1.75, IRR achieved the highest percentage, while the lowest value of PPA is achieved through TES = 6. In addition, the starting cost to set up the plant would be less with six hours storage compared to when the plant is equipped with a larger thermal store of between 8 to 10 hours. Therefore, the best option according to which the plant is designed is a 6-hour thermal store with an optimal SM equal to 1.75.

All the above processes ensure that the most optimal design is selected, so that system costs and PPA price can be minimised, which should make this plant competitive in comparison with conventional energy sources. Hence, it was decided to use a SM=1.75 with thermal storage of six hours, as this direct system was considered to have the best performance.

5.5.4. Simulation Results and Energy Yield for The Optimised Design

Figure 5.23 indicates the simulated energy performance estimated based on the established technical parameters and previously outlined optimal design. According to the simulation, the CSP plant should have a suitable performance throughout the year, minimum power generation capacity of around 30.9 GWh per month and maximum power generation with a total capacity of 43.6 GWh being attained in February and April, respectively.

It can be noted that the energy-producing plant has a constant link with the DNI energy falling on the site, as was explained in Figure 5.9.

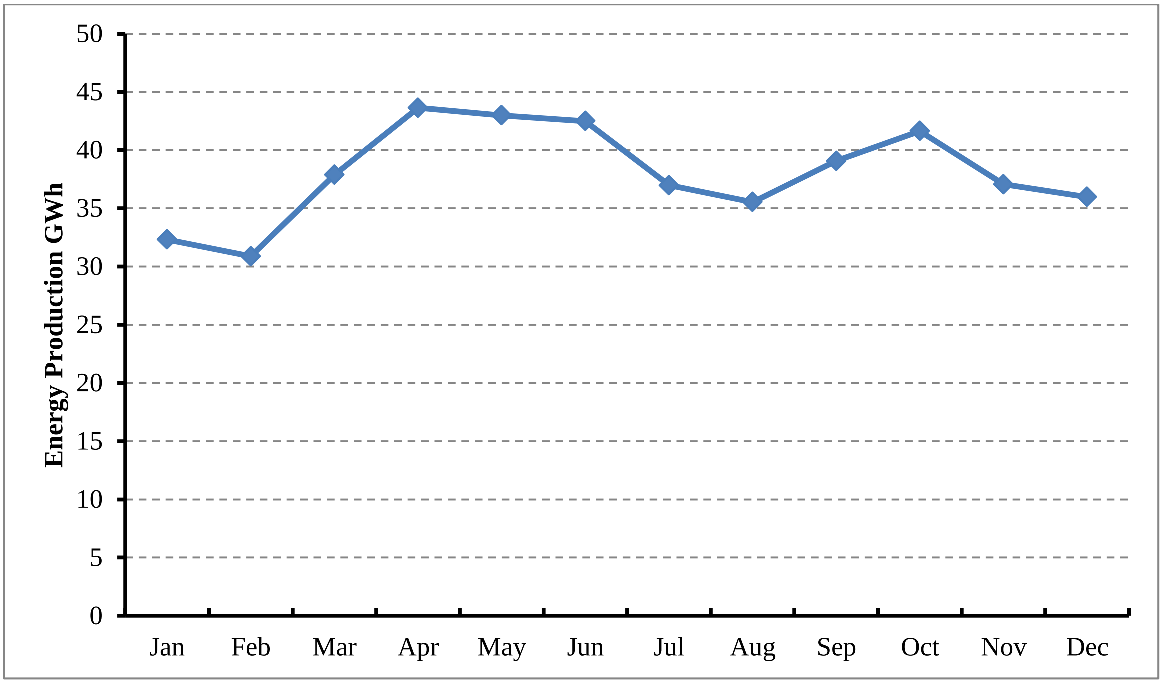


Figure 5.23: Monthly power generation at Shuaibah CSPP

The annual total power generation capacity is estimated to be about 456.4 GWh, which would displace about 1.3 % of the power generation from the existing fossil-fuelled PP in Shuaibah. The overall thermal efficiency of converting solar energy to electricity is about 52.1%.

The proportion of energy produced from the CSP represents a small percentage compared to the plant's current energy produced annually, because of its magnitude, amounting to 5538 MW.

As can be noticed in Figure 5.24, the energy produced from the plant on a yearly basis decreases at an annual rate of 1%. This is the corresponding rate of decrease and deterioration in the plant systems, as assumed for the design given the efficiency of the plant over a period of 25 years. The energy produced from the plant in its 25th year is 347 GWh, which represents a decrease from what it would have been in the first year at a rate of 25%.

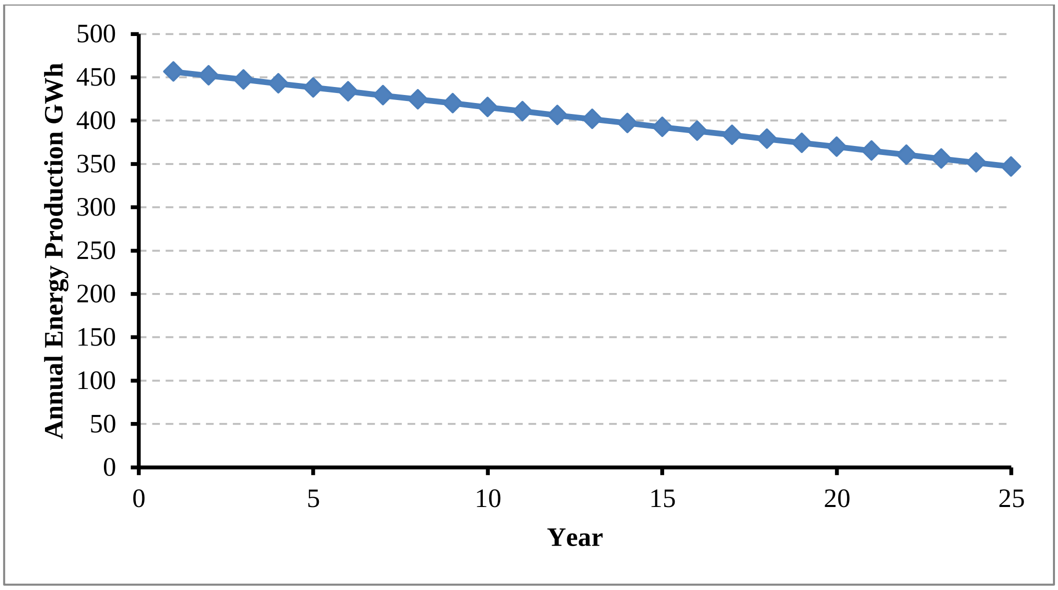


Figure 5.24: Yearly energy yield over 25 years at Shuaibah CSPP

Results obtained from the SAM software computer model on the project cost effectiveness are presented in Table 5.5. In the table, the unit power generation from the solar power plant is seen to be LCOE nominal around 19.75 c/kWh, which is competitive with unsubsidised electricity generation from fossil fuel power plants, but it is somewhat expensive when compared with other technologies.

Further discussion of the results is presented in the discussion section.

Table 5.5: SAM results

Metric	Base
Annual Energy	456.467 GWh
Cross to net conversion	90.83 %
Capacity factor	52.1 %
PPA price (Year 1)	18.43 ¢/kWh
PPA price escalation	2.00 %
Levelised PPA price (nominal)	24.73 ¢/kWh
Levelised COE (nominal)	19.75 ¢/kWh
Net present value (NPV)	$202,588,816
Internal rate of return (IRR)	13.00 %
Year IRR is achieved	25
IRR at end of analysis period	13.00 %
Net capital cost	$ 613,542,336
Equity	$ 613,542,336
Total Land Area (km^2)	6.03 km^2

Figure 5.25 shows the real LCOE at 16.64 ¢/kWh and the real value of PPA at 20.61 ¢/kWh, which is the value that takes into account the impact of the financial analysis for a period of 25 years, such as inflation rate. These results are also discussed in the discussion section.

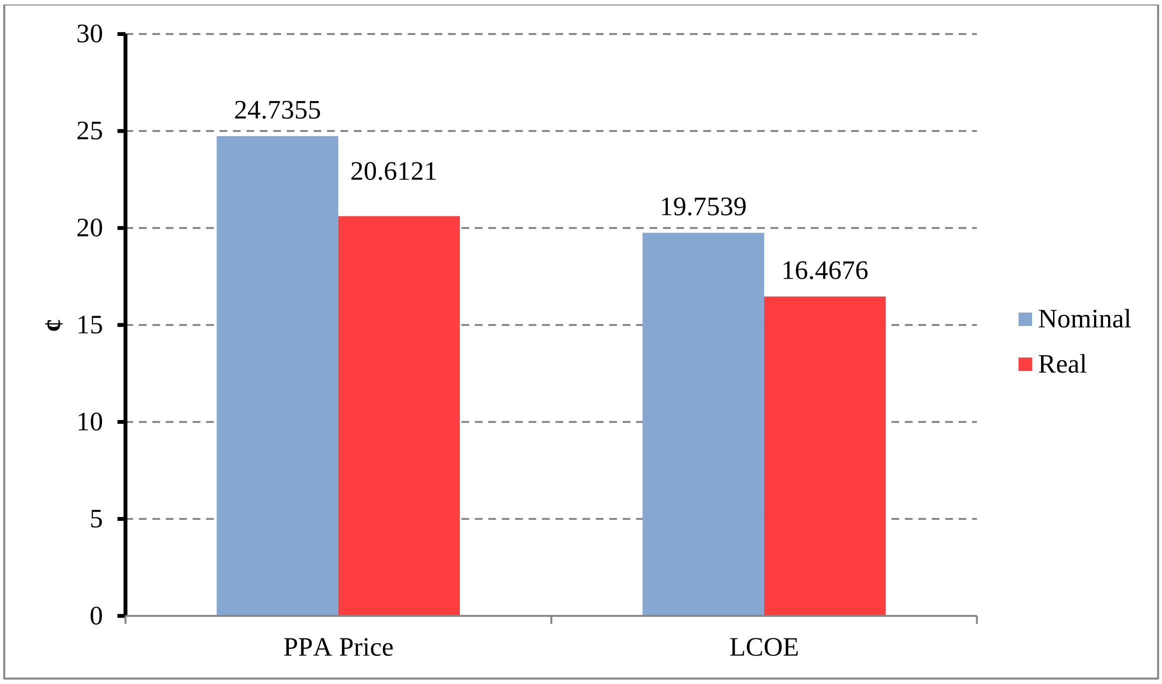


Figure 5.25: Nominal and real PAA price and LCOE

According to the abovementioned prices, the study showed that the project is at profit when the IRR is equal to 13%. However, other tests were carried out to determine the percentage of IRR at which the project would be equal or less. In other words, it is not making profit or proving a loss from the start. Assuming that a price of 16.4676 ¢/kWh for LCOE and a lower price for any PPA would lead to a loss, the LCOE price was adopted as a reference when carrying out the analysis. As illustrated in Figure 5.26, the findings suggest that with any IRR percentage at 9.3, the value of the LCOE is equal to the price of the PPA, which renders the project a no-profit venture. Achieving less than 9.2 may eventually mean that the project would be at a loss and it would be even less feasible when the percentage continues to go down. A discussion of the impact of the PPA and IRR prices for this project will follow later, while taking into consideration the circumstances of the energy sector in KSA, and the government subsidies allocated to this sector.

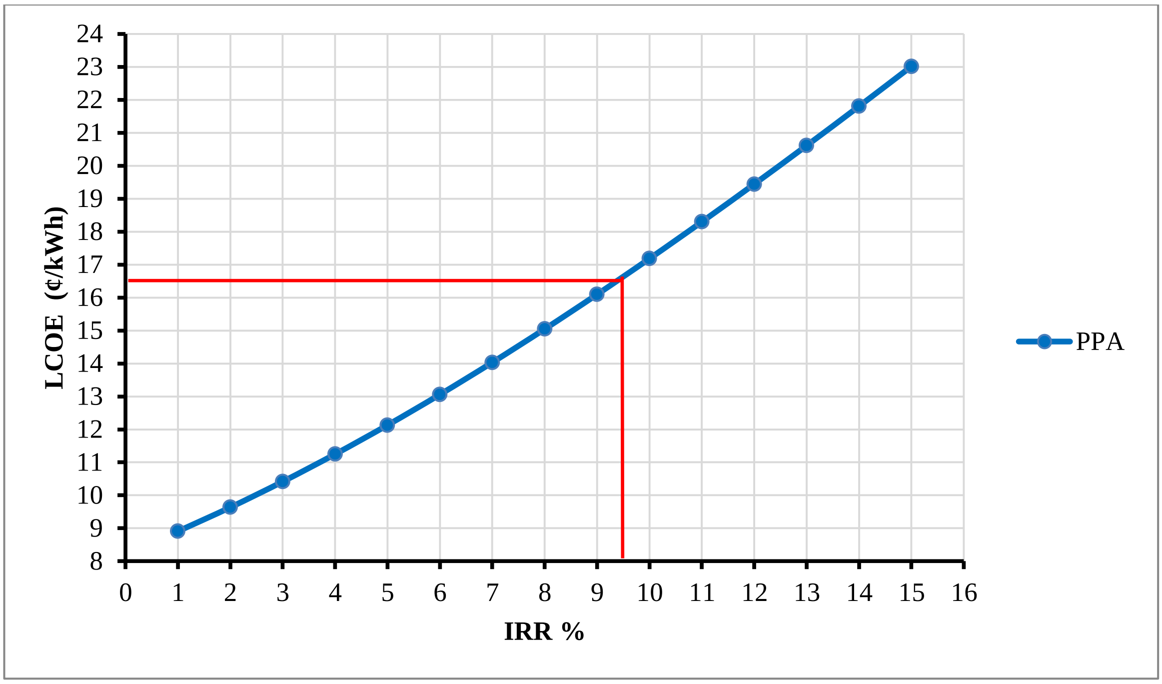


Figure 5.26: Profitable IRR% with PPA vs LCOE

The plant costs are distributed as shown in Figure 5.27 over eight key sections, with the solar field the highest, representing 37% of the plant value. This demonstrates that in CSP power plants, technology is considered the most significant and costliest element in terms of offering free fuel for the solar plant. This is also the case for other technologies related solar systems of the plant, including the tower, storage, and receiver, with total cost ratio of the net plant cost reaching around 25%.

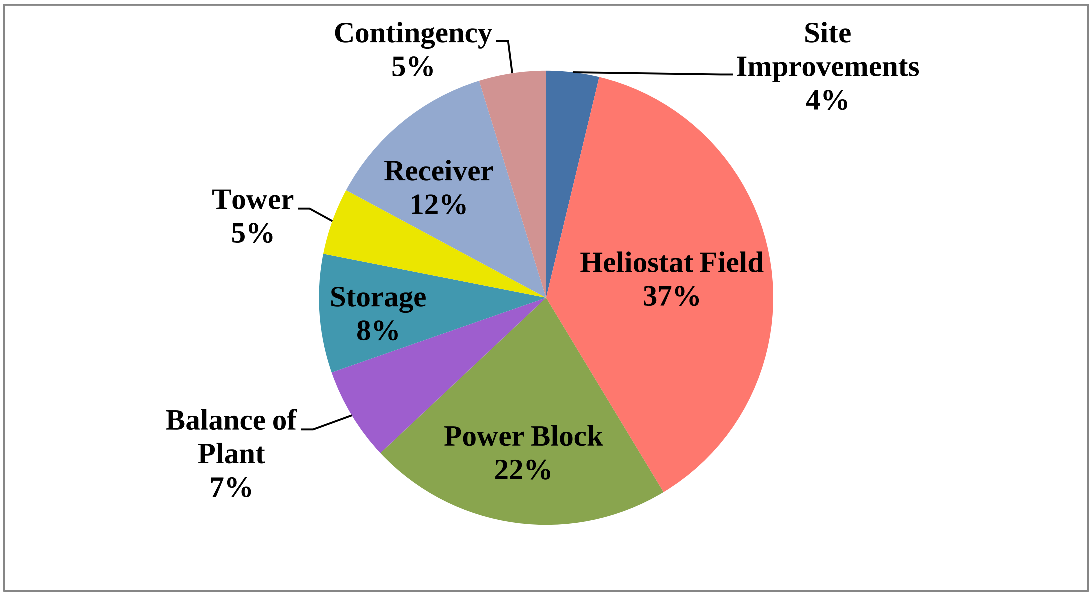


Figure 5.27: Cost breakdown for the proposed CSPP at Shuaibah

Figure 5.28 shows the total revenue of the project all through the entire CSPP life cycle. Thus, in the last year of operation, total revenue amounts to $ 122 Mil. This is the culmination of the anticipated gradual increase in revenue from the first years of operation until completion of CSPP life cycle.

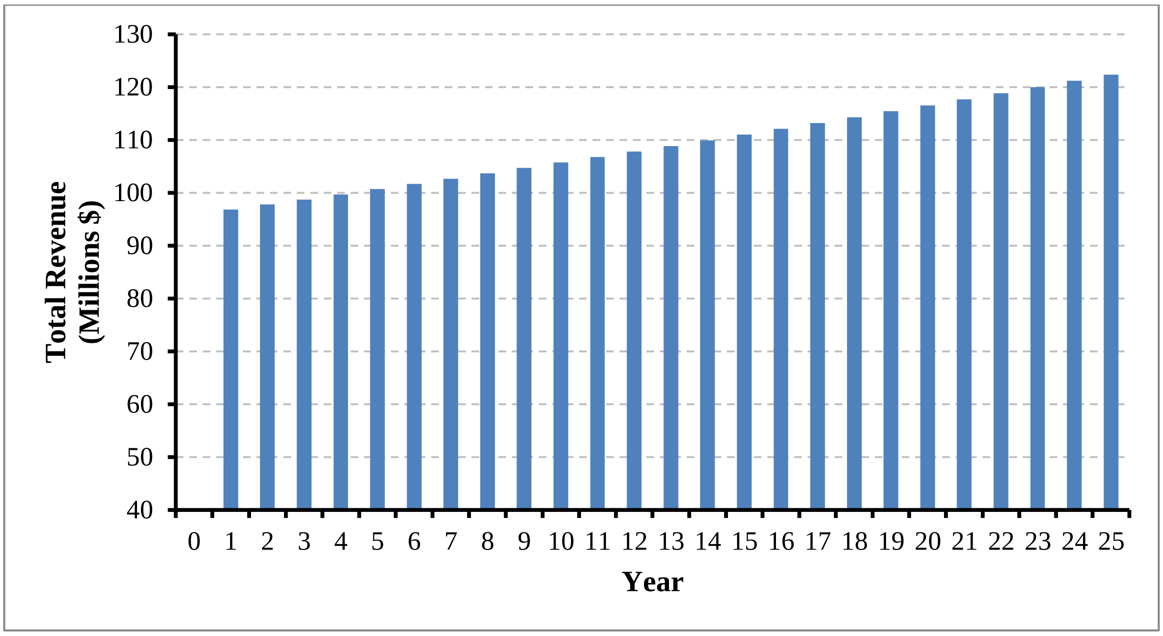


Figure 5.28: Total revenue at Shuaibah CSPP

Figure 5.29 presents tax cumulative IRR (%), which is an indicator of how profitable the project is. It is clear to see that it takes eight years of operation to attain the target 13% IRR, the same percentage recorded at life cycle completion.

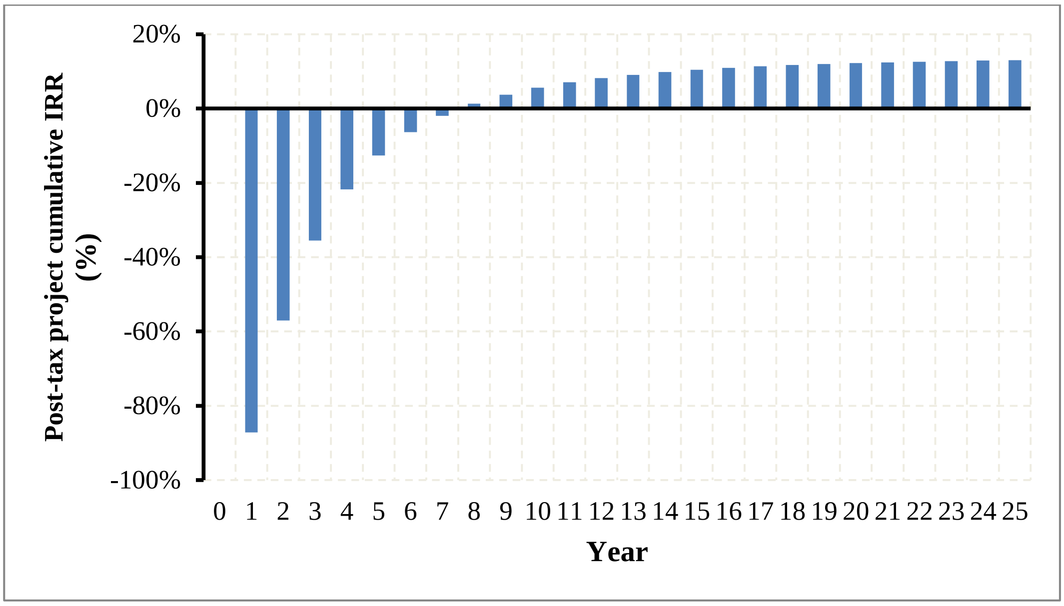


Figure 5.29: Post-tax project cumulative IRR (%) at Shuaibah CSPP

Project cash flow is shown in Figure 5.30. It may be noted that cash flow steady increases from the initial year in operation until the CSPP is decommissioned. Negative cash flow is only seen in the first year of operation.

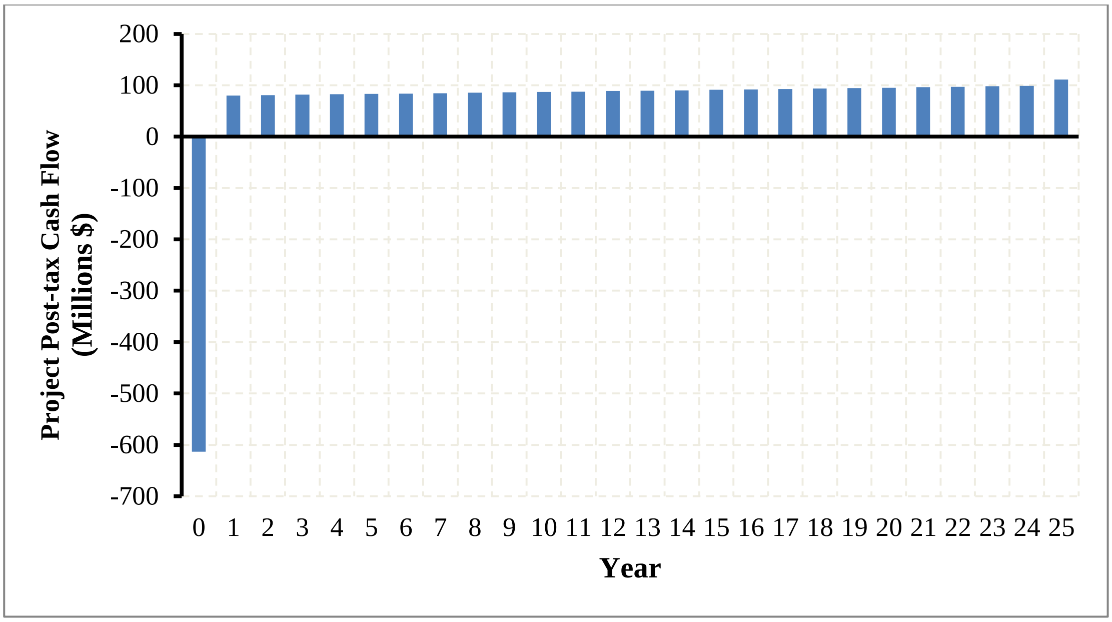


Figure 5.30: Post-tax project returns cash total ($) at Shuaibah CSPP

Post-tax project returns are shown in Figure 5.31. It may be noted that the project operates at a loss in its initial year, while returns increase in subsequent years of operation.

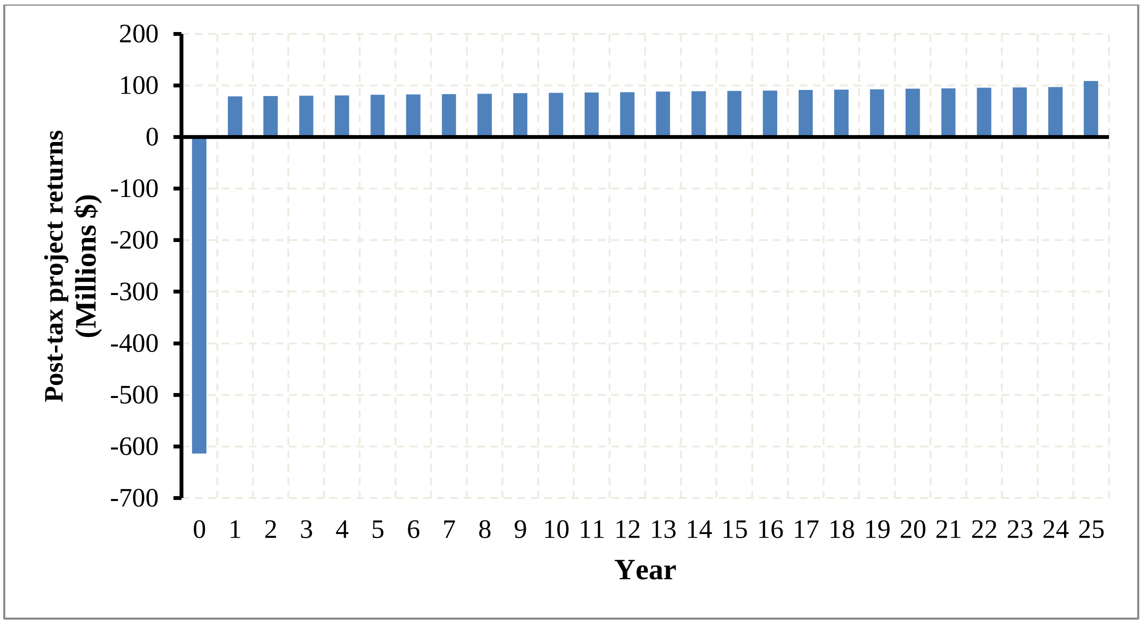


Figure 5.31: Post-tax project returns ($) at Shuaibah CSPP

Project NPV is shown in Figure 5.32. NPV reaches balance after 12 years of operation after which it becomes positive, which a measure of the plant's profitability.

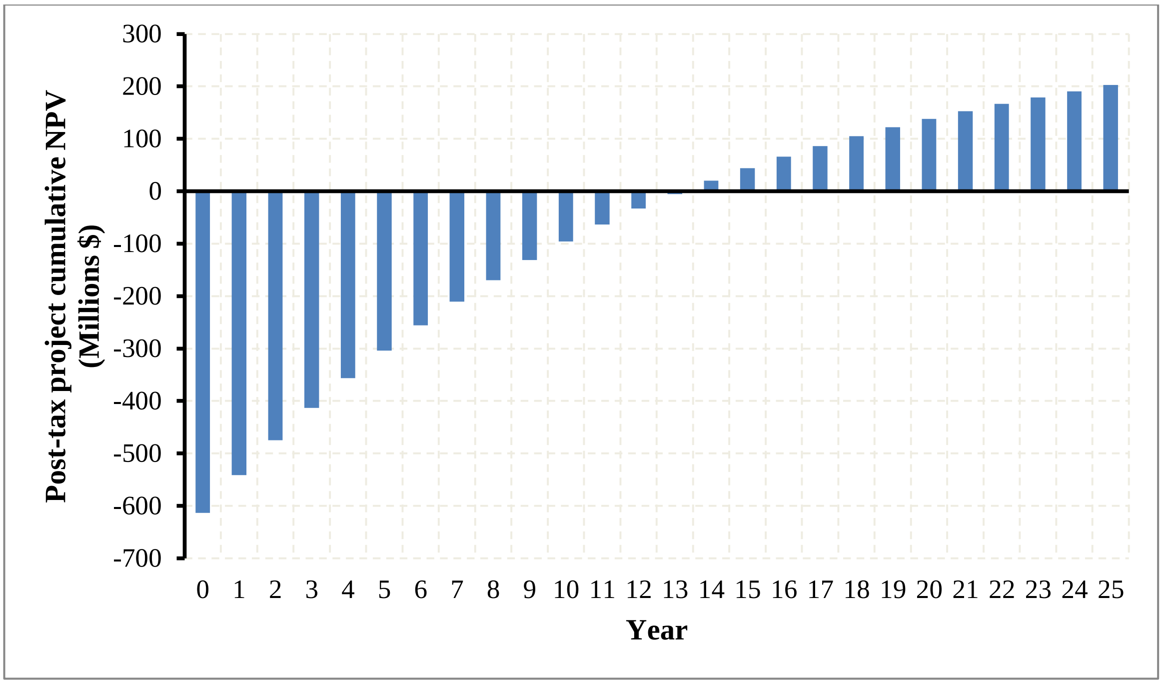


Figure 5.32: Post-tax project cumulative NPV ($) at Shuaibah CSPP

5.6. RETScreen Software Analysis

Following the use of SAM to provide a holistic view and analysis of the PP, as well as achieve the desired results, another analysis was carried on the same plant. This used the same data and results as inputs to the RETScreen program. The latter gives fresh readings due to the different methods in terms of entering the data, and producing the relevant results. It is worth pointing out that an analysis of emissions is performed using RETScreen as it is not possible to do so using SAM. It is then followed by an analysis of the pages available in the program, as well as an explanation of inputs, and how they are entered into each page.

- **Climate data**

As shown in Figure 5.33, the necessary data was entered on the first page of the program, which includes the selection of the type of PP. The solar thermal power option was selected as the RETSCreen program studies and analyses the situation in general and does not have an option to specify the type of method to be utilised be it a tower or otherwise. In addition, method 2 was chosen to analyse and study the situation in the five pages presented by the program, rather than method 1, which gives a very short overview of the five pages of the study. One of the most important inputs in the first page is deciding where the plant would be situated, for which the city of Jeddah was chosen, as it was close to the plant site, as mentioned in *Chapter 3*. The weather data was downloaded from the database of the program, as shown in Figure 5.33.

Project type	Power
Technology	Solar thermal power
Grid type	Central-grid
Analysis type	Method 2
Heating value reference	Higher heating value (HHV)
Show settings	☐

Site reference conditions Select climate data location

Climate data location	Jeddah/King Abdul Aziz I.
Show data	☑

	Unit	Climate data location	Project location
Latitude	°N	21.7	21.7
Longitude	°E	39.2	39.2
Elevation	m	17	17
Heating design temperature	°C	16.2	
Cooling design temperature	°C	39.6	
Earth temperature amplitude	°C	13.1	

Figure 5.33: Start page and weather data for Shuaibah

- **Energy model**

As far as the proposed design is concerned, one was supposed to put the same value of the CF obtained in the previous findings using the SAM program, which is 52.1. Nonetheless, it cannot be trusted enough because RETScreen does not take into consideration the degradation of the system over the 25-year period. For a calculation of this, the power plant's mean energy generated annually has been accounted for during the whole period by depending on the values shown in Figure 5.24 previously, with the average annual value of the energy produced reaching 401.909 GW. As such, the CF has been computed and a value of 45.9 obtained, which is used for the analysis. The electricity export rate was also entered at 206.1 $/MWh, which is the PPA real value calculated using the SAM program.

Figure 5.34 presents the RETScreen energy model sheet, indicating that around 402 GW of energy is delivered each year. This is the target average annual production of energy that the system should achieve over a period of 25 years.

RETScreen Energy Model - Power project

Proposed case power system				
Technology		Solar thermal power		
Solar thermal power				
Power capacity	kW	100,000		
Manufacturer		Abengoa Solar		
Model		PS10		
Capacity factor	%	45.9%		
Electricity exported to grid	MWh	401,909		
Electricity export rate	$/MWh	206.10	$/kWh	0.206

Complete Cost Analysis sheet

Figure 5.34: Energy model worksheet

- **Cost Analysis**

Next step is to define overall project costs.

The analysis focused on two key sections. More specifically, the initial costs and annual costs. It used the value of the direct capital cost of the plant achieved through the SAM program at $ 5763.6 per KW of the total plant capacity of 100MW, with a contingency factor of 5%. Regarding the section on annual costs, the cost of O & M was estimated at $ 30 per MWh for the entire annual volume of energy produced (456.467.7 MWh). However, the program does not consider declining production, where it is known that O&M cost increases as the plant grows older. The cost of insurance was set at 0.5% of the full cost of the plant, and it entered into the program as a cut off value of $ 3,067,711 while adding 5% contingency to the annual expenses in order for the financial analysis to be more conservative.

RETScreen automatically calculates overall system costs by summarising initial costs at $ 605,178,000 and annual costs at $ 17,599,829. Since SAM and RETScreen have different calculation methodologies, it is important to mention that not all input parameters are labelled in the same way. However, it is important to set them in a way that they provide accurate final figures as was done in this modelling work.

Costs analysis sheet is shown in Figure 4.35.

Initial costs (credits)	Unit	Quantity	Unit cost	Amount	Relative costs
Feasibility study					
Wadi Aldawasir	cost	1		$ -	
Subtotal:				$ -	0.0%
Development					
Development	cost	1		$ -	
Subtotal:				$ -	0.0%
Engineering					
Engineering	cost	1		$ -	
Subtotal:				$ -	0.0%
Power system					
Solar thermal power	kW	100,000.00	$ 5,764	$ 576,360,000	
Road construction	km	1		$ -	
Transmission line	km	0	$ -	$ -	
Substation	project	0	$ -	$ -	
Energy efficiency measures	project	0		$ -	
equipment	cost	1		$ -	
thermal storage		0		$ -	
Subtotal:				$ 576,360,000	95.2%
Balance of system & miscellaneous					
Spare parts	%	0.0%		$ -	
Transportation	project	0		$ -	
Training & commissioning	p-d	0		$ -	
	cost			$ -	
Contingencies	%	5.0%	$ 576,360,000	$ 28,818,000	
Interest during construction		12 month(s)	$ 605,178,000	$ -	
Subtotal:				$ 28,818,000	4.8%
Total initial costs				$ 605,178,000	100.0%

Annual costs (credits)	Unit	Quantity	Unit cost	Amount
O&M				
Parts & labour	project	1	$ 3,067,711	$ 3,067,711
User-defined	cost	456,468	$ 30	$ 13,694,031
Contingencies	%	5.0%	$ 16,761,742	$ 838,087
Subtotal:				$ 17,599,829

Figure 5.35: RETScreen cost analysis

It may be noted that using the above listed input parameters, overall project costs are slightly similar to the system cost obtained from SAM, because similar costs with different calculation behaviours are used in the two programs.

- **Emission Analysis**

The emission analysis is considered one of the most important analyses in this case study. While calculating emissions using the RETScreen program, this analysis seeks to provide results that have a direct impact on the environment. Protection of the environment and reduction of emissions are among the key factors for utilising CSPPs. Identifying a framework of benefits gained following the accomplishment of the design and the study of the plant will contribute to a deeper analysis of the positive impacts on the environment through the adoption of this design.

RETScreen software provides very convenient way to complete emission analysis. Method 1 is used for this purpose, and the base case electricity system for KSA was selected from the list of available countries. GHG emission factor for all types of fuel was automatically set to 0.737 tCO_2/MWh. Results indicate for the base case electricity system using 100% fuel mix, electricity production of 401,909 MWh will generate 329,021.9 tCO_2 while from the CSPP is equivalent to 32,902.2 tCO2 taking into account the T&D losses at 10%. Therefore, reduction of 296,119.7 tCO_2 will accrue when the CSPP is considered as an alternative to the equivalent fossil fuel plant. This represents a reduction of 54,234 cars and light trucks. RETScreen emission analysis sheet is shown in Figure 5.36.

Base case electricity system (Baseline)

Country - region	Fuel type	GHG emission factor (excl. T&D) tCO2/MWh	T&D losses %	GHG emission factor tCO2/MWh
Saudi Arabia	All types	0.737	10.0%	0.819

☐ Baseline changes during project life

Base case system GHG summary (Baseline)

Fuel type	Fuel mix %	Fuel consumption MWh	GHG emission factor tCO2/MWh	GHG emission tCO2
Electricity	100.0%	401,909	0.819	329,021.9
Total	100.0%	401,909	0.819	329,021.9

Proposed case system GHG summary (Power project)

Fuel type	Fuel mix %			Fuel consumption MWh	GHG emission factor tCO2/MWh	GHG emission tCO2
Solar	100.0%			401,909	0.000	0.0
Total	100.0%			401,909	0.000	0.0
Electricity exported to grid	MWh	401,909	T&D losses 10.0%	40,191	0.819	32,902.2
					Total	32,902.2

GHG emission reduction summary

	Base case GHG emission tCO2	Proposed case GHG emission tCO2	Gross annual GHG emission reduction tCO2	GHG credits transaction fee %	Net annual GHG emission reduction tCO2
Power project	329,021.9	32,902.2	296,119.7	0%	296,119.7

Net annual GHG emission reduction 296,120 tCO2 is equivalent to 54,234 Cars & light trucks not used

Complete Financial Analysis sheet

Figure 5.36: RETScreen emission analysis

- **Financial Analysis**

The main financial parameters determining how commercially feasible the project is can be selected from the financial sheet in RETScreen. Table 5.6 presents an overview of financial parameters. The financial analysis used the same values assumed in the financial analysis for the SAM program. The same values were entered on the basis of what had been gathered from the SEC along with other references. It is worth pointing out that the insurance rate had already been computed in the cost analysis page.

Table 5.6: RETScreen Financial input parameters

Page	Variable	Input Value
Financial Analysis	Minimum Required IRR	Is calculated
	Analysis period	25 Year
	PPA Escalation Rate	2 %
	Inflation Rate	2.1 %
	Real Discount Rate	7 %
	Federal Income Tax	2.5%
	State Income Tax	0 %
	Insurance Rate	0.5 %
	Debt percent	0 %
	Construction Period - Months	24
	Annual Interest Rate	2 %
	Depreciation	4 % per year
	Degradation rate	Not measured

Financial analysis worksheet is shown in Figure 5.37.

Financial parameters		
General		
Fuel cost escalation rate	%	2.0%
Inflation rate	%	2.1%
Discount rate	%	7.0%
Project life	yr	25
Finance		
Incentives and grants	$	0
Debt ratio	%	0.0%
Income tax analysis		☑
Effective income tax rate	%	2.5%
Loss carryforward?		No
Depreciation method		Straight-line
Depreciation tax basis	%	4.0%
Depreciation period	yr	25
Tax holiday available?	yes/no	No
Annual income		
Electricity export income		
Electricity exported to grid	MWh	401,909
Electricity export rate	$/MWh	206.10
Electricity export income	$	82,833,404
Electricity export escalation rate	%	2.0%

Project costs and savings/income summary			
Initial costs			
Power system	95.2%	$	576,360,000
Balance of system & misc.	4.8%	$	28,818,000
Total initial costs	**100.0%**	**$**	**605,178,000**
Annual costs and debt payments			
O&M		$	17,599,829
Fuel cost - proposed case		$	0
Total annual costs		**$**	**17,599,829**
Periodic costs (credits)			
Annual savings and income			
Fuel cost - base case		$	0
Electricity export income		$	82,833,404
Total annual savings and income		**$**	**82,833,404**

Figure 5.37: RETScreen financial analysis

Drawing on the aforementioned financial assumptions, the program provided an up-to-date account of the clear-cut findings in Figure 5.38. One can note that the energy production cost was calculated at $ 152.7 / MWh, which achieves an IRR of 11.9% for the CSPP. Hence, the payback period is nine years with an NPV of almost $ 297.844 million. There was not much difference when comparing these results to those from SAM. As such, the key findings are discussed for each program separately and the reasons underpinning the differences and similarities so that one can gain clear insights into the most likely results to be adopted.

Financial viability		
Pre-tax IRR - equity	%	11.9%
Pre-tax IRR - assets	%	11.9%
After-tax IRR - equity	%	11.6%
After-tax IRR - assets	%	11.6%
Simple payback	yr	9.3
Equity payback	yr	8.6
Net Present Value (NPV)	$	297,844,015
Annual life cycle savings	$/yr	25,558,149
Benefit-Cost (B-C) ratio		1.49
Energy production cost	$/MWh	152.70
GHG reduction cost	$/tCO2	(86)

Figure 5.38: Financial viability

The following graph (Figure 5.39) gives a brief description of the cumulative cash flows graph of the proposed plant.

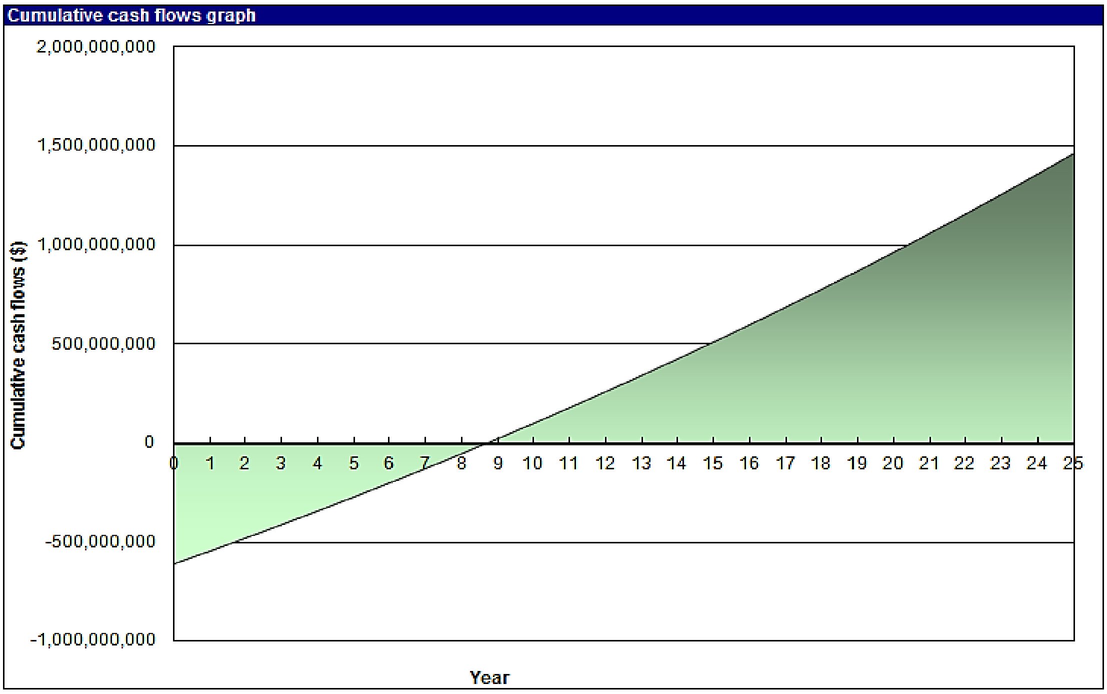


Figure 5.39: Cumulative cash flow of the proposed CSPP

5.7. Results Comparison of SAM and RETScreen Analysis

Table 5.7 illustrates the most significant findings achieved using the two programs that should lead to a better description of the feasibility of the project and analysis of the identified results.

Table 5.7: Results comparison

Software	SAM	RETScreen
Annual Energy (GWh)	456.467	401.909 (Average over 25 years)
Capacity factor	52.1 %	45.9 % (Average over 25 years)
PPA price (¢/kWh)	20.6121	20.61
LCOE (¢/kWh)	16.46	15.27
IRR (%)	13 %	11.9 %
Payback period	8.6	8.6
Net capital cost (m$)	613,542,336	605,178,000
Net present value (NPV) (m$)	202,588,816	297,844,015

The energy generated from the PP, which was modelled using the SAM is almost equal to the result obtained from RETScreen, taking into consideration the mean CF of 45.9 for the plant over a period of 25 years. This is a positive outcome allowing the adoption of the SAM results as they simulate the behaviour of the energy produced from the plant during its years in service, while also considering the rate of depreciation in the system when performing the financial analysis.

The PPA in the SAM results were gained from the technical and financial design of the PP. However, the results achieved utilising RETScreen were analysed and studied from a purely financial viewpoint. As such, it was considered worthy to refer directly to the results from the SAM and enter them into RETScreen in order to confirm them or to gain fresh results for the financial analysis and profitability of the project, more specifically the price of LCOE. As clearly shown, the LCOE results in SAM are higher than the results of RETScreen, which may have an effect on the results of the financial analysis in terms of profits, IRR, payback period, and NPV.

Among the useful findings identified using RETScreen are an IRR of 11.9, a simple payback at 9.3, and NPV of 297.844 $ million, which seem to be more interesting than the results achieved through the SAM program. However, when considering the feasibility factors, it is certainly worth pointing out that the conservative results achieved by SAM are more useful and dependable. In particular, they focused on the accurate details of technical and financial specifications of the plant in a manner that simulates the behaviour of the PP almost as if it were real.

Therefore, the results given by SAM are adopted, as highlighted in the financial analysis, while utilising RETScreen as a verification tool. Even though there were similarities as demonstrated in the findings, one should take into consideration the factors stated for the slight differences. As shown in the analysis, the results obtained using RETScreen refer to the environmental analysis, which is considered a positive aspect that is missing in the SAM program among other vital findings.

5.8. Discussion

5.8.1. Discussion on Technical Feasibility

The CSPP at Shuaibah using tower technology has a total heliostat reflective area of 1,137,529m^2 and an optimal selected SM of 1.75. With an annual generation of 456.467GWh, the solar plant is planned to complement the existing PP at Shuaibah and meet future energy demands. KSA falls within the high solar resource regions, and when properly utilised, it will could become a leading exporter of solar energy, and technology. Combining the current Shuaibah PP capacity of 5,538MW with the CSPP capacity of 100MW, a total annual generation of 35,307.783 GWh will be achieved, in what is called ISCC. This is a recent hybrid technology, which increases generation capacity and reduces fossil fuel use. Table 5.8 shows a list of existing ISCC plants in operation around the globe using tower technology. ISCC is an approach used in countries with viable DHI to increase power generation and still be environmental friendly. The data is sourced from the NREL database .

Table 5.8: Existing ISCC plants using tower technology currently in operation round the globe

Name	**Country**	**Capacity (MW)**	**Start year**	**Elect Gen** MWh/yr	**Cost (million)**	**Fossil Type**	**Storage Capacity**	**HTF**
Crescent Dunes Solar Energy Project	USA	110.0	2015	500,000	$ 737	none	10 hrs	Molten salt
Dahan PP	China	1.0	2014	1,950	CNY 32	Oil-fired boiler	1 hour	Water/Steam
Gemasolar Thermosolar Plant	Spain	19.9	2009	110,000	€ 230	Natural gas	15 hour(s)	Molten salts
Greenway CSP Mersin Tower Plant	Turkey	1.4	2012				4 MW/h	Molten salts
Ivanpah Solar Electric Generating System	USA	377	2014	1,079,232	$ 1600	Natural gas	None	None
Jemalong Solar Thermal	Australia	1.1		2,200	AU$ 10		3 hours	Liquid sodium
Planta Solar 10	Spain	11	2007	23,400	€ 6.2	Natural gas	1	
Planta Solar 20	Spain	20	2009	48,000	€ 1.9	Natural gas	1	Water
Khi Solar One (Under construction)	South Africa	50	2014	180,000			2	Water/Steam
Rice Solar Energy Project (Under Construction)	USA	150	2016	450000		None	25	Molten Salt

Net Annual Solar-to-Electric Efficiency is the ratio of solar energy to which the heliostats are exposed to the electric energy output. This can be estimated using the following simplified equation:

$$\eta = \frac{E_p}{A_c I_s} \qquad (5.4)$$

Where Ep is the annual power generated, A_c the solar collector area and I_s the annual solar energy collected. In this study the annual power energy generation is 456.467 GWh and the collector area is 449,103m² considering the 7,879 heliostats are used, each with an area of 57 m^2. The annual insolation is the cumulative for all the solar energy striking the collector area over the period of one year. The number of hours in a year is 8,760. Shuaibah's irradiance used in the power plant design is 780 W/m^2, which results in an annual insolation of 6,832.8 kWh/m^2. The Net Annual Solar-to-Electric Efficiency of the proposed plant is 0.1487 (14.87%), which falls within NREL's acceptable range. The actual Net Annual Solar-to-Electric Efficiency depends on a number of factors, such as heliostat efficiency, mirror cleanliness and reflectivity, field optical efficiency, annual thermal storage efficiency, annual receiver efficiency, parasitic losses, field availability and plant-wide availability. Improving any of these factors will improve the Net Annual Solar-to-Electric Efficiency, thereby maximising the solar energy conversion to electric energy (Sargent et al., 2003).

The plant is designed to achieve a gross to net conversion of 90.83 % (0.9083) from the gross generation of 111 MW. The energy losses during the conversion accounts for the reduction of about 10%. As tower technology matures, the conversion efficiency will increase to achieve conversion efficiency similar to convectional energy generation technologies. These losses are inevitable and arise from geometric, optical and thermal factors at different stages of the energy conversion.

Shuaibah solar plant has TES for 6 hours, which results in an increase from 35% with no TES to a CF of 52.1%. The plant availability using tower technology is similar to that of parabolic trough systems. PP availability varies depending on the plant operation, design and energy source. The CF depends on the PP availability factor, since the CF captures the ratio of the actual output over a period of one year and its output if it had operated at nominal power for the entire year. The plant has the potential of easy expansion to meet future energy demands, while utilising clean renewable energy. Future addition of TES will increase the CF and the total annual energy of the PP, increasing the SM to 3.0, which will potentially double the energy generation. Increasing the thermal storage will increase the CF and hence, the annual energy generation. As the technology matures with more research being conducted to reduce cost and increase efficiency, the annual generation based on the suggested values could be higher and cost cheaper than conventional energy generation technology.

5.8.2. Discussion on Financial Feasibility

Current technology research indicates that solar power plant projects that are located in areas with DNI values greater than 2200 KWh/m^2/year are likely to be viable and Shuaibah has DNI value more than 2200 KWh/m^2/year. This makes it a viable option to explore the feasibility of using solar energy generation technologies to meet energy demands. The plant has a low cost in taxes (2.5%), no land cost, no debt, and no loan repayment with interest, which boosts viability. With a total capital cost of about $614million and IRR of 13%, the profit over the life expectancy of the plant is very promising, assuring SEC of a good return on investment. The current investment cost for solar tower technology power plants with storage is between USD 4500/kW and USD 7150/kW. CSPPs with TES tend to be significantly more expensive, but allow higher capacity factors and shifting of generation to when the sun does not shine and/or the ability to maximise generation at peak demand times.

LCOE is used in comparing and analysing the costs and viability of power plants. This is a consideration linked to the volatility of money, where the value of money today does not have the same economic value next year, or beyond. In order to properly add costs that occur at different points in time, they are converted into "present value" terms through the use of "discounting." This will ensure inflation and other factors are captured in the feasibility studies . A relatively low LCOE means that electricity is being produce(Lovegrove et al., 2013, Kost et al., 2013)d at a low cost, with likely higher returns for the investor. For optimal performance of the plant with profitability, a LCOE value of 16.5 cents and levelised PPA price of 20.6 ¢/kWh is selected to give a good return on investment. A PPA is a financial contract in which one party develops, owns, operates, and maintains the PP and another party agrees to purchase the electricity generated. This agreement allows the customer to receive a stable supply of lower cost electricity. On the other hand, the solar energy provider receives stable income from the sale of electricity. Table 4.10 shows the US average levelised costs ($/MWh) for plants entering service.

Conventional energy generation plant currently offers cheaper levelised capital cost, because most renewable energy generation technologies are still in their infancy, with more research and development required to mature the technologies. It is important to note that the total system LCOE cost of conventional plant does not capture the impact of waste and the cost of disposing of such waste. While data is not available, factoring waste from conventional energy generation plants will increase the total system LCOE, which will exceed that of renewable energy generation plants. The data are average values with a variation of about 20% (EIA, 2015a). The USA currently has one of the largest investment schemes in solar energy generation, which is frequently used as reference in comparison with other countries. The data from Table 4.10 is used for comparison, as most power plant will have similar capital cost (EIA, 2015b).

As with any power generation plant, depreciation is inevitable. The key to reducing the negative impact on Shuaibah solar plant is to get a fair taxation policy for solar technology. The solar field could be classified as a fuel supply, and tax it in a similar way fuel is taxed in a conventional PP. This approach will ensure that property tax would not be charged on the collectors in the solar field. In addition, a one year depreciation of equipment will be permitted, which will reduce the operation and maintenance cost.

Putting in place the right solar field support structure is key to the durability and reliability of the collectors. The arid region could experience sand storms, which could have negative impact on solar fields. Sand/dust storms are meteorological phenomena when a strong wind blows loose sand and dirt from a dry surface. The loose sand and dirt are transported by saltation and suspension from one place and deposited in another. KSA experiences sand/dust storms, and this needs to be put into consideration in the selection of suitable heliostats. The heliostats structure consists of a metal support system and reflector support elements. Wind speeds could peak at 3.3m/s, which could pull down collectors (Youlin et al., 2001). Sand storms during maximum wind speeds will dictate the required strength of the collectors, which is necessary for long-term reliability and delivery of the required annual energy generation.

5.8.3. Socio-Economic Impact

A key problem the new PP will address economically is reducing the unemployment rate in KSA, which is currently 5.7%. Over the lifespan of the solar plant, it will provide employment opportunities and develop skills locally. Renewable energy plants are more labour intensive compared to fossil fuel technologies, which are typically mechanised. Building solar plants will give rise to spin-off companies, which will also stimulate the local economy through the creation of businesses to provide goods and services for the project during both construction and operations.

5.8.4. Discussion on Environmental Impact

The globe is currently facing environmental problems due to the impact of burning fossil fuels and nuclear elements, which has resulted in acidification of eco system, global climate change, and accumulation of radioactive waste. The power sector globally accounts for about 40% of carbon emissions, and the demand for more electrical energy is on the rise due to the growth in population and development. Encouraging the use of renewable energy resources will help in fighting climate change and preserving the earth for future generations. Using solar energy generation technology, there will be no carbon emissions, which is currently a global threat to the livelihood and existence of man. RETs generate clean energy, which means no GHGs, no toxic waste, and no environmentally devastating accidents. Individual countries' carbon footprint differ substantially. KSA's carbon footprint is used to estimate the environmental benefit of using solar energy in Shuaibah, instead of using fossil fuel in meeting rising demand. Emissions in $kgCO_2$ per unit energy is calculated and compared to the conventional electricity generation system. KSA has a carbon footprint of 0.754 $kgCO_2$ per kWh (IG, 2015). Shuaibah solar plant will generate 456.467GWh electrical energy annually and the amount of carbon saving will be about 380,000 tons. This is significant in reducing the carbon footprint of KSA. If renewable energy is not used in meeting future energy demands, the carbon footprint will increase. In addition, electricity consumption in KSA will also increase due to projected temperature increases from global warming and the associated increasing demand for space cooling. The calculation of carbon savings per annum was carried out through the multiplication of the energy generation and electricity mix carbon footprint value, and the subtraction of carbon emissions by renewables.

5.9. Summary

This case study discusses the Shuaibah electricity generation plant in KSA. The initial step in this project was to study the site specification in terms of different factors, such as the solar radiation, temperature, relative humidity and other factors discussed in the chapter. Analysing the available data on solar radiation, whether beam or direct normal, for the Shuaibah site, DNI was used to estimate the CSP potential. The solar radiation data adopted was for a nearby site, Jeddah city. The average annual DNI on site was calculated to be 2345.4 kWh/m^2/year, while global horizontal radiation was 2264.7 kWh/m^2/year.

The present project employed solar power technology. Two-axis mechanisms orient heliostat mirrors on the azimuth and elevation angles, and facilitate the tracking of the sun. These are positioned to reflect radiation to the top of the tower or central receiver systems. This leads to a temperature rise, heating a HTF or directly generating steam. The resulting steam drives the rotation of a turbine linked to a generator, which in turn supplies electricity to the grid. In order to estimate plant performance, financial feasibility, and energy yield of the proposed CSPP at Shuaibah, the SAM simulation program was used. From the program, monthly energy performance was predicted, where energy yield is between 30.9 GWh to 43.6 GWh.

Subsequently, the performance, cost and emissions of the plant were simulated in RETScreen. The procedure followed was similar to that for the SAM program, and yielded comparable results. However, RETScreen additionally provided an estimate of the reduction in the amount of GHG emissions, as a result of implementing this CSPP project.

The following is a summary of the points that have been identified in this chapter:

- Carrying out an analysis and evaluation of the Heliostat Field of the site, which has been studied with the Weather Data analysis, including the DNI, GHI and

DHI received by the site at different times of the year. These were also examined at different annual and monthly intervals.

- Undertaking the simulation and design of the plant, as well as providing a detailed explanation of the technical and financial obstacles and the reasons for their selection. Also covered are inputs in terms of the technical aspects, including the location and the Heliostat field, where the best possible SM for the plant was approached, with a value of 1.75, in addition to the choice of the type of the HTF. The Tower data was also covered, alongside the receiver and the power block.
- The various thermal storage capacities were analysed to reach the optimum number of hours for the design, which reflected positively on the technical and financial design of the plant, with the optimal design of the plant having a thermal storage capacity of 6 hours.
- The financial parameters and system costs were examined and analysed to be suitable for the period, by covering the whole operational period of analysis (25 years), with a rate of decline of 1% per annum.
- An extensive analysis was conducted on the responses of the plant to different speeds of the TES and the SM, where their optimal results for the plant accounting for 6 and 1.75 hours, respectively.
- The energy produced from the plant on a yearly basis was estimated at 456.467 GWh and the computed LCOE stood at 16.4676 ¢ /kWh. A financial analysis was carried out on the results and cost of each of the main parts of the plant.

After arriving at the results and the dimensions of the plant's design, the discussion section looked at the results from several angles, including the technical and financial feasibility. It also addressed the availability of plant and the socio-economic and environmental impacts of the plant.

CHAPTER 6

RISK ASSESSMENT

6.1. Introduction

Risk Analysis is the systematic study and assessment of uncertainties and risks that can occur during the course of certain activities. These activities may be classified and categorised as business, engineering and policymaking. The aim of risk assessment and analysis is to seek out and identify particular threats, risks, responsibilities, and liabilities faced during the research work and understand how they affect the course of action. The assessment also evaluates and estimates how these risks arise, and the necessary mitigating action. These assessments and analyses are done prior to the initiation of the project to ensure a feasible approach to the research work and accomplishment of set objectives (Li, 2014).

Solar energy is one of the sources of renewable energy that will play an important role in providing a secure energy supply, and contribute significantly in the movement towards a low carbon economy. Though some of the current CSP technologies, such as parabolic trough, have been in operation for over 20 years and are technologically mature, the perception of the risks associated with CSP technology is a constraint to its progress. Many years of research and development have been put into CSP technologies, but there is still a gap between CSP technology advocates and financial institutions in implementation. Being able to analyse the risks associated with the CSP technologies adequately, will aid in bridging the divide between the advocates of CSP technology and financial institutions (Miller and Lumby, 2012).

Conventional power generation plants have matured their technologies and refined their risk methodologies for over many decades with the goal of minimising impact. This chapter will cover the risk assessment of developing and operating both parabolic trough, and solar tower technology plants in KSA.

6.2. Risk Methodology

Risk assessment methodologies for renewable and conventional systems are similar. Some transferable concepts are applied in assessing CSP technologies in KSA. A risk assessment and methodology is necessary to examine all potential risk associated with electricity generation systematically, in both parabolic and tower CSP systems. The assessment and methodology aims to:

- Identify significant hazards/challenges associated with renewable power generation. The identification process will look at both global risk associated with renewable power generation and unique local risk associated with renewable power generation in KSA.
- Evaluate current risk mitigation practices associated with renewable power generation with view of analysing its suitable use in KSA.
- Deciding further control and mitigating measures to embark upon with the goal of reducing risk to an acceptable minimum.

Figure 6.1 shows the risk identification and management circle (Michelez et al., 2011) which comprises:

- **Risk identification**

  Risk identification considers and lists all likely risk that could be encountered during planning, operation and putting it out of use.
- **Risk Evaluation**

  Risk Evaluation determines the risk categories based on the understanding of similar projects done, or the context where the required project will be executed. The context in question includes financial, social, political, technological elements etc.
- **Identification of suitable responses**

  Identification of suitable responses is a key part in the risk methodology. Evaluated risks are followed by appropriate procedures based on the categories they fall under. Risk evaluated as high level, such as spillage of molten salt, will require high priority attention and shutdown of the sections plant until risk falls to a low level.
- **Actions to be implemented**

  After identifying a suitable response, each identified risk is then followed by corporate control procedure on the required actions that are unique to the risk and allocates the responsibility to the appropriate person or group. The management strategy will normally include, specifying objectives, resources, timeline, accountability and reporting template.

- **Report and Review**

  A risk report is compiled at the end of the project and compared with the projected risk mitigation measures. This is reviewed and the lessons learned are incorporated into the risk management processes to enrich future management exercises.

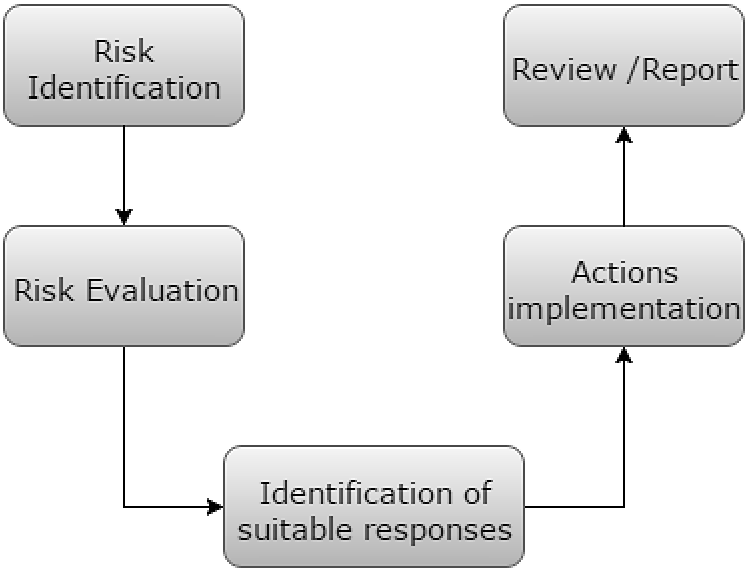


Figure 6.1: Risk Identification and Management Circle

6.3. Risk Analysis

The main risks associated with a CSP project can be categorised into financial, health, environmental and ecological, technology, regulation, political and strategic risks. The SEC is a government agency funded and supported by the KSA government. As a state-owned and -funded company, risk associated with interest rate, creditworthiness, cost of capital, and exchange rate fluctuations will have little impact on the solar power plant investment. The value of debt is zero, because the project implementation is by the SEC, which would inject the full value of the project right from its inception. The company has been offered significant government support, which is estimated at 100 billion interest-free loan, to be reimbursed over a period of 25 years. Renewable energy generation, especially CSP plants, pose less health risk compared to conventional power generation plants. While CSP reduces GHG emissions, other risks are associated with it during development and construction.

Qualitative risk evaluation is used to provide an understanding and prioritisation of risk in building the parabolic trough solar system and solar tower technology. In a quantitative risk assessment, risk probability and risk consequence are the two main estimate characteristics, which could be built into a probabilistic model. Qualitative risk assessment method is used in analysing the risk factors of both plants. A risk assessment matrix is one of the tools used to assign a risk rating when using qualitative risk assessment. A standard risk matrix is used in assessing the probability of events occurring and their corresponding consequences (Michelez et al., 2011, Guttman, 2012). The likelihood and consequences are both graded between 1 to 5 and the product for a particular event becomes the risk factor

$$\text{Risk} = \text{likelihood} * \text{consequences}$$

The outlines of the grading system for both likelihood and consequence are shown in Tables 6.1 and 6.2. Tables 6.3 to 6.8 show the assessment and analysis of technological, financial, regulatory, political, and health risks.

Table 6.1: Possible likelihood of outcomes (BP-Solar, 2001)

Likelihood	**Description**	**grade**
Catastrophic	Critical impacts, and major consequent disruption, heavy costs	5
Major	Intense impacts, manageable but at considerable cost and some disruption	4
Moderate	Serious impacts occurring but with ready capacity to manage	3
Minor	Minor management action required	2
Insignificant	Impacts not requiring any treatment	1

Table 6.2: Possible consequences outcome (BP-Solar, 2001)

Consequence	**Description**	**grade**
Almost certain	Expected to occur in most circumstances	5
Likely	Will probably occur	4
Possible	Might Occur at some time in the future	3
Unlikely	Could occur but doubtful	2
Rare	May occur but only in exceptional circumstances	1

Table 6.3: Technological Risk assessment

Risk identification	Risk evaluation	Response/Implementation
Non-optimal location choice	- Parabolic trough technology - For hybrid plant with existing fossil fuel plant on an uneven land/terrain, the losses may lead to low efficiency and may outweight the energy yield of solar field.	- Detailed and careful site and plant evaluation could mitigate this risk from happening.
Insufficient experience with the CSP technology	- Solar tower technology is a relatively new technology with a number of demonstrations currently underway across the globe. - Parabolic trough technology has been in operation for about 30 years at SEG PP in California. The reflectors have traced the sun accurately all this while (IRENA, 2012).	- Secure warranties and client/customer support from manufacturers where possible throughout the operation lifetime. - Collected data from the plant is used to analyse the field solar efficiency.
Potential technical challenges at the interface between both solar (tower and parabolic trough) technology and fossil fuel component	- Determining the exact contribution in a hybrid plant consisting of solar and fossil fuel is complex. When forecasted output is not met, detailed analysis might be challenging - Plants do degrade over time and operational parameters at the interface in particular change over time.	- For most hybrid plants, interfacing usually occur at the steam generator for standard configuration. When properly analysed, major complications at the interface are unlikely. - Solar generation usually does not contribute to the energy at certain times of the day or under certain weather conditions. During such periods, the combined circle performance can be reaffirmed. - During commission of the hybrid plant, the actual performance of the plant can be determined. Accurate sets of curves for each parameter can be generated, and serve as reference during the operational life of the plant (Bashford and Wilson, 2014).
Total solar plant failure	- Complete failure of the plant can occur while the construction	- Avoid non- compliance by drafting

	of the (solar tower and parabolic trough) plants are still ongoing. This could happen due to the following I. bankruptcy of the main solar supplier II. Reversal of regulation policies, such as change in PPA, incentives III. Damage of collectors by natural disasters, e.g sandstorms, earthquake, flooding, tornado IV. Financial collapse / economic meltdown (Bashford and Wilson, 2014)	comprehensive power purchasing agreements (PPAs) - Gaps in the plant, such as damage by sandstorm, could be made up by using a duct burner. A duct burner provides supplementary firing with the goal of increasing the available heat energy at a gas turbine's exhaust, thereby making it possible to increase the output of the steam generator.

Table 6.4: Financial Risk assessment

Risk identification	Risk evaluation	Response/Implementation
Fossil fuel price increase	- Using a hybrid plant will help reduce exposure to fuel price fluctuation in the market. Though KSA is the 4th largest exporter of fuel, during peak demand, more fuel could be exported while CSP plants are used to cover the gaps.	- Using storage facilities with sufficient number of hours will significantly increase the CF of the solar share and be able to provide adequate cover during peak demand.
Non-guaranteed power purchase	- Solar plants require large investment at the initial phase, and investors generally want a guaranteed RoI. SEC is an arm of the KSA government and the sole provider of electricity in KSA. This means that SEC will likely have a long-term power purchasing agreement to guarantee its viability.	- Risk is comparative small in KSA, as the electricity demand rises annually. Increase in demand will generally lead to increase in prices.
Currency conversion (exchange rate risk)	- Transactions are done in different currency with different international companies delivering different products and services. Due to the time difference between signing the contracts and execution, exchange rate fluctuation could greatly affect the total cost of investment (Bashford and Wilson, 2014).	- To mitigate the effect of exchange rate, SEC could implement financial hedging strategies through financial institutions.
Market monopoly	- Currently only very few companies manufacture heliostat collectors, receiver, reflectors etc. Manufacturing companies	- Incentives could be given to attract businesses to make the market competitive.

	could drive the prices up due to lack of competition.	- Long-term contracts with stable prices before project deployment will avoid suppliers driving up prices.

Table 6.5: Regulatory Risk assessment

Risk identification	Risk evaluation	Response/Implementation
Poor incentives to maximise the full operating potential of the solar field.	- From most solar plant operators' viewpoint, operation of the plant will only be viable if the selling price of the electricity is more than the operation and maintenance cost.	- Make sure incentives / rewards and bonuses are given to SEC when their required performance targets are reached. - Ensure appropriate penalties are put in place to ensure the operator delivers minimum energy generation targets.
Lack of confidence in developers due to unforeseeable long-term assurance growth	- Pushing and implementing new technology is a large hurdle that companies do not normally embark upon except where the associated risks are well compensated and the market has long term potential that is attractive. - For SEC, the KSA government have guaranteed compensating measures with grants up to 10 billion dollars for investment in the energy sector to increase energy generation using renewable sources.	- More investment and grants in the research and development of CSP technologies to make them more cost effective, reliable and attractive to the market. - Consultative discussion with a long-term view to mature CSP technologies.
Low competitive market structures	- Opening the electricity market could have impacts that are either negative or positive.	- Guarantee attractive returns and stable tariff - KSA has vast arid desert lands, and could be used to harness the energy potential for export to other countries.

Table 6.6: Political risk

Risk identification	Risk evaluation	Response/Implementation
Stability	- Quite a number Middle East countries have gone through or are going through political turmoil, which could make investments suffer losses. Though KSA has been peaceful, concern could be raised due to the possibility of such turmoil affecting the country.	- The investment could be covered with a comprehensive insurance policy, which could protect the investment fully. - The government could make strong legislation to protect investment from negative impact if necessary.
Corruption	- Corrupt officials could increase the total investment cost with the aim of siphoning a percentage.	- Strong legislation to deter corrupt practices from happening.
Policy risk	- Frequent change of policy by government could affect the operation and maintenance cost.	- The KSA government has stable policies on renewable energy, which will not change any time soon.
Licensing, commissioning and approvals risks	- Delay and difficulties in obtaining clearances and certifications.	- Implement simplified and transparent processes to gain trust of investors and partners at all stages.

Table 6.7: Environmental and ecological risk

Risk identification	Risk evaluation	Response/Implementation
Natural hazards	- Natural hazards such as sandstorms, erosion, flood, earthquake etc. could greatly damage the reflectors.	- Sites less susceptible to natural disaster should be preferred. - Mechanism to mitigate or reduce the hazards should be in place.
Solar	In California, the tower technology plant has resulted in significant number of birds killed due the reflection and heat from the reflectors to the receiver on the tower (Kraemer, 2015).	- Preventive method must be put in place to minimise the death toll of birds within the plant location.

Table 6.8: Health Risk

Risk identification	Risk evaluation	Response/Implementation

Health risk assessment	- A health risk assessment should be done to evaluate the potential of health related risk (cancer and non-cancer risk) that could affect employees and the public.	- A health risk assessment of CSP plants.
Accident risk	- Risk or accident during both construction and operation of the plant.	- Safety regulations should be enhanced strictly before executing the plants and should be followed by workers.
Aviation safety	- Impact of reflectivity and temporary flash occurrences from the reflectors - Height and location of structures -Clear space within Compatibility Zone D	- Solar field location should be located away from aviation paths and zones.

6.4. Risk Evaluation and Responses

Table 6.9 shows the qualitative risk evaluation matrix, highlighting the risk categories based on their values with the critical risk as the highest and very low risk at the lowest. Each category has its corresponding and appropriate action to be taken to mitigate the risk from occurring or minimised the risk when it occurs. Table 6.10 and 6.11 show the risk grade of parabolic trough and solar tower technology respectively. Each grade is determine by the associated likelihood and consequence. Both parabolic trough and solar tower technology show very similar risk grade because they are both operated in the same country with similar conditions and developed by SEC.

Table 6.9: Qualitative risk grade evaluation matrix

Consequences / **Likelihood**	1	2	3	4	5
1	1	2	3	4	5
2	2	4	6	8	10
3	3	6	9	12	15
4	4	8	12	16	20
5	5	10	15	20	25

20-25	Critical	Such risk cannot be tolerated and mitigating it is compulsory
14-19	High	The risk is high and necessary solutions to reduce it must be developed
8-13	Moderate	This could be reduce if there are viable means of reducing it
3-7	Low	This category of risk is reasonably practicable and not a potential threat
1-2	Very low	This category of risk is broadly acceptable and does not require any urgent

Table 6.10: Parabolic trough solar plant

	Item	Likelihood	consequence	Risk grade	Comment
1	Technological Risk: Non-optimal location choice	1	4	4	Low
2	Technology risk: Insufficient experience with the CSP technology	2	4	8	Moderate
3	Technology risk : the interface between both solar	3	3	9	Moderate
4	Technology risk : Total solar plant failure	2	5	5	Low
5	Technology risk : Insufficient experience with CSP technology	1	4	4	Low
6	Financial risk: Fossil fuel price increase	4	2	8	Moderate
7	Financial risk: Non-guaranteed power purchase	1	3	3	low
8	Financial risk: Currency conversion (exchange rate risk)	2	3	6	Low
9	Financial risk: Market monopoly	5	2	5	Moderate
10	Financial risk: Fossil fuel price increase	4	2	8	moderate
11	Regulatory risk: Poor incentives to maximise the full operating potential of the solar field.	2	3	6	low
12	Regulatory risk: Lack of confidence in developers due unforeseeable long term assurance growth	1	3	3	Low
13	Political risk: Instability	1	4	4	Low
14	Political risk: Corruption	1	3	3	Low
15	Health risk assessment	2	4	8	Moderate
16	Health risk: Accident risk	3	5	15	High

Table 6.11: Solar Tower technology

	Item	Likelihood	consequence	Risk grade	Comment
1	Technological Risk: Non-optimal location choice	1	4	4	Low
2	Technology risk: Insufficient experience with the CSP technology	2	5	10	Moderate
3	Technology risk : the interface between both solar	3	3	9	Moderate
4	Technology risk : Total solar plant failure	2	5	5	Low
5	Technology risk : Insufficient	1	4	4	Low

	Item	Likelihood	consequence	Risk grade	Comment
	experience with the CSP technology				
6	Financial risk: Fossil fuel price increase	4	2	8	Moderate
7	Financial risk: Non-guaranteed power purchase	1	3	3	low
8	Financial risk: Currency conversion (exchange rate risk)	2	3	6	Low
9	Financial risk: Market monopoly	5	2	5	Moderate
10	Financial risk: Fossil fuel price increase	4	2	8	Moderate
11	Regulatory risk: Poor incentives to maximise the full operating potential of the solar field.	3	2	6	Moderate
12	Regulatory risk: Lack of confidence in developers, due to unforeseeable long-term assurance growth	1	3	3	Low
13	Political risk: Instability	1	4	4	Low
14	Political risk: Corruption	1	3	3	Low
15	Health risk assessment	2	4	8	Moderate
16	Health risk: Accident risk	3	5	15	High

Figure 2 shows the most problematic factors for doing business in KSA from the perspective of the World Economic Forum. The figure shows KSA as stable country with low corruption (4.2 %) and low policy instability (0.9). These factors will guarantee that the SEC secures a RoI over the 25 years life span of the parabolic trough plant and the solar tower plant. Inflation (2.4 %) is relatively low, which will help the projected total cost of building and operating the plants during the lifespan to be accurate. Restrictive labour regulation (25.6 %) might pose a problem, if more foreign skilled workers will be required to fill a shortage in skilled labour. This could prevent future plant expansion due to shortage of labour force. Mitigating such a risk is to offer comprehensive local content training that will bridge the necessary gap in the future.

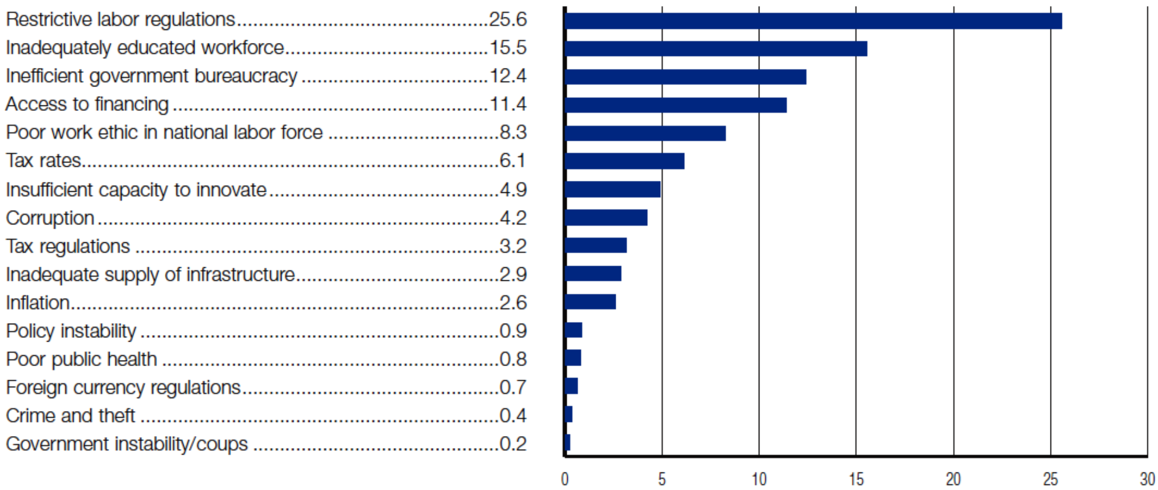


Figure 6.2: Problem factors in doing business in KSA from the 2013 World Economic Forum (Schwab, 2013)

Giving the right response to identified risk is the most vital stage in risk management. Each risk could be allocated to appropriate persons to administer the right tool in controlling and managing the risk. The key for both parabolic trough and tower solar plants to have market competitiveness and reduction of technology risk is having incentives that will make CSP energy generation competitive against the cost of conventional power generation.

6.5. Summary

In the process of studying and implementing solar power plants, there are some risks associated with such project implementation. In both case studies used for the purpose of this research, and as mentioned in this chapter, the risk analysis and assessment has been carried out using a systematic methodology focused on the identification and evaluation of risks and then presenting the most important steps to deal with them and the course of action that should be followed to avoid any potential or likely risks or minimising their negative impacts if they ever occur.

An analysis of the risks was carried out by covering of the main aspects that could arise alongside other aspects related to the project, which generally include technological, financial, political, regulatory, environmental and health risks.

CHAPTER 7

CONCLUSIONS, RECOMMENDATIONS AND FURTHER WORK

In this thesis, the potential solar energy in KSA has been reviewed thoroughly and established its economic and environmental feasibility through two real case study scenarios of CSP generation. As widely acknowledged in current literature, this work is in support for the proposition for significance increase in exploiting the solar resource available in KSA. This work demonstrated the competitiveness of CSP in the two case scenarios in which design, analysis and feasibility for two concentrated solar energy plants using solar troughs and solar tower technology were conducted. The thesis particularly investigated the technical parameters (harvestable solar energy, power output, plant efficiency, etc.) and financial viability (levelised cost of power, cost of installation, return on investment, etc.) of the schemes.

In this chapter, a briefly review of the results of the work has been performed and formulation of recommendations for future work through which the process of integration in the research field can be completed.

7.1. Outcomes of This Work

In this research, several aspects of the energy industry have been illustrated in terms of consumption and energy sources. In *Chapter One*, the research outlined the sources of energy production from renewable energy worldwide, and in KSA in particular. Moreover, it focused on the potential of solar energy and the advanced stages reached in today's investment and provision of electricity. The introductory literature also covered solar technology with more focus on the solar thermal technologies and the impact of these technologies on the investment environment and the feasibility of its application on the one hand, and on preserving the environment against harmful emissions on the other.

As most scientific and applied research efforts in KSA have generally been focused on solar energy applications from non-thermal technologies (e.g., PV), this research has provided some extensive insights into the analysis, design, and feasibility of using two of the most important solar thermal techniques in order to produce energy in a sustainable way in KSA.

As such, the research undertook an exhaustive study of parabolic trough and solar tower technology application in terms of design and simulation, as well as a financial analysis and feasibility study for a power plant with a capacity of 100 MW in the city of Wadi Aldawasir and Jeddah (the Shuaibah Power plant) in central and on western cost of KSA respectively.

SAM and RETScreen software were selected and used in this work, as they are widely adopted and considered to yield reliable results in the field of design, analysis and evaluation of renewable energy, in particular solar energy for SAM. The results for both sites from these two software in terms of the technical and financial results were also presented. RETScreen contributed to the presentation of the relevant environmental consequences of the two plants. Data, inputs and the technical and financial factors of both designs, as well as the methods of research and aspects related to the design, selection and sizing of the plants solar fields were explored after undertaking data collection, interviews, and field visits following a scientific methodology, as outlined in *Chapter Three* to achieve the results of the two case studies.

7.2. Conclusion

In the case of Wadi Aldawasir, which was addressed in *Chapter Four* in this research, a solar thermal power plant was designed with a capacity of 100 MW, using the parabolic troughs solar field technology. The site of the proposed CSPP receives approximately 2754 kWh/m^2/year of the DNI energy. Using SAM software, a solar field and energy receiver manufactured by Siemens , SunField 6 and UAVC 2010 respectively were specified in additional to the selection of a high temperature heat transfer fluid (HTF) namely Hitec Solar Salt. The simulation and optimisation found that the optimal design and operating parameters of the plant would be achieved without thermal storage for a solar multiple (SM) and number of array subsections of 1.25 and 2, respectively. This gives a solar collection total aperture area of 585,330 m^2 and annual power generation from the power plant of 252.362 GWh. The overall conversion efficiency of the solar collection system is 84% and the CF of the power plant is 28.8%. The cost of the investment was evaluated from required initial capital outlay of $ 317,354,304 and useable land area of 2.13 km^2 which results in LCOE of 15.63 ¢ / kWh, PPA of 18.7579 ¢ / kWh and IRR equivalent to 13 percent over a period of 25 years. This analysis and plant specifications was verified and validated using the RETScreen program. It was found that the two software produced similar optimal technical and financial estimates. The software were also complement in for example the environmental impact was better quantified using RETScreen, which shows that the plant is capable of saving of around 165,034 tCO_2 annually compared to a fossil fuel plant of similar generation capacity. Therefore, the proposed parabolic trough solar power plant is a sound investment from environmental point of view as well as a competitive and viable compared to other similar plants around the world. It is also seen as almost competitive in terms of global prices to power plants using fossil fuels. As for domestic prices in KSA, the plant is quite promising in terms of feasibility, given the tremendous support that energy companies receive from SEC and reduced prices for the fossil fuels used in the power plants for power generation, a government subsidy in providing low oil prices.

In *Chapter Five* a similar case study was undertaken in which a CSP using solar tower technology was designed with a capacity of 100 MW. The CSP plant was located on the western coast of the country, with high solar DNI energy (2345.4 kWh/m^2/year) being received. The SAM analysis demonstrated that the best specifications were achieved for TES=6, SM of 1.75 and a heliostat total reflective area of 1,137,529 m^2. It was also estimated that the plant will generate about 456.467 GWh per year at a CF of 52.1%. The cost of electricity generation from the plant was evaluated using LCOE to be 16.4676 ¢ / kWh, which was slightly higher than that of the parabolic trough counterpart. Similarly, the PPA was equivalent to 20.6121 ¢ / kWh to achieve a rate of IRR equivalent to 13% over a period of 25 years. The initial cost of the plant was $613,542,336, which would be spread over an area of 6.03 km^2. the RETScreen analysis also predicts that up 296,119.7 of CO_2 can be saved compared to an oil-fired power plant of equal capacity. As in the case of the parabolic trough power plan in Wadi Aldawasir, the Shuaibah solar tower plant is estimated to be cost effective and the unit power generated be competitive with modern fossil fuelled power plants if government subsidies of oil fuelled station is taken away.

The price of electrical energy produced from the two CSP plants studied in this thesis are considered competitive in comparison to their counterparts around the world. According to the IRENA Report (2015), which published the latest developments of energy production from renewable sources, the prices of generation of electrical energy from renewable sources have decreased markedly over the last five years (IRENA, 2015). When comparing the LCOE from published in IRENA report for CSP plants built around the world to those proposed in Wadi Aldawasir and Shuaibah CSP plants, KSA, it is no surprise that the latter power plants are the most competitive as shown in Figure 7.1.

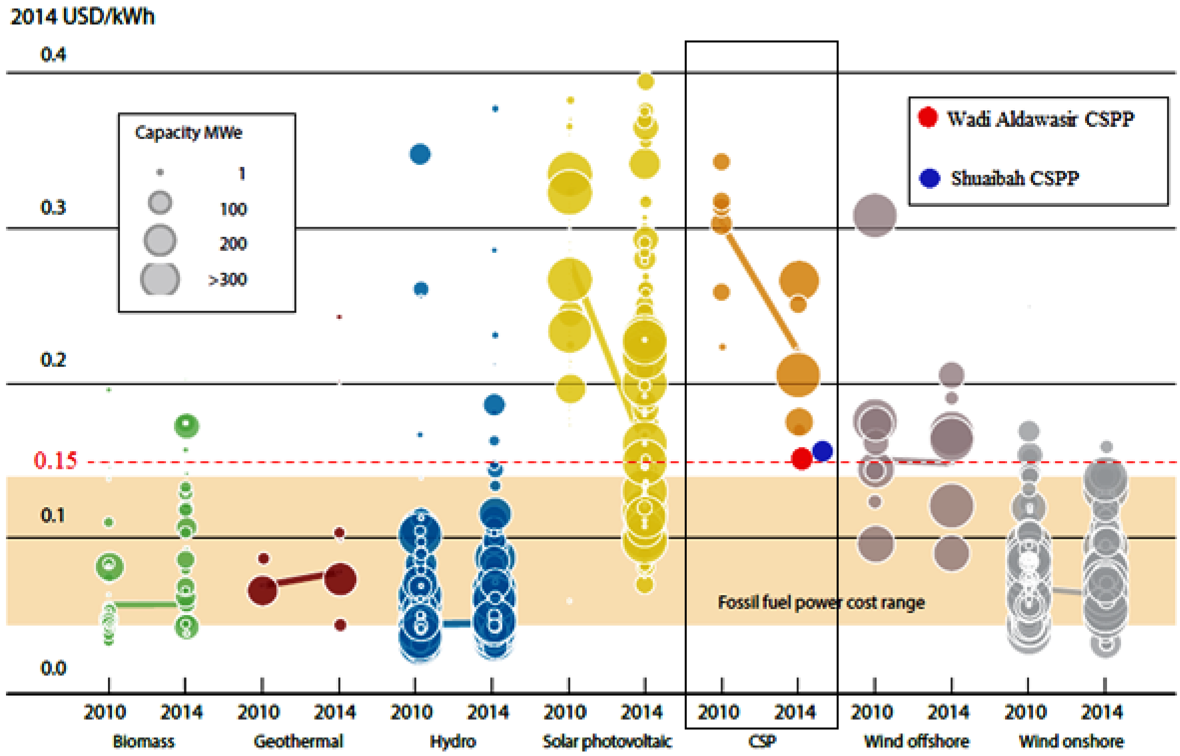


Figure 7.1: The levelised cost of electricity from utility-scale renewable technologies, 2010 and 2014 (IRENA, 2015)

The technical and economic risks associated with the construction of proposed CSP power plants was assessed and a simplified analysis presented in *Chapter Six*. This analysis gives the course of action that need to be followed for every perceived risk. Overall, the study shows that the risks involved in exploiting solar energy using CSP in KSA is manageable and the degree of occurrence is low, enhancing further the acceptability of the adoption of the technology in the medium to long term.

7.3. Recommendations

The government agency (KACARE) responsible for renewable energy development in the KSA should play a prominent role in support of solar energy by providing same level playing field for solar energy to compete with subsidised fossil fuelled power stations. Initiating meaningful energy reforms for the exploitation of solar energy will trigger the transition process to an economy that relies less on oil and government subsidies. In addition, this will afford the government to reduce the countries growing energy consumption of oil reserve and make more available for export, provide a positive impact on the environment and the wellbeing of the citizens.

Finally, this discussion can lead to a number of recommendations that should be a short term energy priority for the government. These recommendations are summarised as follows:

1. It is important to establish a unified organisation with clear identity to make available reliable and accessible data, references and studies, as well as designs and any other relevant data on the field of solar energy in the Kingdom of Saudi Arabia. Preferably, this should be KACARE, especially as this aspect is still in its early days.
2. It is crucial to start preparing regulatory policies and guidelines for the renewable energy sector, in particular solar energy and its various technologies in terms of production, investment and consumption all the way to the end user. This will encourage the private and public sectors to invest in the "green energy" industry in a clearly defined and effective environment.
3. Significant effort should be exercised by the relevant government agencies to encourage and support the energy industry using friendly environmentally renewable sources, which will reflect positively on keeping exhaustible oil reserves for future generations or using them for the benefit of the Saudi economy. In addition, these sectors should contribute in spreading awareness among citizens of the benefits of solar energy and its applications with large and small capacities as those used domestically. In so doing, people will be prepared to accept the financial implications after putting in place long-term plans and strategies for its implementation.
4. Alongside large CSP project, small scale project on application of solar energy should be encouraged and incentivised. These could include electricity generation, heating and cooling for homes and the encouragement of individuals and the private sector to install these technologies by means of giving out incentives as in other countries. Plans should also include working on a proactive studies to gauge how receptive those social segments to such changes.
5. It is essential to move systematically and seriously in the application of solar technology and involving all stakeholders such as universities, business and government agencies. this work could form a basis for further investigations into the viability of CSP with the aim to realise pilot plants for further feasibility analysis.
6. Another recommendation pertains to the transfer of technology and identification of interested research centres in this area in KSA, as well as manufacturing these technologies locally.

7.4. Further Work

In terms of the future effort that will complement this research, it is briefly summarised in the following:

i. A comprehensive study of the Wadi Aldawasir parabolic trough plant incorporating high level of thermal storage, (e.g., providing up to six hours of storage) and a cost estimate for future capacity expansion of the plant as demand increases.
ii. A complementary study to integrate the current fossil fuel power plant of Wadi Aldawasir and Shuaibah with the proposed solar energy harvesting field to generate steam and run current turbines during the non-peak seasons other than the summer, as known in the ICC, as well as the study of the financial and environmental impacts and the extent of keeping fossil fuels for both designs.
iii. Expanding research effort into the challenges facing the creation of solar power plants in KSA, along with the challenges that reduce the efficiency of operating solar power plants, including dust, high temperature and humidity, and their impact on some solar technologies and identifying solutions for these challenges.
iv. There should be contributory efforts to the study and development of regulatory policies for the energy production sector through the solar technologies in KSA.

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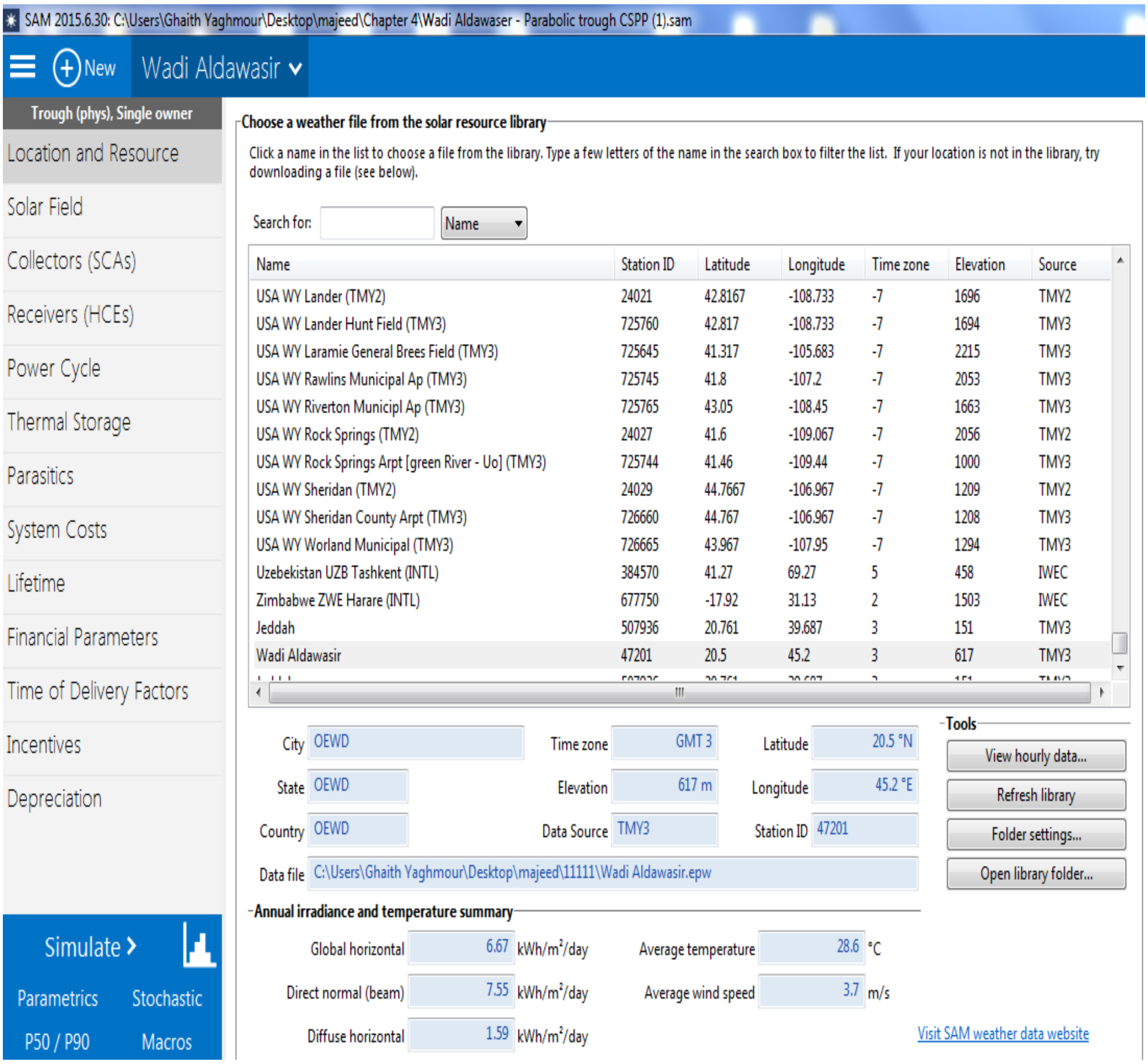
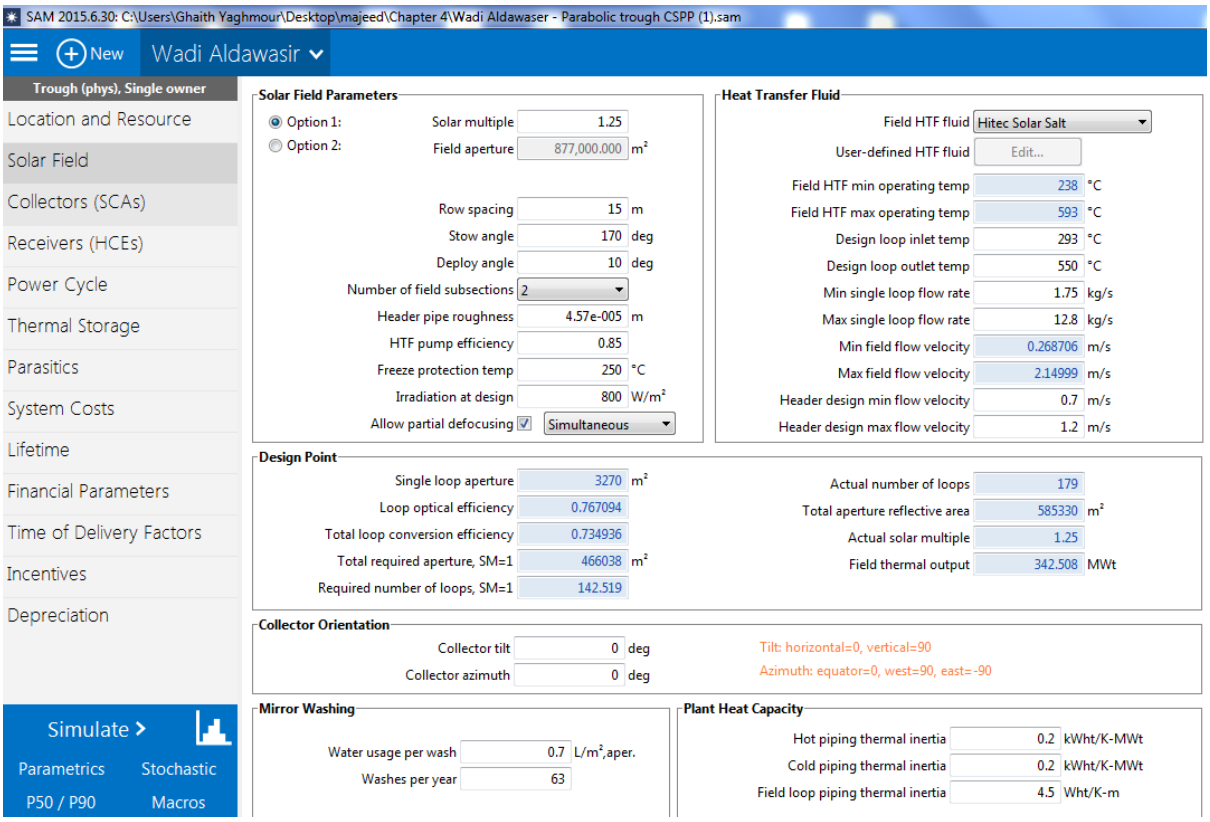
APPENDIX A

A.1 SAM Simulation pages of Wadi Aldawasir CSPP

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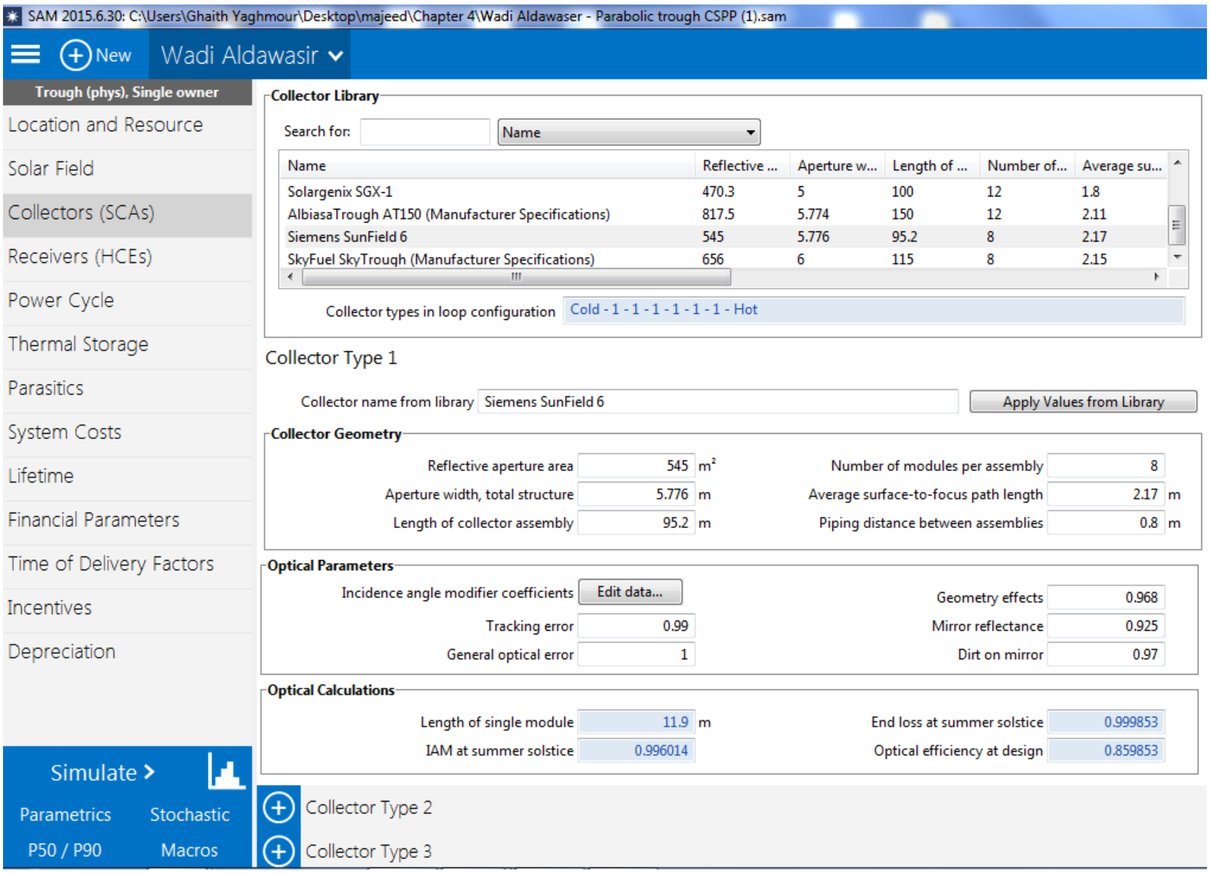
New
Wadi Aldawasir
Trough (phys), Single owner
Location and Resource
Solar Field
Collectors (SCAs)
Receivers (HCEs)
Power Cycle
Thermal Storage
Parasitics
System Costs
Lifetime
Financial Parameters
Time of Delivery Factors
Incentives
Depreciation
Simulate >
Parametrics
Stochastic
P50 / P90
Macros
Solar Field Parameters
Option 1: Solar multiple 1.25
Option 2: Field aperture 877,000.000 m²
Row spacing 15 m
Stow angle 170 deg
Deploy angle 10 deg
Number of field subsections 2
Header pipe roughness 4.57e-005 m
HTF pump efficiency 0.85
Freeze protection temp 250 °C
Irradiation at design 800 W/m²
Allow partial defocusing Simultaneous
Heat Transfer Fluid
Field HTF fluid Hitec Solar Salt
User-defined HTF fluid Edit...
Field HTF min operating temp 238 °C
Field HTF max operating temp 593 °C
Design loop inlet temp 293 °C
Design loop outlet temp 550 °C
Min single loop flow rate 1.75 kg/s
Max single loop flow rate 12.8 kg/s
Min field flow velocity 0.268706 m/s
Max field flow velocity 2.14999 m/s
Header design min flow velocity 0.7 m/s
Header design max flow velocity 1.2 m/s
Design Point
Single loop aperture 3270 m²
Loop optical efficiency 0.767094
Total loop conversion efficiency 0.734936
Total required aperture, SM=1 466038 m²
Required number of loops, SM=1 142.519
Actual number of loops 179
Total aperture reflective area 585330 m²
Actual solar multiple 1.25
Field thermal output 342.508 MWt
Collector Orientation
Collector tilt 0 deg
Collector azimuth 0 deg
Tilt: horizontal=0, vertical=90
Azimuth: equator=0, west=90, east=-90
Mirror Washing
Water usage per wash 0.7 L/m²,aper.
Washes per year 63
Plant Heat Capacity
Hot piping thermal inertia 0.2 kWht/K-MWt
Cold piping thermal inertia 0.2 kWht/K-MWt
Field loop piping thermal inertia 4.5 Wht/K-m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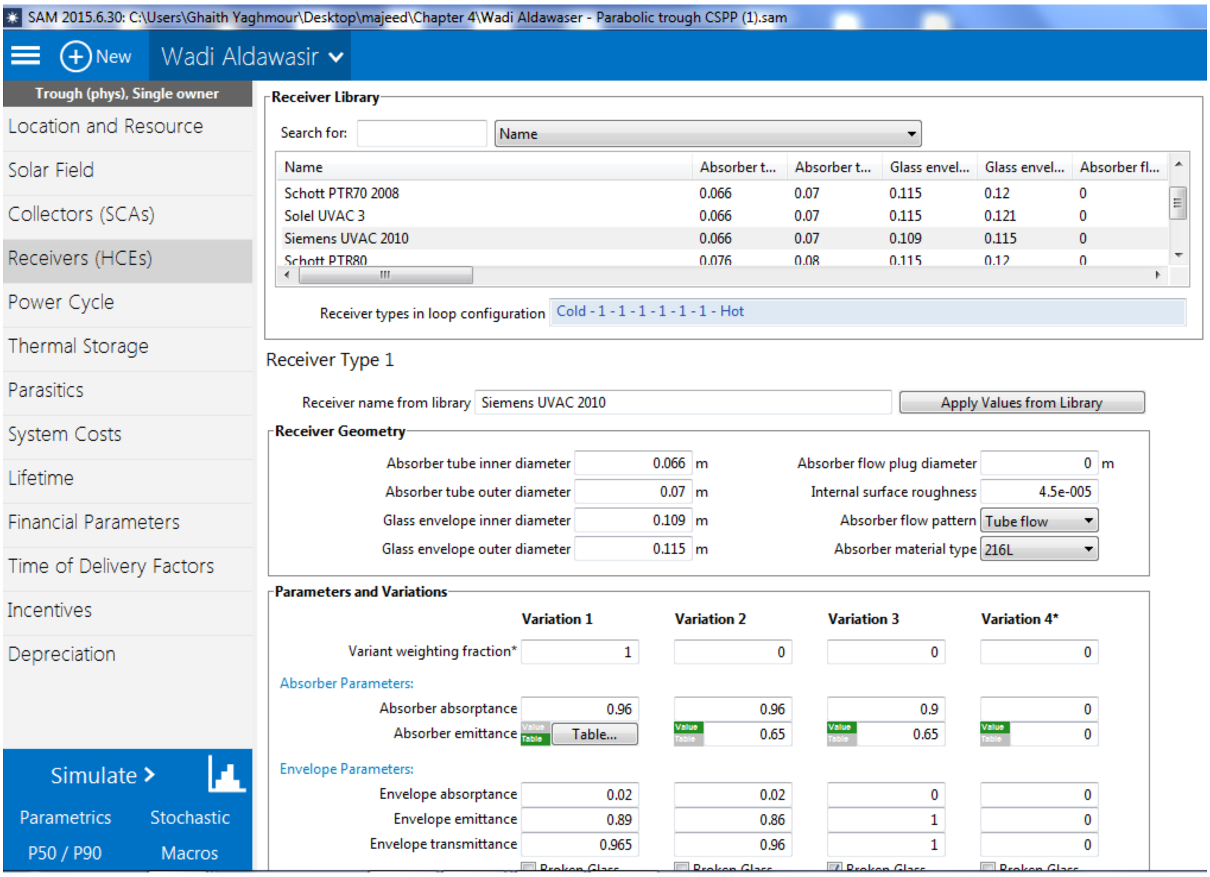
New
Wadi Aldawasir
Trough (phys), Single owner
Location and Resource
Solar Field
Collectors (SCAs)
Receivers (HCEs)
Power Cycle
Thermal Storage
Parasitics
System Costs
Lifetime
Financial Parameters
Time of Delivery Factors
Incentives
Depreciation
Simulate >
Parametrics
Stochastic
P50 / P90
Macros
Collector Library
Search for: Name
Name Reflective ... Aperture w... Length of ... Number of... Average su...
Solargenix SGX-1 470.3 5 100 12 1.8
AlbiasaTrough AT150 (Manufacturer Specifications) 817.5 5.774 150 12 2.11
Siemens SunField 6 545 5.776 95.2 8 2.17
SkyFuel SkyTrough (Manufacturer Specifications) 656 6 115 8 2.15
Collector types in loop configuration Cold - 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1 - Hot
Collector Type 1
Collector name from library Siemens SunField 6
Apply Values from Library
Collector Geometry
Reflective aperture area 545 m²
Aperture width, total structure 5.776 m
Length of collector assembly 95.2 m
Number of modules per assembly 8
Average surface-to-focus path length 2.17 m
Piping distance between assemblies 0.8 m
Optical Parameters
Incidence angle modifier coefficients Edit data...
Tracking error 0.99
General optical error 1
Geometry effects 0.968
Mirror reflectance 0.925
Dirt on mirror 0.97
Optical Calculations
Length of single module 11.9 m
IAM at summer solstice 0.996014
End loss at summer solstice 0.999853
Optical efficiency at design 0.859853
Collector Type 2
Collector Type 3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New
Wadi Aldawasir
Trough (phys), Single owner
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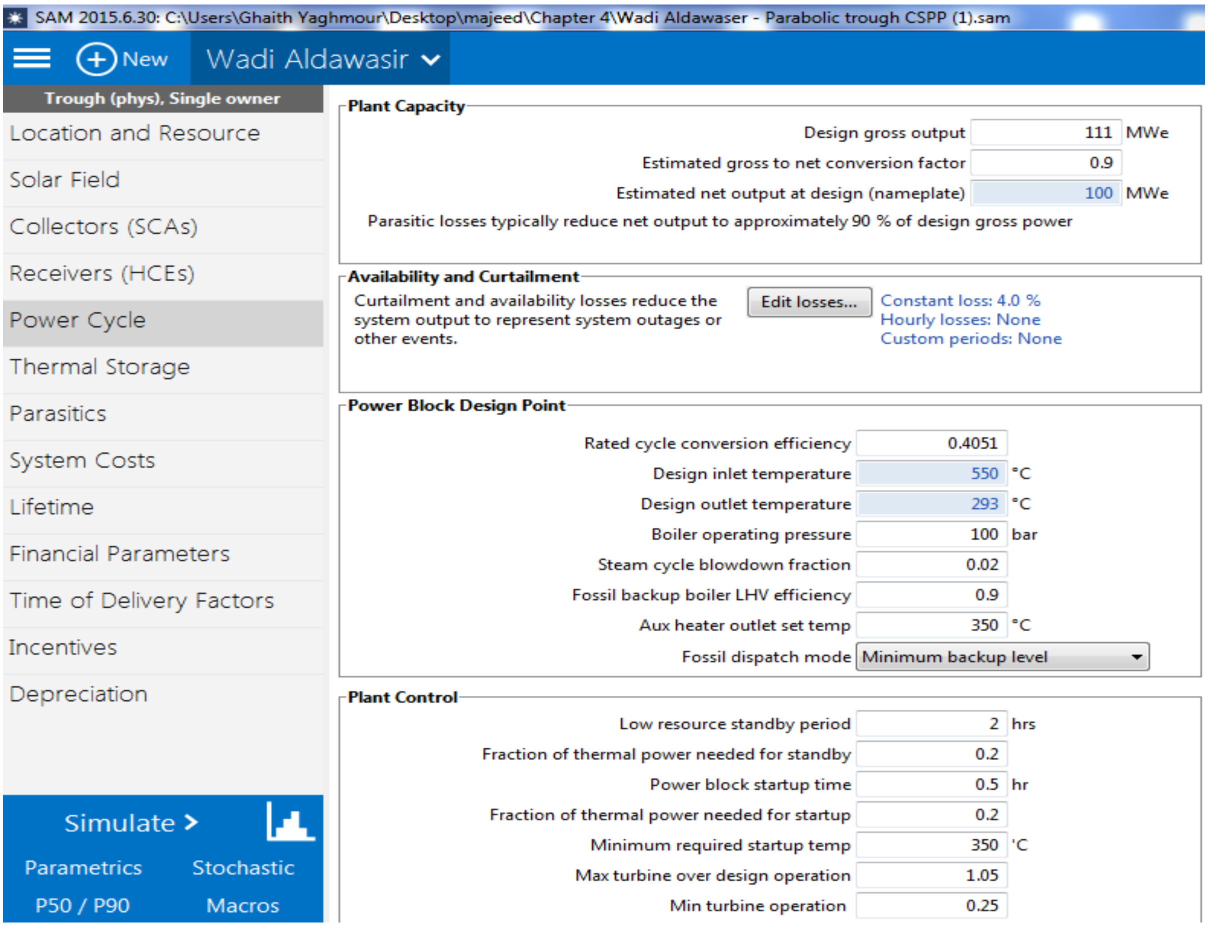
Collectors (SCAs)
Receivers (HCEs)
Power Cycle
Thermal Storage
Parasitics
System Costs
Lifetime
Financial Parameters
Time of Delivery Factors
Incentives
Depreciation
Simulate >
Parametrics
Stochastic
P50 / P90
Macros
Receiver Library
Search for:
Name
Name
Absorber t...
Absorber t...
Glass envel...
Glass envel...
Absorber fl...
Schott PTR70 2008 0.066 0.07 0.115 0.12 0
Solel UVAC 3 0.066 0.07 0.115 0.121 0
Siemens UVAC 2010 0.066 0.07 0.109 0.115 0
Receiver types in loop configuration
Cold - 1 - 1 - 1 - 1 - 1 - 1 - Hot
Receiver Type 1
Receiver name from library
Siemens UVAC 2010
Apply Values from Library
Receiver Geometry
Absorber tube inner diameter 0.066 m
Absorber tube outer diameter 0.07 m
Glass envelope inner diameter 0.109 m
Glass envelope outer diameter 0.115 m
Absorber flow plug diameter 0 m
Internal surface roughness 4.5e-005
Absorber flow pattern Tube flow
Absorber material type 216L
Parameters and Variations
Variation 1
Variation 2
Variation 3
Variation 4*
Variant weighting fraction* 1 0 0 0
Absorber Parameters:
Absorber absorptance 0.96 0.96 0.9 0
Absorber emittance Table... 0.65 0.65 0
Envelope Parameters:
Envelope absorptance 0.02 0.02 0 0
Envelope emittance 0.89 0.86 1 0
Envelope transmittance 0.965 0.96 1 0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New
Wadi Aldawasir
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Lifetime
Financial Parameters
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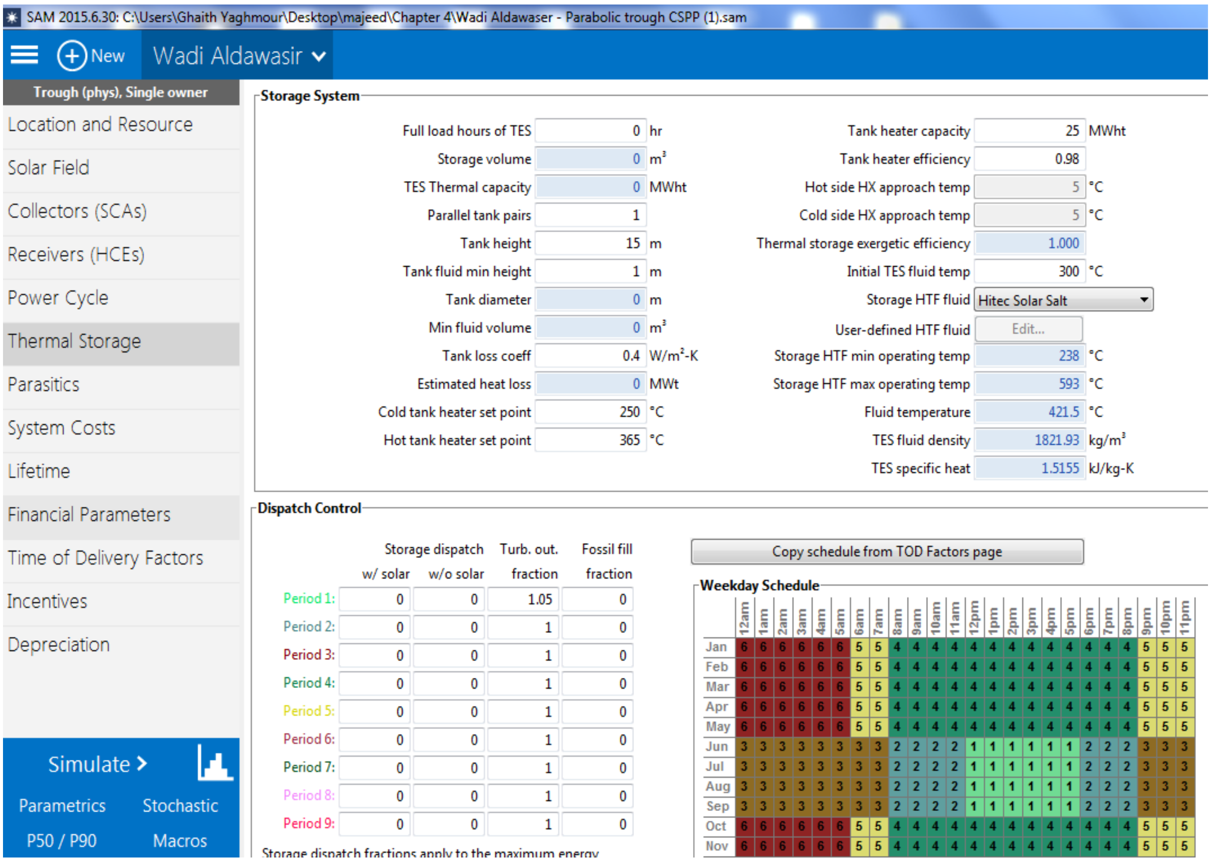
Incentives
Depreciation
Simulate >
Parametrics
Stochastic
P50 / P90
Macros
Plant Capacity
Design gross output 111 MWe
Estimated gross to net conversion factor 0.9
Estimated net output at design (nameplate) 100 MWe
Parasitic losses typically reduce net output to approximately 90 % of design gross power
Availability and Curtailment
Curtailment and availability losses reduce the system output to represent system outages or other events.
Edit losses...
Constant loss: 4.0 %
Hourly losses: None
Custom periods: None
Power Block Design Point
Rated cycle conversion efficiency 0.4051
Design inlet temperature 550 °C
Design outlet temperature 293 °C
Boiler operating pressure 100 bar
Steam cycle blowdown fraction 0.02
Fossil backup boiler LHV efficiency 0.9
Aux heater outlet set temp 350 °C
Fossil dispatch mode Minimum backup level
Plant Control
Low resource standby period 2 hrs
Fraction of thermal power needed for standby 0.2
Power block startup time 0.5 hr
Fraction of thermal power needed for startup 0.2
Minimum required startup temp 350 'C
Max turbine over design operation 1.05
Min turbine operation 0.25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New
Wadi Aldawasir
Trough (phys), Single owner
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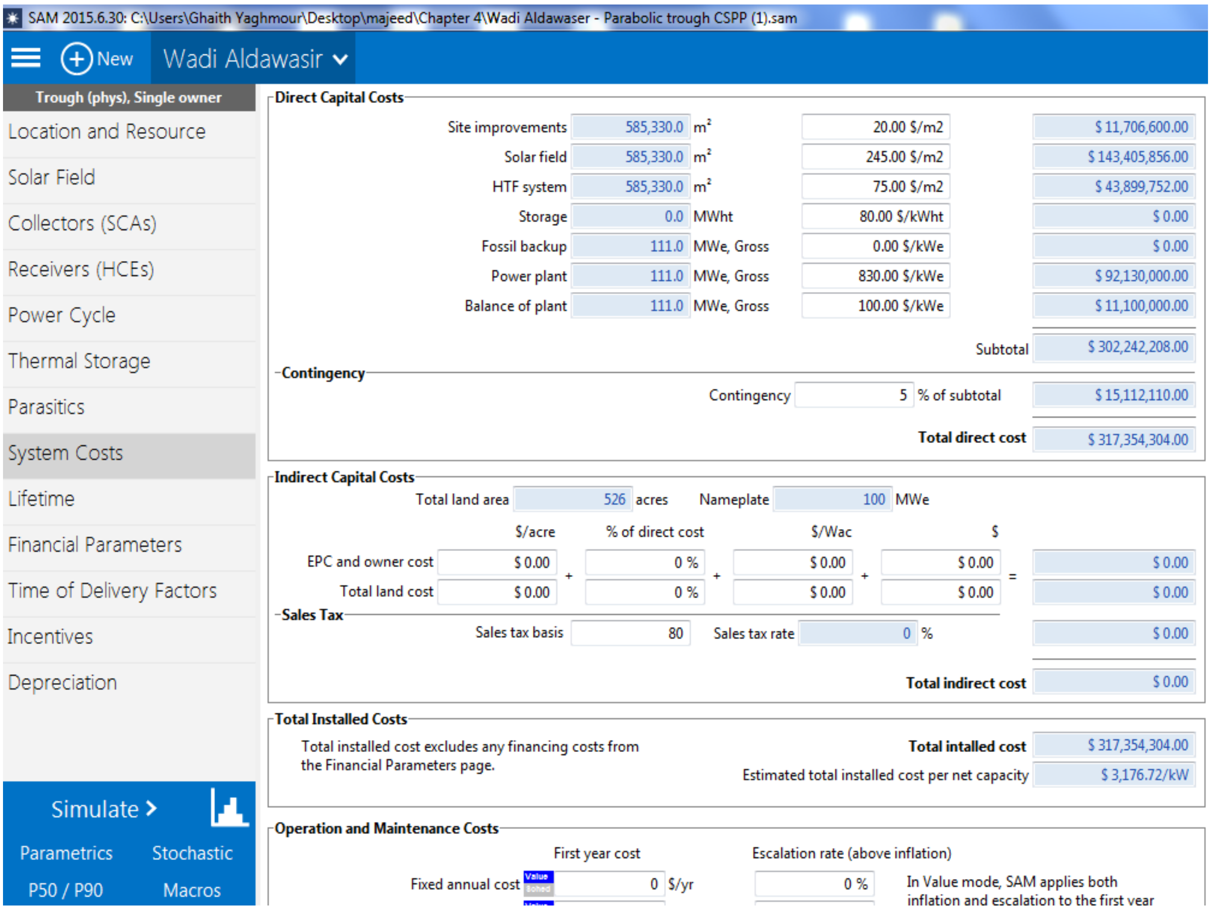
Parasitics
System Costs
Lifetime
Financial Parameters
Time of Delivery Factors
Incentives
Depreciation
Simulate >
Parametrics
Stochastic
P50 / P90
Macros
Storage System
Full load hours of TES 0 hr
Storage volume 0 m³
TES Thermal capacity 0 MWht
Parallel tank pairs 1
Tank height 15 m
Tank fluid min height 1 m
Tank diameter 0 m
Min fluid volume 0 m³
Tank loss coeff 0.4 W/m²-K
Estimated heat loss 0 MWt
Cold tank heater set point 250 °C
Hot tank heater set point 365 °C
Tank heater capacity 25 MWht
Tank heater efficiency 0.98
Hot side HX approach temp 5 °C
Cold side HX approach temp 5 °C
Thermal storage exergetic efficiency 1.000
Initial TES fluid temp 300 °C
Storage HTF fluid Hitec Solar Salt
User-defined HTF fluid Edit...
Storage HTF min operating temp 238 °C
Storage HTF max operating temp 593 °C
Fluid temperature 421.5 °C
TES fluid density 1821.93 kg/m³
TES specific heat 1.5155 kJ/kg-K
Dispatch Control
Storage dispatch w/ solar
w/o solar
Turb. out. fraction
Fossil fill fraction
Period 1: 0 0 1.05 0
Period 2: 0 0 1 0
Period 3: 0 0 1 0
Period 4: 0 0 1 0
Period 5: 0 0 1 0
Period 6: 0 0 1 0
Period 7: 0 0 1 0
Period 8: 0 0 1 0
Period 9: 0 0 1 0
Copy schedule from TOD Factors page
Weekday Schedule
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov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New
Wadi Aldawasir
Trough (phys), Single owner
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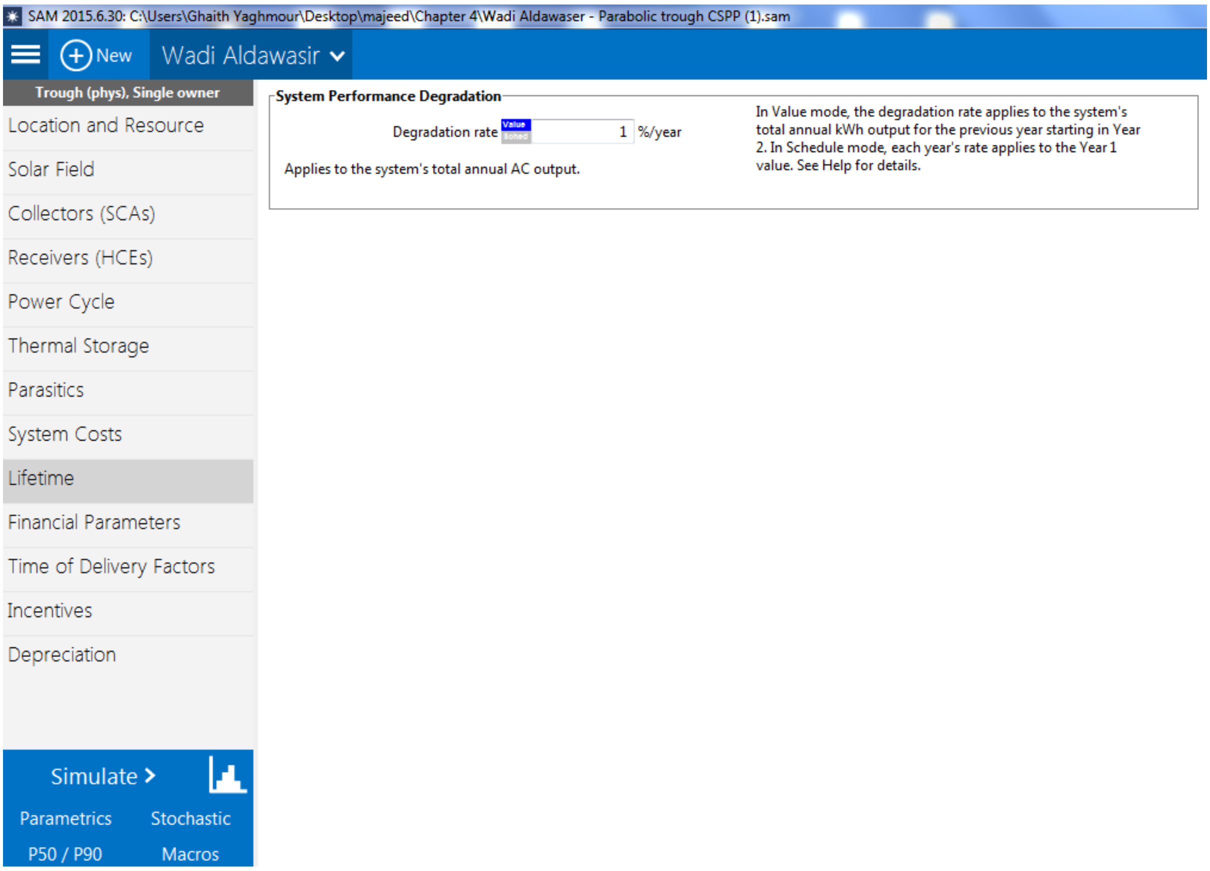
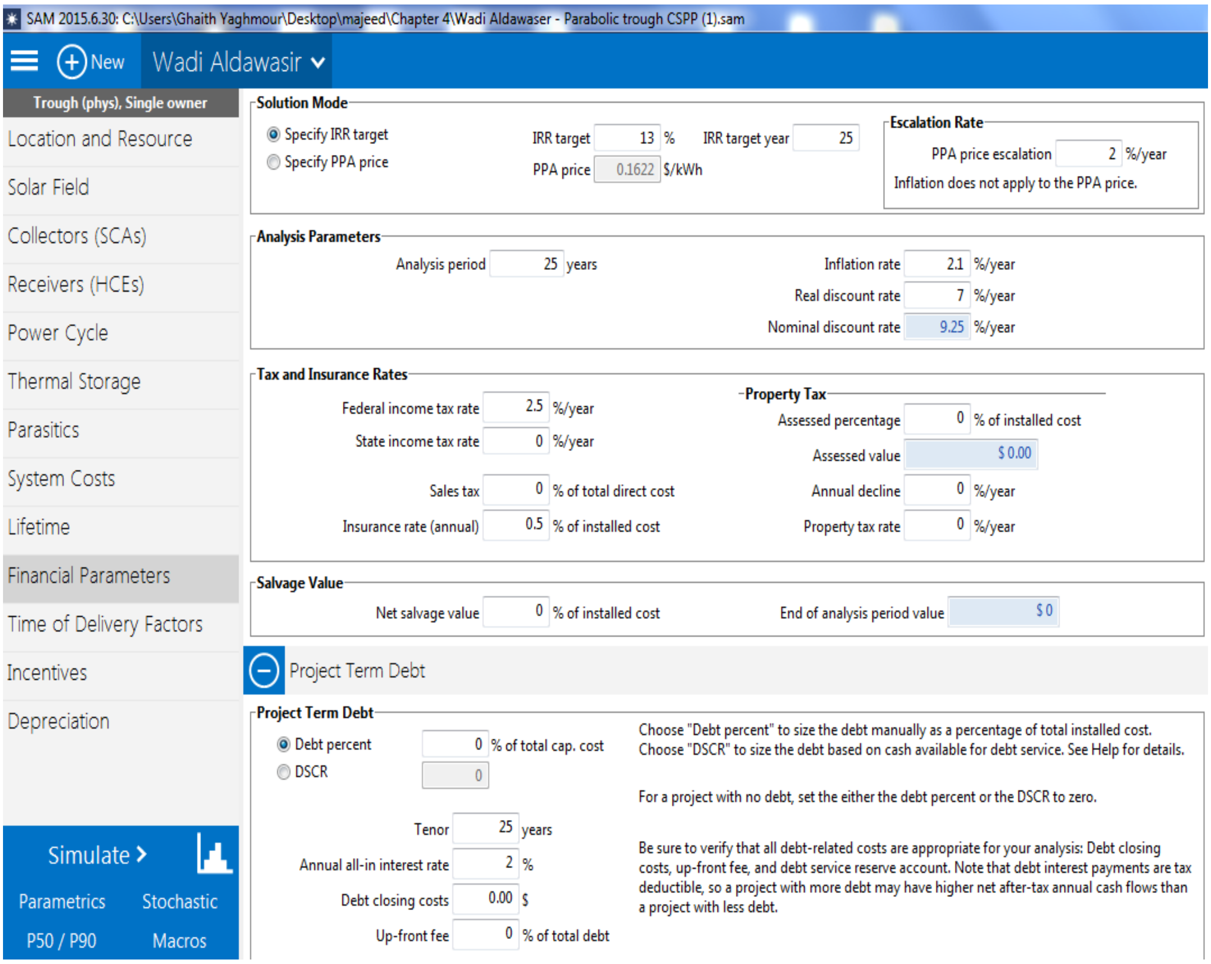
Thermal Storage
Parasitics
System Costs
Lifetime
Financial Parameters
Time of Delivery Factors
Incentives
Depreciation
Simulate >
Parametrics
Stochastic
P50 / P90
Macros
Direct Capital Costs
Site improvements 585,330.0 m² 20.00 $/m2 $ 11,706,600.00
Solar field 585,330.0 m² 245.00 $/m2 $ 143,405,856.00
HTF system 585,330.0 m² 75.00 $/m2 $ 43,899,752.00
Storage 0.0 MWht 80.00 $/kWht $ 0.00
Fossil backup 111.0 MWe, Gross 0.00 $/kWe $ 0.00
Power plant 111.0 MWe, Gross 830.00 $/kWe $ 92,130,000.00
Balance of plant 111.0 MWe, Gross 100.00 $/kWe $ 11,100,000.00
Subtotal $ 302,242,208.00
Contingency
Contingency 5 % of subtotal $ 15,112,110.00
Total direct cost $ 317,354,304.00
Indirect Capital Costs
Total land area 526 acres
Nameplate 100 MWe
$/acre
% of direct cost
$/Wac
$
EPC and owner cost $ 0.00 0 % $ 0.00 $ 0.00 $ 0.00
Total land cost $ 0.00 0 % $ 0.00 $ 0.00 $ 0.00
Sales Tax
Sales tax basis 80
Sales tax rate 0 % $ 0.00
Total indirect cost $ 0.00
Total Installed Costs
Total installed cost excludes any financing costs from the Financial Parameters page.
Total intalled cost $ 317,354,304.00
Estimated total installed cost per net capacity $ 3,176.72/kW
Operation and Maintenance Costs
First year cost
Escalation rate (above inflation)
Fixed annual cost 0 $/yr 0 %
In Value mode, SAM applies both inflation and escalation to the first year


SAM 2015.6.30: C:\Users\Ghaith Yaghmour\Desktop\majeed\Chapter 4\Wadi Aldawaser - Parabolic trough CSPP (1).sam
New
Wadi Aldawasir
Trough (phys), Single owner
Location and Resource
Solar Field
Collectors (SCAs)
Receivers (HCEs)
Power Cycle
Thermal Storage
Parasitics
System Costs
Lifetime
Financial Parameters
Time of Delivery Factors
Incentives
Depreciation
Simulate >
Parametrics
Stochastic
P50 / P90
Macros
System Performance Degradation
Degradation rate
Value
1
%/year
Applies to the system's total annual AC output.
In Value mode, the degradation rate applies to the system's total annual kWh output for the previous year starting in Year 2. In Schedule mode, each year's rate applies to the Year 1 value. See Help for details.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New
Wadi Aldawasir
Trough (phys), Single owner
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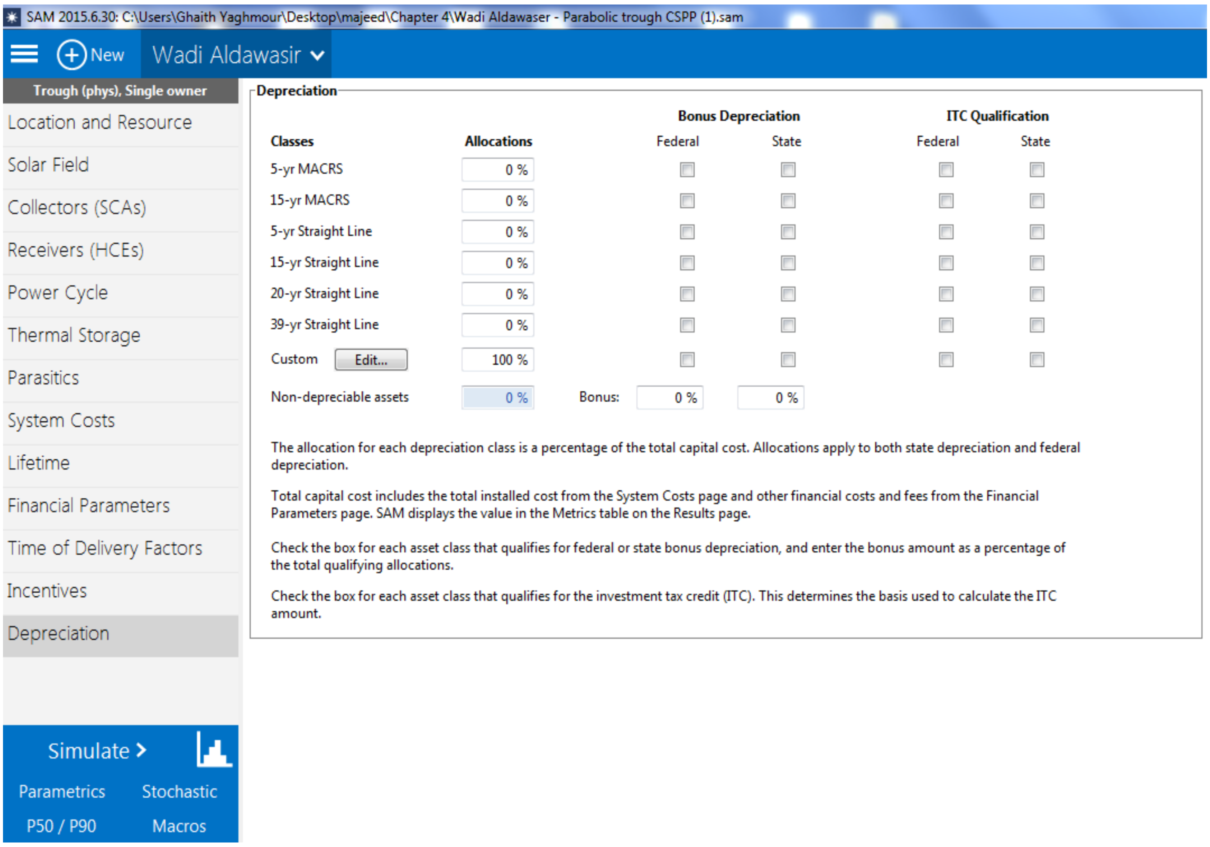
Solar Field
Collectors (SCAs)
Receivers (HCEs)
Power Cycle
Thermal Storage
Parasitics
System Costs
Lifetime
Financial Parameters
Time of Delivery Factors
Incentives
Depreciation
Simulate >
Parametrics
Stochastic
P50 / P90
Macros
Solution Mode
Specify IRR target
Specify PPA price
IRR target 13 %
IRR target year 25
PPA price 0.1622 $/kWh
Escalation Rate
PPA price escalation 2 %/year
Inflation does not apply to the PPA price.
Analysis Parameters
Analysis period 25 years
Inflation rate 2.1 %/year
Real discount rate 7 %/year
Nominal discount rate 9.25 %/year
Tax and Insurance Rates
Federal income tax rate 2.5 %/year
State income tax rate 0 %/year
Sales tax 0 % of total direct cost
Insurance rate (annual) 0.5 % of installed cost
Property Tax
Assessed percentage 0 % of installed cost
Assessed value $ 0.00
Annual decline 0 %/year
Property tax rate 0 %/year
Salvage Value
Net salvage value 0 % of installed cost
End of analysis period value $ 0
Project Term Debt
Project Term Debt
Debt percent 0 % of total cap. cost
DSCR 0
Tenor 25 years
Annual all-in interest rate 2 %
Debt closing costs 0.00 $
Up-front fee 0 % of total debt
Choose "Debt percent" to size the debt manually as a percentage of total installed cost. Choose "DSCR" to size the debt based on cash available for debt service. See Help for details.
For a project with no debt, set the either the debt percent or the DSCR to zero.
Be sure to verify that all debt-related costs are appropriate for your analysis: Debt closing costs, up-front fee, and debt service reserve account. Note that debt interest payments are tax deductible, so a project with more debt may have higher net after-tax annual cash flows than a project with less debt.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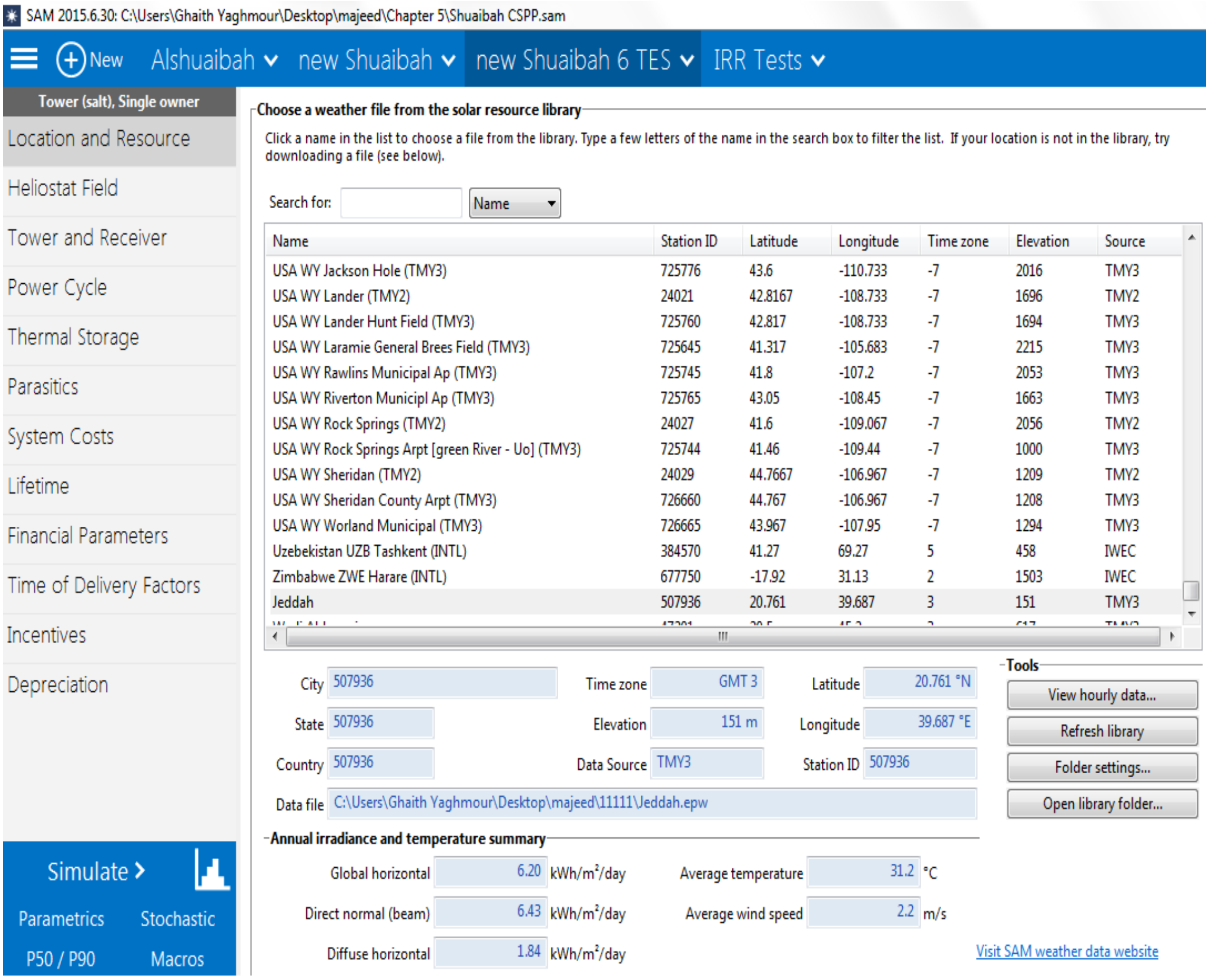
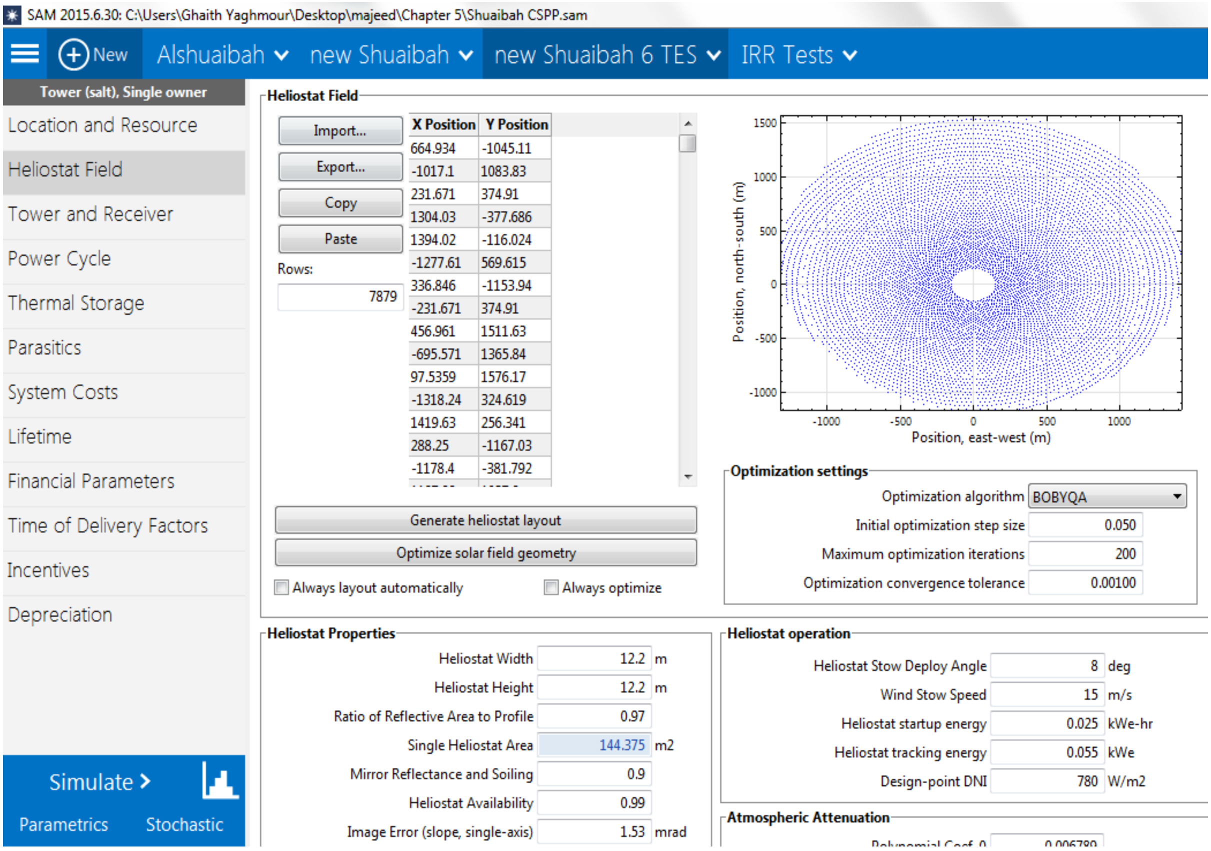
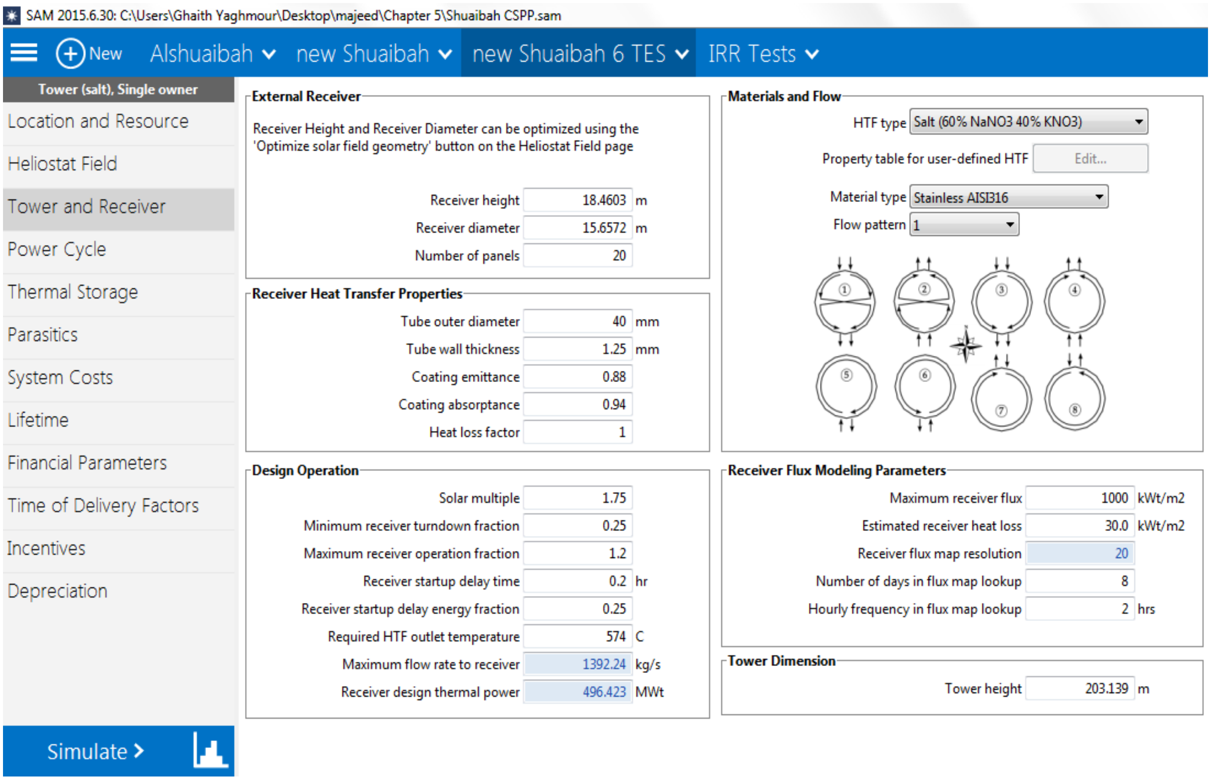
New
Wadi Aldawasir
Trough (phys), Single owner
Location and Resource
Solar Field
Collectors (SCAs)
Receivers (HCEs)
Power Cycle
Thermal Storage
Parasitics
System Costs
Lifetime
Financial Parameters
Time of Delivery Factors
Incentives
Depreciation
Simulate >
Parametrics
Stochastic
P50 / P90
Macros
Depreciation
Bonus Depreciation
ITC Qualification
Classes
Allocations
Federal
State
Federal
State
5-yr MACRS 0 %
15-yr MACRS 0 %
5-yr Straight Line 0 %
15-yr Straight Line 0 %
20-yr Straight Line 0 %
39-yr Straight Line 0 %
Custom Edit... 100 %
Non-depreciable assets 0 %
Bonus: 0 % 0 %
The allocation for each depreciation class is a percentage of the total capital cost. Allocations apply to both state depreciation and federal depreciation.
Total capital cost includes the total installed cost from the System Costs page and other financial costs and fees from the Financial Parameters page. SAM displays the value in the Metrics table on the Results page.
Check the box for each asset class that qualifies for federal or state bonus depreciation, and enter the bonus amount as a percentage of the total qualifying allocations.
Check the box for each asset class that qualifies for the investment tax credit (ITC). This determines the basis used to calculate the ITC amount.

A.2 SAM Simulation pages of Shuaibah CSPP




SAM 2015.6.30: C:\Users\Ghaith Yaghmour\Desktop\majeed\Chapter 5\Shuaibah CSPP.sam
New
Alshuaibah
new Shuaibah
new Shuaibah 6 TES
IRR Tests
Tower (salt), Single owner
Location and Resource
Heliostat Field
Tower and Receiver
Power Cycle
Thermal Storage
Parasitics
System Costs
Lifetime
Financial Parameters
Time of Delivery Factors
Incentives
Depreciation
Simulate >
Parametrics
Stochastic
Heliostat Field
Import...
Export...
Copy
Paste
Rows:
7879
X Position Y Position
664.934 -1045.11
-1017.1 1083.83
231.671 374.91
1304.03 -377.686
1394.02 -116.024
-1277.61 569.615
336.846 -1153.94
-231.671 374.91
456.961 1511.63
-695.571 1365.84
97.5359 1576.17
-1318.24 324.619
1419.63 256.341
288.25 -1167.03
-1178.4 -381.792
Position, north-south (m)
Position, east-west (m)
Generate heliostat layout
Optimize solar field geometry
Always layout automatically
Always optimize
Optimization settings
Optimization algorithm BOBYQA
Initial optimization step size 0.050
Maximum optimization iterations 200
Optimization convergence tolerance 0.00100
Heliostat Properties
Heliostat Width 12.2 m
Heliostat Height 12.2 m
Ratio of Reflective Area to Profile 0.97
Single Heliostat Area 144.375 m2
Mirror Reflectance and Soiling 0.9
Heliostat Availability 0.99
Image Error (slope, single-axis) 1.53 mrad
Heliostat operation
Heliostat Stow Deploy Angle 8 deg
Wind Stow Speed 15 m/s
Heliostat startup energy 0.025 kWe-hr
Heliostat tracking energy 0.055 kWe
Design-point DNI 780 W/m2
Atmospheric Attenuation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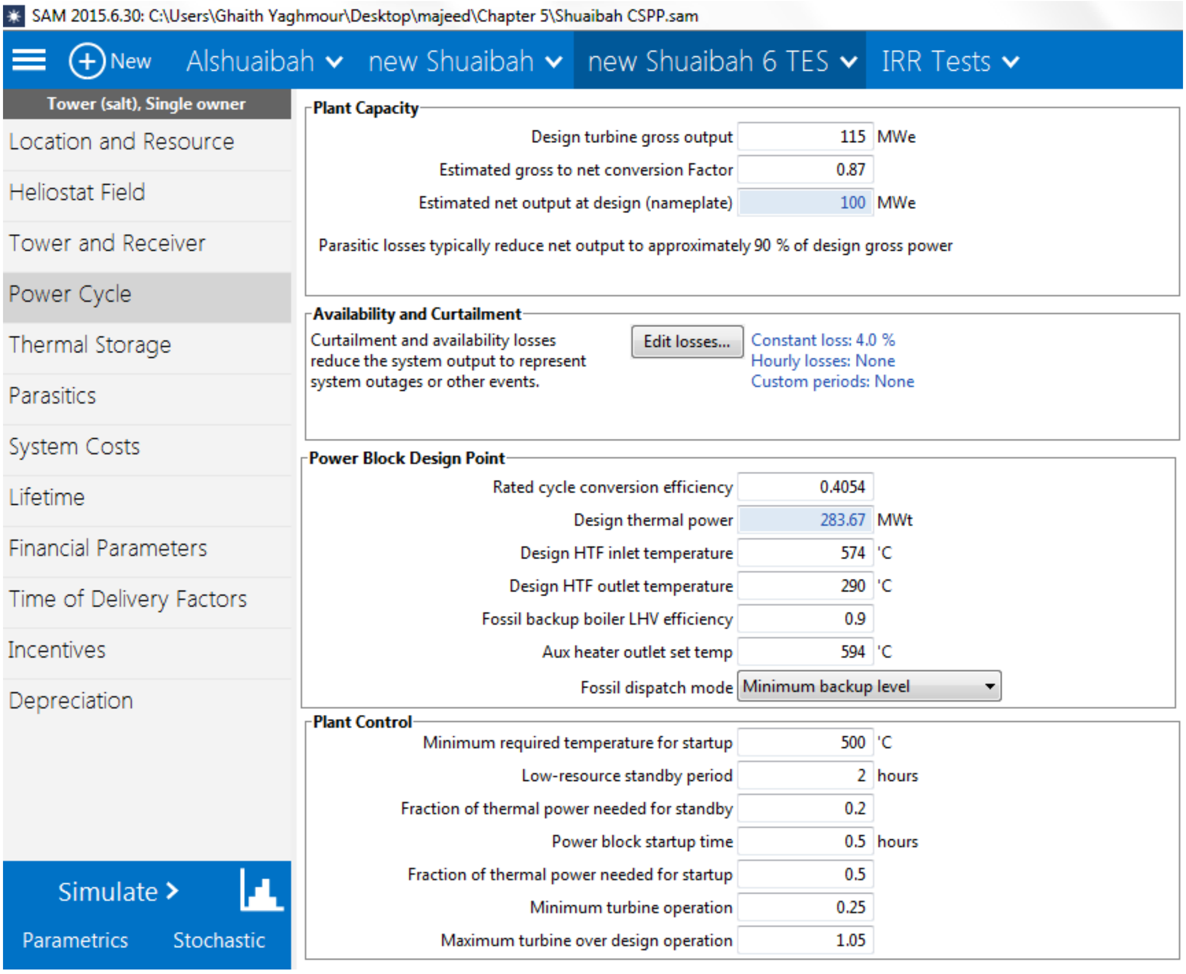
New
Alshuaibah
new Shuaibah
new Shuaibah 6 TES
IRR Tests
Tower (salt), Single owner
Location and Resource
Heliostat Field
Tower and Receiver
Power Cycle
Thermal Storage
Parasitics
System Costs
Lifetime
Financial Parameters
Time of Delivery Factors
Incentives
Depreciation
Simulate >
External Receiver
Receiver Height and Receiver Diameter can be optimized using the 'Optimize solar field geometry' button on the Heliostat Field page
Receiver height 18.4603 m
Receiver diameter 15.6572 m
Number of panels 20
Receiver Heat Transfer Properties
Tube outer diameter 40 mm
Tube wall thickness 1.25 mm
Coating emittance 0.88
Coating absorptance 0.94
Heat loss factor 1
Design Operation
Solar multiple 1.75
Minimum receiver turndown fraction 0.25
Maximum receiver operation fraction 1.2
Receiver startup delay time 0.2 hr
Receiver startup delay energy fraction 0.25
Required HTF outlet temperature 574 C
Maximum flow rate to receiver 1392.24 kg/s
Receiver design thermal power 496.423 MWt
Materials and Flow
HTF type Salt (60% NaNO3 40% KNO3)
Property table for user-defined HTF Edit...
Material type Stainless AISI316
Flow pattern 1
Receiver Flux Modeling Parameters
Maximum receiver flux 1000 kWt/m2
Estimated receiver heat loss 30.0 kWt/m2
Receiver flux map resolution 20
Number of days in flux map lookup 8
Hourly frequency in flux map lookup 2 hrs
Tower Dimension
Tower height 203.139 m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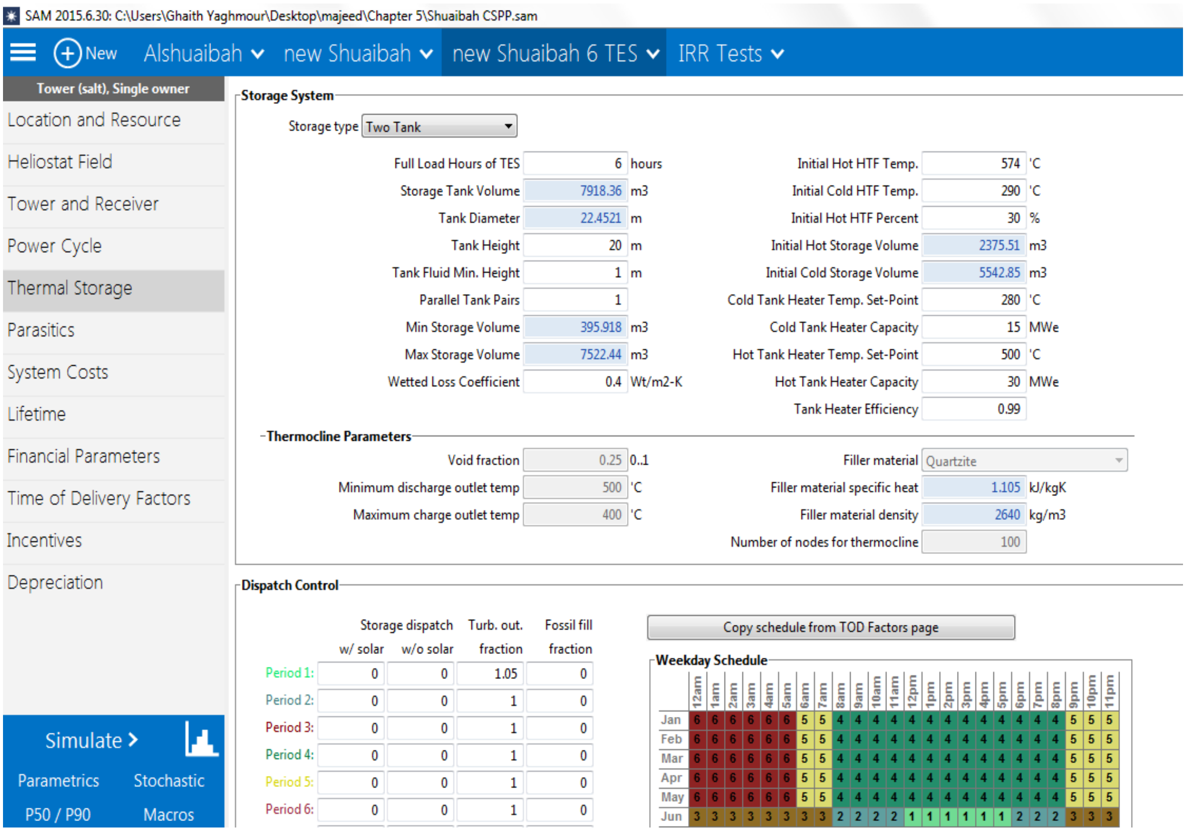
New
Alshuaibah
new Shuaibah
new Shuaibah 6 TES
IRR Tests
Tower (salt), Single owner
Location and Resource
Heliostat Field
Tower and Receiver
Power Cycle
Thermal Storage
Parasitics
System Costs
Lifetime
Financial Parameters
Time of Delivery Factors
Incentives
Depreciation
Simulate >
Parametrics
Stochastic
Plant Capacity
Design turbine gross output 115 MWe
Estimated gross to net conversion Factor 0.87
Estimated net output at design (nameplate) 100 MWe
Parasitic losses typically reduce net output to approximately 90 % of design gross power
Availability and Curtailment
Curtailment and availability losses reduce the system output to represent system outages or other events.
Edit losses...
Constant loss: 4.0 %
Hourly losses: None
Custom periods: None
Power Block Design Point
Rated cycle conversion efficiency 0.4054
Design thermal power 283.67 MWt
Design HTF inlet temperature 574 'C
Design HTF outlet temperature 290 'C
Fossil backup boiler LHV efficiency 0.9
Aux heater outlet set temp 594 'C
Fossil dispatch mode Minimum backup level
Plant Control
Minimum required temperature for startup 500 'C
Low-resource standby period 2 hours
Fraction of thermal power needed for standby 0.2
Power block startup time 0.5 hours
Fraction of thermal power needed for startup 0.5
Minimum turbine operation 0.25
Maximum turbine over design operation 1.05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New
Alshuaibah
new Shuaibah
new Shuaibah 6 TES
IRR Tests
Tower (salt), Single owner
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Heliostat Field
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Power Cycle
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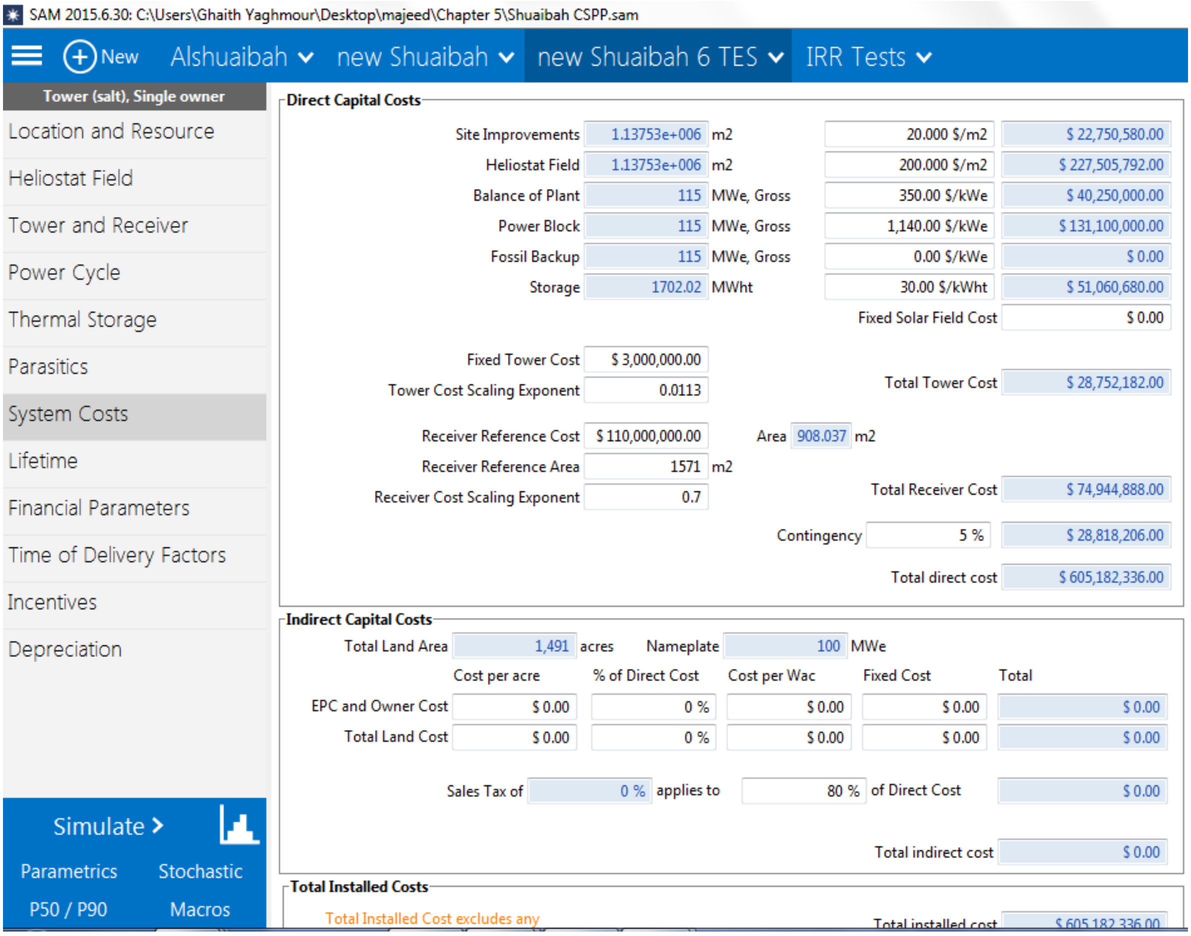
Parasitics
System Costs
Lifetime
Financial Parameters
Time of Delivery Factors
Incentives
Depreciation
Simulate >
Parametrics
Stochastic
P50 / P90
Macros
Storage System
Storage type Two Tank
Full Load Hours of TES 6 hours
Storage Tank Volume 7918.36 m3
Tank Diameter 22.4521 m
Tank Height 20 m
Tank Fluid Min. Height 1 m
Parallel Tank Pairs 1
Min Storage Volume 395.918 m3
Max Storage Volume 7522.44 m3
Wetted Loss Coefficient 0.4 Wt/m2-K
Initial Hot HTF Temp. 574 'C
Initial Cold HTF Temp. 290 'C
Initial Hot HTF Percent 30 %
Initial Hot Storage Volume 2375.51 m3
Initial Cold Storage Volume 5542.85 m3
Cold Tank Heater Temp. Set-Point 280 'C
Cold Tank Heater Capacity 15 MWe
Hot Tank Heater Temp. Set-Point 500 'C
Hot Tank Heater Capacity 30 MWe
Tank Heater Efficiency 0.99
Thermocline Parameters
Void fraction 0.25 0..1
Minimum discharge outlet temp 500 'C
Maximum charge outlet temp 400 'C
Filler material Quartzite
Filler material specific heat 1.105 kJ/kgK
Filler material density 2640 kg/m3
Number of nodes for thermocline 100
Dispatch Control
Storage dispatch w/ solar w/o solar
Turb. out. fraction
Fossil fill fraction
Period 1: 0 0 1.05 0
Period 2: 0 0 1 0
Period 3: 0 0 1 0
Period 4: 0 0 1 0
Period 5: 0 0 1 0
Period 6: 0 0 1 0
Copy schedule from TOD Factors page
Weekday Schedule
12am 1am 2am 3am 4am 5am 6am 7am 8am 9am 10am 11am 12pm 1pm 2pm 3pm 4pm 5pm 6pm 7pm 8pm 9pm 10pm 11pm
Jan 6 6 6 6 6 6 5 5 4 4 4 4 4 4 4 4 4 4 4 4 4 5 5 5
Feb 6 6 6 6 6 6 5 5 4 4 4 4 4 4 4 4 4 4 4 4 4 5 5 5
Mar 6 6 6 6 6 6 5 5 4 4 4 4 4 4 4 4 4 4 4 4 4 5 5 5
Apr 6 6 6 6 6 6 5 5 4 4 4 4 4 4 4 4 4 4 4 4 4 5 5 5
May 6 6 6 6 6 6 5 5 4 4 4 4 4 4 4 4 4 4 4 4 4 5 5 5
Jun 3 3 3 3 3 3 3 3 2 2 2 2 1 1 1 1 1 1 2 2 2 3 3 3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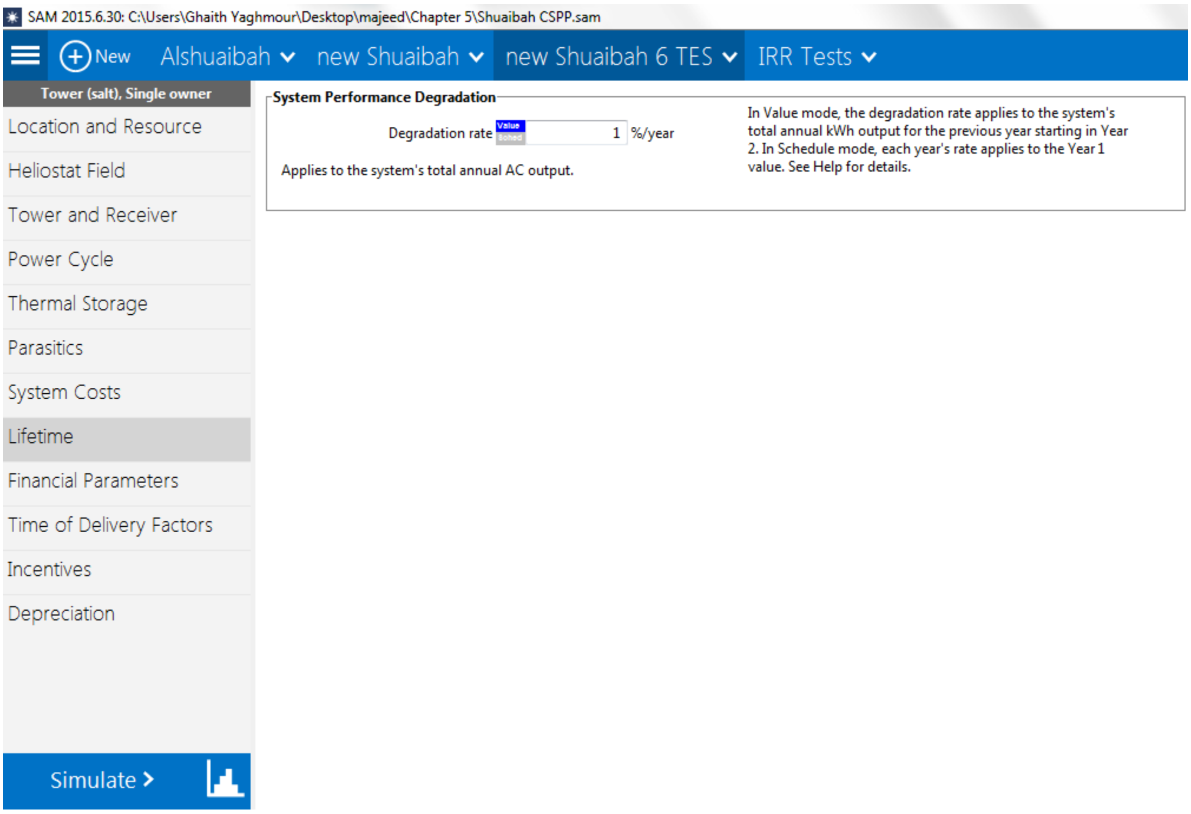
Direct Capital Costs
Site Improvements 1.13753e+006 m2 20.000 $/m2 $ 22,750,580.00
Heliostat Field 1.13753e+006 m2 200.000 $/m2 $ 227,505,792.00
Balance of Plant 115 MWe, Gross 350.00 $/kWe $ 40,250,000.00
Power Block 115 MWe, Gross 1,140.00 $/kWe $ 131,100,000.00
Fossil Backup 115 MWe, Gross 0.00 $/kWe $ 0.00
Storage 1702.02 MWht 30.00 $/kWht $ 51,060,680.00
Fixed Solar Field Cost $ 0.00
Fixed Tower Cost $ 3,000,000.00
Tower Cost Scaling Exponent 0.0113
Total Tower Cost $ 28,752,182.00
Receiver Reference Cost $ 110,000,000.00
Area 908.037 m2
Receiver Reference Area 1571 m2
Receiver Cost Scaling Exponent 0.7
Total Receiver Cost $ 74,944,888.00
Contingency 5 % $ 28,818,206.00
Total direct cost $ 605,182,336.00
Indirect Capital Costs
Total Land Area 1,491 acres
Nameplate 100 MWe
Cost per acre
% of Direct Cost
Cost per Wac
Fixed Cost
Total
EPC and Owner Cost $ 0.00 0 % $ 0.00 $ 0.00 $ 0.00
Total Land Cost $ 0.00 0 % $ 0.00 $ 0.00 $ 0.00
Sales Tax of 0 % applies to 80 % of Direct Cost $ 0.00
Total indirect cost $ 0.00
Total Installed Costs
Total Installed Cost excludes any
Total installed cost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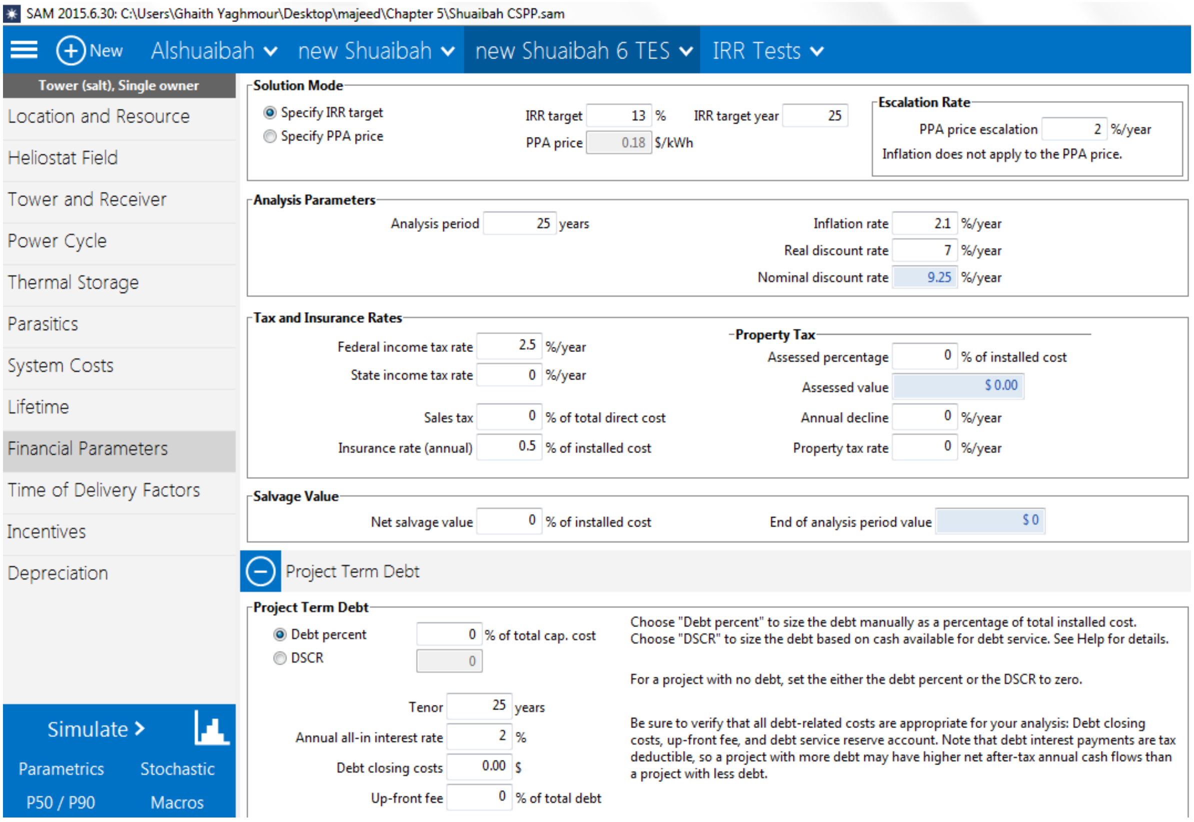
System Performance Degradation
Degradation rate 1 %/year
Applies to the system's total annual AC output.
In Value mode, the degradation rate applies to the system's total annual kWh output for the previous year starting in Year 2. In Schedule mode, each year's rate applies to the Year 1 value. See Help for details.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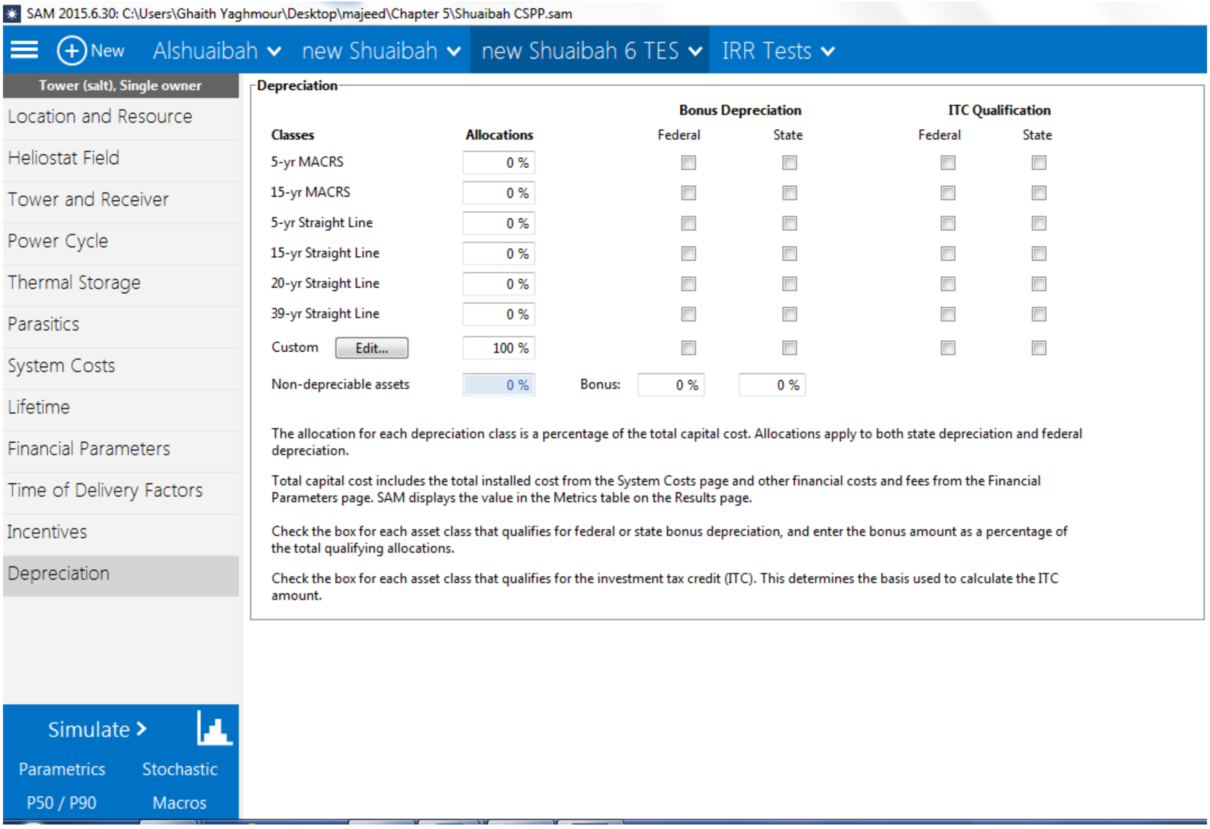
Solution Mode
Specify IRR target
Specify PPA price
IRR target 13 %
IRR target year 25
PPA price 0.18 $/kWh
Escalation Rate
PPA price escalation 2 %/year
Inflation does not apply to the PPA price.
Analysis Parameters
Analysis period 25 years
Inflation rate 2.1 %/year
Real discount rate 7 %/year
Nominal discount rate 9.25 %/year
Tax and Insurance Rates
Federal income tax rate 2.5 %/year
State income tax rate 0 %/year
Sales tax 0 % of total direct cost
Insurance rate (annual) 0.5 % of installed cost
Property Tax
Assessed percentage 0 % of installed cost
Assessed value $ 0.00
Annual decline 0 %/year
Property tax rate 0 %/year
Salvage Value
Net salvage value 0 % of installed cost
End of analysis period value $ 0
Project Term Debt
Project Term Debt
Debt percent 0 % of total cap. cost
DSCR 0
Tenor 25 years
Annual all-in interest rate 2 %
Debt closing costs 0.00 $
Up-front fee 0 % of total debt
Choose "Debt percent" to size the debt manually as a percentage of total installed cost. Choose "DSCR" to size the debt based on cash available for debt service. See Help for details.
For a project with no debt, set the either the debt percent or the DSCR to zero.
Be sure to verify that all debt-related costs are appropriate for your analysis: Debt closing costs, up-front fee, and debt service reserve account. Note that debt interest payments are tax deductible, so a project with more debt may have higher net after-tax annual cash flows than a project with less debt.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Depreciation
Bonus Depreciation
ITC Qualification
Classes
Allocations
Federal
State
Federal
State
5-yr MACRS
0 %
15-yr MACRS
0 %
5-yr Straight Line
0 %
15-yr Straight Line
0 %
20-yr Straight Line
0 %
39-yr Straight Line
0 %
Custom
Edit...
100 %
Non-depreciable assets
0 %
Bonus:
0 %
0 %
The allocation for each depreciation class is a percentage of the total capital cost. Allocations apply to both state depreciation and federal depreciation.
Total capital cost includes the total installed cost from the System Costs page and other financial costs and fees from the Financial Parameters page. SAM displays the value in the Metrics table on the Results page.
Check the box for each asset class that qualifies for federal or state bonus depreciation, and enter the bonus amount as a percentage of the total qualifying allocations.
Check the box for each asset class that qualifies for the investment tax credit (ITC). This determines the basis used to calculate the ITC amount.