Investigating the Feasibility of Solar Photovoltaic Systems in Kuwait

By

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Abstract

This thesis presents work undertaken to investigate the feasibility of implementing solar photovoltaic (PV) systems in Kuwait. Performance parameters, environmental, and economic evaluations and assessments, as well as a numerical modelling study, were conducted as the main investigative elements to help judge the feasibility. The effect of using single-axis and dual-axis tracking systems was also considered.

An assessment of the performance parameters of the proposed PV systems at selected locations in Kuwait was conducted on a monthly basis, using different tracking systems to compare the sites. Moreover, an annual basis analysis was carried out to compare the obtained results with those of different studies in the existing literature. An environmental assessment was conducted in the form of a Life Cycle Assessment (LCA), estimating the levels of greenhouse gas (GHG) emissions that could be avoided. An economic assessment of implementing the proposed PV systems at the selected locations, and a cost-benefit analysis were conducted. In addition, modelling of a two-axis solar tracker was performed to ensure the stability and reliability of the proposed solar tracker in Kuwait. This was done using a 3D finite element model to examine the soil-structure interaction using COMSOL Multiphysics software.

The results show that the performance parameters values obtained by implementing single-axis and dual-axis systems are very beneficial to the electricity generation in Kuwait. It was also found that using single-axis and dual-axis PV systems can increase the average annual production by 24.7% and 29%, respectively. The CO_2 emission rates obtained in this study, which ranged between 46.38 and 56.94 g-CO_2,eq/kWh, were within the range of the results obtained in previous studies. Moreover, a large amount of GHGs could be avoided by using such a technology. Furthermore, it was found that utilising the proposed PV systems is economically viable compared with conventional power plants when the oil prices are equal to or more than $30 (£23) per barrel and a significant amount of oil barrels would be saved by using PV systems instead of conventional power plants.

The modelling showed that the proposed PV solar tracker is stable under the wind design speed of Kuwait (40 m/s). The effect of wind speed should not be underestimated, especially when wind speed is high and the solar tracker defence position strategy is need to be applied in order to protect the structure from external forces caused by high wind speeds.

Overall, the obtained results of the performance parameters, environmental and economic evaluations were encouraging. The main conclusion of this work is that utilising PV systems to generate electricity as an alternative to conventional power plants in Kuwait would be beneficial. It was also found that the single-axis tracking system is the best choice for use in these systems. The implementation of solar PV systems in the State of Kuwait will be a significant step in terms of global contribution to increasing the use of renewable energy technology.

Nomenclature

3D	Three-Dimensional
AC	Alternating Current
AM	Air Mass
ARR	Accounting Rate of Return
ASCE	American Society of Civil Engineers
a-Si	Amorphous Silicon
ASTM	International Standards Organization
BH	Borehole
BOS	Balance of System
BP	British Petroleum
BS	British Standards
Btu	British thermal units
c	Cohesion
CdTe	Cadmium Telluride
CED	Cumulative Energy Demand
CF	Capacity Factor
CFD	Computational Fluid Dynamics
CIGS	Copper Indium Gallium Diselenide
CN	China
CO_2	Carbon Dioxide
CPV	Concentrated Photovoltaic
CRF	Capital Recovery Factor
CSP	Concentrated Solar Power
DC	Direct Current
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance

E	Modulus of Elasticity
EAC	Energy produced by the PV system
Enertech	Holding Company of energy in Kuwait
EPA	United States Environmental Protection Agency
EPBT	Energy Payback Time
EPIA	European Photovoltaic Industry Association
EYR	Energy Yield Ratio
FEM	Finite Elements Method
FFC	Fossil Fuel Consumption
FOS	Factor of Safety
G	Reference irradiation
GCC	Gulf Cooperation Council
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GHI	Global Horizontal Irradiance
GWEC	Global Wind Energy Council
GWP	Global Warming Potential
Ht	Total solar irradiation
i	Interest rate
I	Importance factor
ICERD	International Conference on Energy Research & Development
IEA	International Energy Agency
IEA-PVPS	International Energy Agency Photovoltaic Power System Programme
IEEE	Institute of Electrical and Electronics Engineers
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
K_d	Wind directionality factor

KISR	Kuwait Institute for Scientific Research
KPC	Kuwait Petroleum Corporation
K_z	Velocity pressure exposure coefficient
K_{zt}	Topographic factor
LCA	Life-Cycle Assessment
LCOE	Levelized Cost of Energy
MEW	Ministry of Electricity and Water
MG-Si	Metallurgical Grade Silicon
MIGD	Million Imperial Gallons per Day
MSF	Multi-Stage Flash
Mt	Million tonnes
n	Project life
NA	Not Available
NOx	Nitrogen Oxides
NPV	Net Present Value
OM	Operations and Maintenance
OECD	Organization for Economic Co-operation and Development
Paci	Public Authority for Civil Information
PBT	Payback Time
$P_{PV,\ rated}$	Rated output power of the used PV system
PR	Performance Ratio
PV	Photovoltaic
PV_{syst}	Commercial software
Q_z	Velocity pressure
RE	Renewable energy
REN21	Renewable Energy Policy Network for the 21st Century
SAM	Solar Advisor Model

SC	Clayey sand
SM	Silty sand
SMA	Solar Energy Company in Germany
SO_2	Sulfur Dioxide
SoG-Si	Solar Grade Silicon
SP	Poorly graded sand - USCS system
SP-SM	Poorly graded silty sand - USCS system
STC	Standard Test Conditions
SW-SM	Well graded sand with silt
TMY	Typical Meteorological Year
UL	Underwriters Laboratories
UNFCCC	United Nations Framework Convention on Climate Change
V	Basic wind speed
VLS-PV	Very Large-Scale Photovoltaic power generation
YF	Yield Factor
YR	Reference yield
γ	Unit Weight
ν	Poisson's Ratio
ϕ	Angle of Internal Friction

Dedicated

To

my mother, my wife and children

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Chapter 1 – Background

1.1 Introduction

In recent years, energy demand across the world has increased significantly. It is generally expected that global energy consumption will increase by 56% between 2010 and 2040, from 524 quadrillion Btu (British thermal units) to 820 Btu, as a result of rapid and significant economic growth across the globe (U.S. Energy Information Agency, 2013). It is also expected by U.S. Energy Information Agency that by 2040, liquid fuels, natural gas, and coal will account for the largest percentage of the total energy consumed across the world (more than 75% of total energy consumption). Moreover, it is expected that the consumption of petroleum and liquid fuels will decrease by 34% from 2010 to 2040, as a result of high oil prices.

A BP Statistical Review (2014) states that global energy demand will increase at an average of 1.5% a year until 2035, with stable development during this period – increases are expected at an average of 2% per year to 2020, and then by approximately 1.2% per year to 2035. Moreover, the report states that 95% of this increase is anticipated to come from non-OECD (Organization for Economic Co-operation and Development) economies, with China and India accounting for more than half of the growth by 2035. In addition, energy use in non-OECD economies is expected to be around 70% higher than in 2012. The BP Statistical Review also states that fossil fuels account for the highest percentage (87%) of the total resources used in energy production globally. Fossil fuels, such as oil and natural gas, which are one of the main causes of air pollution and global warming, represented approximately 55.6% of fuels' share of CO_2 (carbon dioxide) emissions in 2012, as shown in Figure 1.1.

Global CO_2 emissions from fuel consumption were equal to 31734 Mt (million tonnes) in 2012, an increase of 392 Mt (1.25%) from 2011; the OECD was responsible for the largest percentage, and Africa the smallest, at 38.3% and 3.3%, respectively (Figure 1.2). The increased amount of CO_2 emissions, for which there is clear evidence from across the world, is a serious problem that must be dealt with carefully and effectively. CO_2 is one of the main greenhouse gases in the atmosphere, and is emitted in large quantities by various human activities taking place on Earth. This gas, and other greenhouse gases (GHG), such as water vapour and ozone, play a vital role in help keeping the planet at a stable temperature. Recently, the increasing levels of CO_2, particularly those resulting from burning fossil fuels to generate electricity over the globe, are directly contributing to raising the temperature of the Earth by trapping the emitted heat in the atmosphere, a process that causes global warming.

The Middle East, which includes the Gulf Cooperation Council (GCC) comprised of Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates, contributed 5.1% in 2012, an increase of 0.1% from 2011 (Al-Khouri, 2012). In the last two decades, GCC countries have experienced rapid economic development, and a significant increase in population. Specifically, the population of GCC countries increased by 12,700,109 (37.57%) from 2005 (33,803,177) to 2010 (46,503,286) (Al-Khouri, 2012).

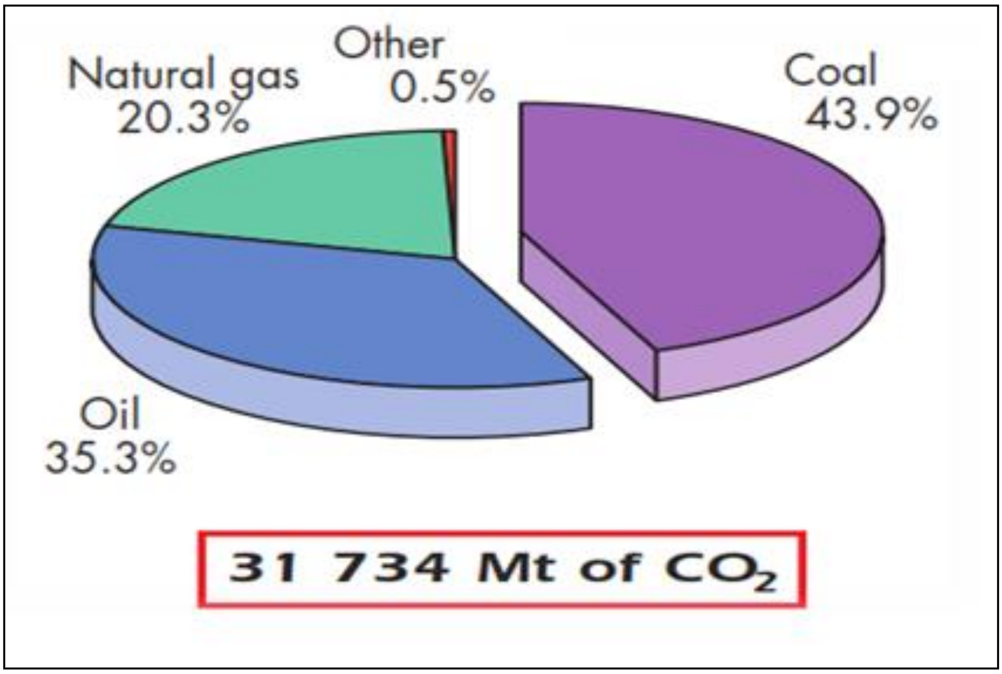


Figure 1.1 2012 Fuel share of CO_2 emissions (IEA, 2014)

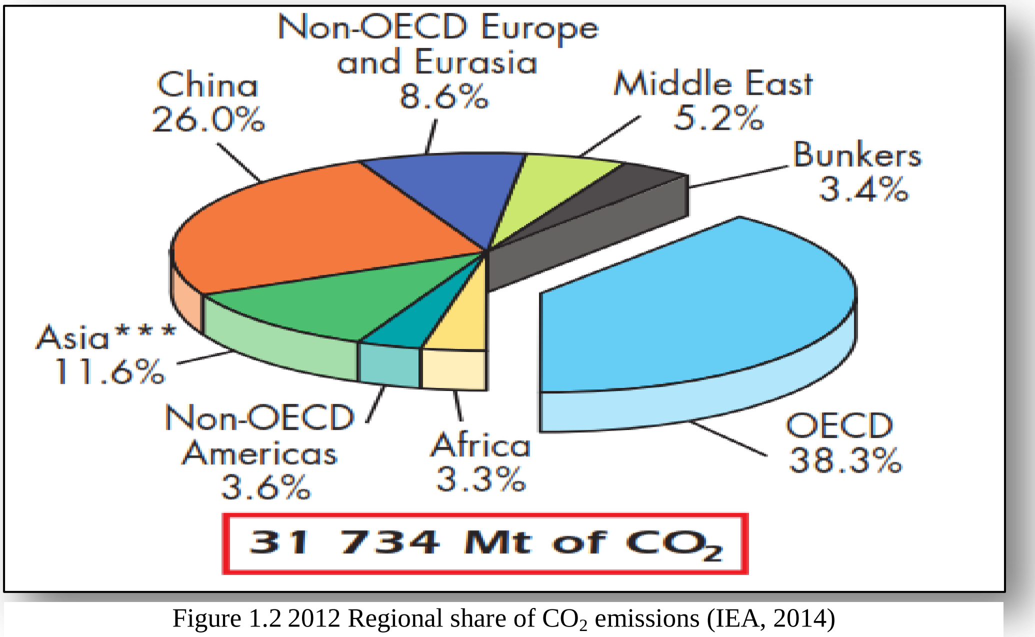


Figure 1.2 2012 Regional share of CO_2 emissions (IEA, 2014)

As a result of the economic expansion, population growth, and high gross domestic product (GDP) values for these GCC countries, the demand for energy has increased remarkably. It was found that energy consumption in GCC countries increased by 74% during the period 2000 to 2010, and is expected to increase again by 10-15 % between 2010 and 2020 (Kinninmont, 2010). From Figure 1.3, it can be seen that the average energy consumption per capita in GCC countries is high, with Kuwait and Qatar showing the highest values. GCC countries are in possession of 40% of the world’s oil reserves, and 21.7% of its gas reserves (Bhutto et al., 2014). Table 1.1 lists the leading crude oil producing countries across the world, and Figure 1.4 presents the top proved oil reserves.

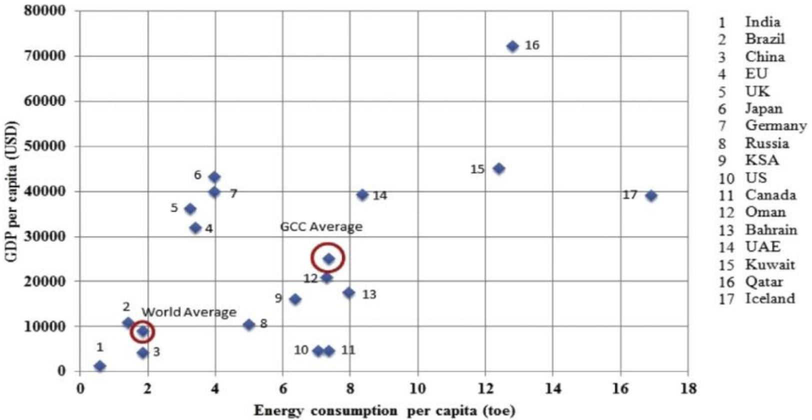


Figure 1.3 Per capita primary energy consumption relative to population in GCC countries, and selected country comparisons. The bubble size indicates per capita fossil fuel consumption (Bhutto et al., 2014).

Table 1.1 Leading crude oil producers, first quarter of 2014 (U.S Energy Administration, 2014)

Rank	**Country**	**Million Barrels per Day**
1	Russia	10.1
2	Saudi Arabia	9.8
3	United States	8.1
4	China	4.2
5	Canada	3.5
6	Iraq	3.3
7	Iran	3.3
8	United Arab Emirates	2.8
9	Kuwait	2.7
10	Mexico	2.5

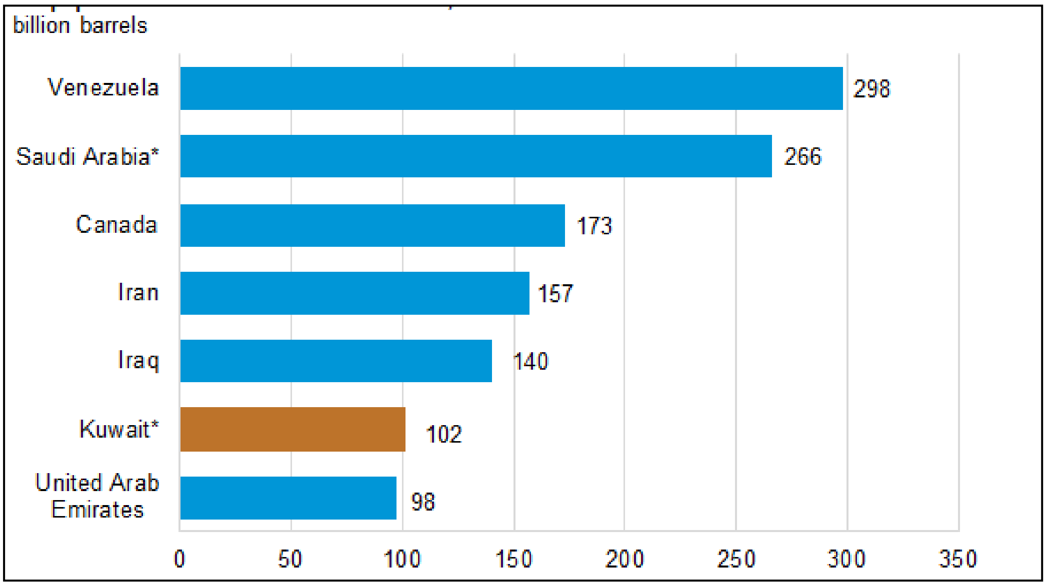


Figure 1.4 Top proved oil reserves, 2014 (U.S. Energy Administration, 2014)

GCC countries use conventional power plants to generate electricity, which mainly use oil and natural gas as the fuel source for production. Table 1.2 shows the percentages of natural gas and oil used in GCC countries. From the table, it is clear that Kuwait and Saudi Arabia are dependent on oil, whereas the other GCC countries are dependent on natural gas. In 2010, GCC countries were responsible for approximately 2.4% of global greenhouse gas emissions, and all the GCC countries fell within the top 25 countries in terms of carbon dioxide emissions per capita (Reiche, 2010). By 2013, this amount had increased to (2.8%). However, this level is considered low when compared with levels in other developing countries such as China (28.6%) and the United States (14.5%). However, the CO_2 emissions per capita of GCC countries varies between 16.5 and 37.8 in metric tonnes per capita; these levels are high compared with other developing countries such as China (7.6 metric tonnes per capita) and the United States (16.4 metric tonnes per capita).

Table 1.2 Sources of energy for consumption in the GCC. (Benyahia, 2012)

State	**Natural gas**	**Oil**
Bahrain	84.20 %	15.80 %
Kuwait	37.40 %	62.60 %
Oman	69.30 %	30.70 %
Qatar	75.30 %	24.70 %
K.S.A	37.60 %	62.40 %
U.A.E	82.40 %	17.60 %

Figure 1.5 shows that total CO_2 emissions increased by 632,818 Mt (Million metric tonnes) (178.84%) from 1990 to 2013. Figure 1.6 presents the CO_2 emissions per capita of GCC countries, and some other selected countries (the United States, United Kingdom, Germany and China). Qatar and Kuwait – considered high per capita electricity consumers – have the highest CO_2 emissions per capita which is attributed to the significant economic growth during the last decade supported by the high rates of GDP values and a relative high population density of these countries. All GCC countries are signatories of the United Nations Framework Convention on Climate Change (UNFCCC), and the Kyoto Protocol (Bhutto et al., 2014; Breidenich et al., 1998). The main objective of the Kyoto Protocol is to mandate national reductions in greenhouse gas emissions, as the effect of these types of agreements clearly manifest in many government policies around the world, encouraging investment in all types of renewable resources, and providing incentives for companies working in this field. For example, free tax and low interest rates are given to companies as incentives for investing in renewable energy. In addition, the large-scale consumption of natural resources threatens future generations in terms of the availability, or rather scarcity, of natural resources.

As a result of the above, the need for renewable resources, such as wind and solar, is becoming a key concern for researchers and all stakeholders. Renewable energy (RE), which is clean and sustainable, is becoming a worthy target and a key goal. In other words, due to the need for energy security, the impact of fossil fuel emissions on the environment, and fluctuating and high world oil prices, there is significant global interest in renewable energy. In addition, most countries, are primarily aiming to begin moving towards the use of renewable resources instead of conventional energy sources.

From another perspective, using renewable energy to achieve energy diversity will help to support any future plans related to economic development, and will increase the range of options open to the government in the future.

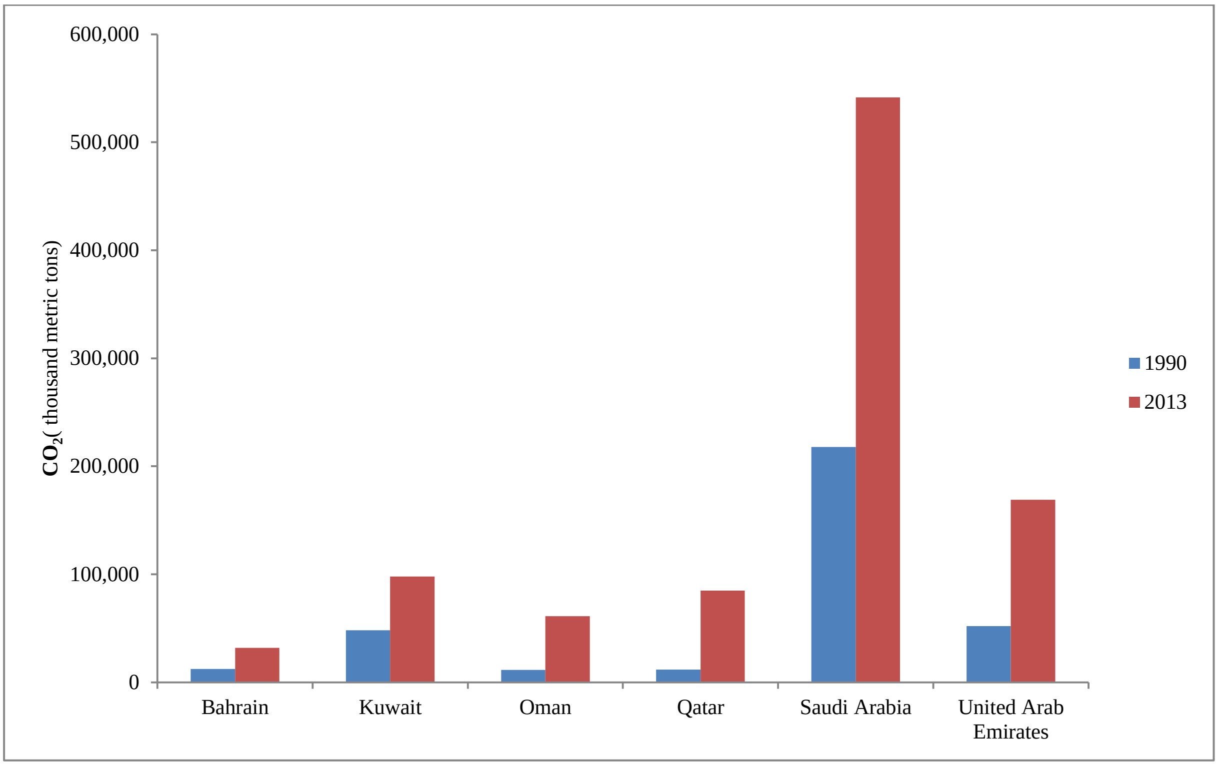


Figure 1.5 CO_2 total emissions in GCC countries (1990 and 2013). (Data taken from World Development Indicators, 2017)

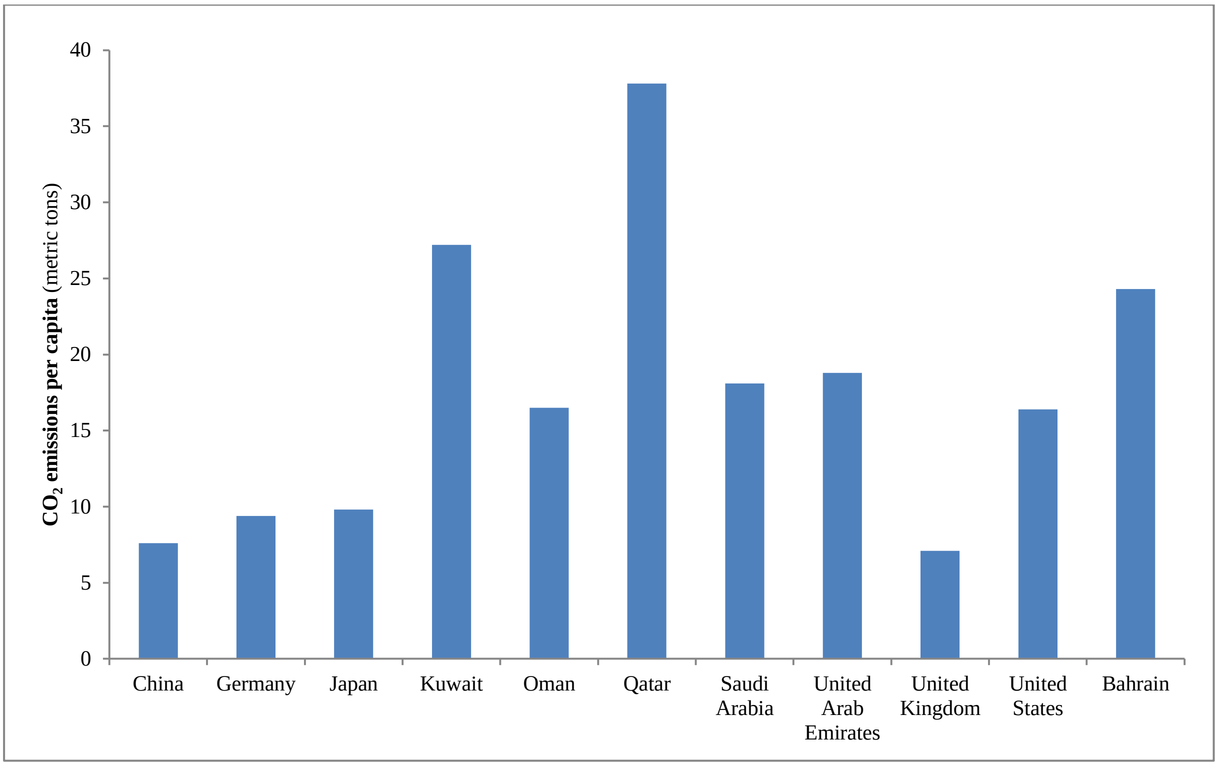


Figure 1.6 CO_2 emissions per capita of GCC countries and selected countries. (Data ken from World Development Indicators, 2017)

Current predictions about how long the Earth's fossil fuel reserves will last are a subject of intense discussion, as such fuels are considered finite resources. In other words, if the quantities of fossil fuel were precisely estimated and the anticipated rate of consumption estimated fairly, then the time fossil fuels will last could then be effectively approximated. However, the estimations regarding the continued availability of fossil fuels are implicitly dependent on several complex factors, such as demand and the price of fossil fuels. Moreover, the shale oil revolution, which allows oil to be extracted from low permeability rock formations, is an important new parameter that should be considered when estimating the timeframe in which fossil fuels are likely to run out. According to BP's annual report (2014), the proven global oil reserves are approximately equal to 1.688 trillion barrels of crude oil, which represents a 53.3 year supply assuming current rates of extraction and consumption.

It is crucial to reemphasise here that fossil fuels, such as oil and natural gas are finite natural resources. It is this fact that is one of the primary drivers for the development of sources of renewable energy.

From Table 1.3, it is clear that Saudi Arabia and Kuwait have the highest solar power values, due to the long duration of sunshine they experience, which is an excellent indication of the applicability of using solar energy. The use of renewable energy and nuclear power is increasing at a fast rate, and it is estimated that approximately 11% of the world's marketed energy consumption is currently derived from renewable energy sources (biofuels, biomass, geothermal, hydropower, solar and wind), which is expected to rise to approximately 15% by 2040 (U.S. Energy Information Administration, 2014). In addition to GCC countries possessing the largest amount of natural resources (natural gas and oil), they also benefit from a large amount of renewable energy, due to their geographical positioning. The potential for renewable energy in GCC countries is thus tremendous, particularly solar energy, as every year, each square kilometre of land receives a high amount of solar energy (approximately 500-600 W/m^2) (Alnaser and Alnaser, 2011).

Table 1.3 Solar versus wind power in Arabian Gulf countries (W/m^2) (Alnaser and Alnaser, 2011).

Country	**Solar energy** (Wh/m^2)	**Sunshine duration** (h)	**Solar power** (W/m^2)	**Wind power** (W/m^2)	**Solar/wind**
Bahrain	5180	9.2	563	78	7.2
Saudi Arabia	5670	8.7	683	71	9.6
Kuwait	5990	8.9	673	140	4.8
Qatar	5260	9.3	565	85	6.6
UAE	5078	8.8	577	57	10.1
Oman	5410	9.6	564	141	4

In order to satisfy the substantial energy demand increases (due to the increasing population, and rates of economic and social development), GCC countries are keen to invest in renewable energy (El-katiri and Husain, 2014). They have created a road map with a timescale in order to measure their progress in implementing and achieving pre-specified targets (Table 1.4).

From the table, it is clear that Saudi Arabia is planning to use 50% renewable energy in electricity generation by 2032, through harnessing different types of renewable energy, such as solar, wind, and geothermal energy, while the other GCC countries are focusing on solar and wind energy, and intend to be generating approximately 5-15% of their electricity this way by 2030.

It is clear that the GCC countries are late in terms of using renewable energy technologies and that is due to the high dependency on oil and natural gas as the basic source of the countries income. In addition, the high cost of renewable energy projects for electricity generation compared with conventional power plants.

A summary of existing renewable energy projects in the GCC countries is listed in Table 1.5. It can be seen that most GCC countries are focussing on solar and wind energy, due to the lack of specialist people in renewable energy technologies as well as no clear support from governments to the companies in the private sector, in other words, there is no serious support from governments in these countries which have a vital role in the private sector.

Encouragement and support is therefore needed in order to attract people and companies to invest in renewable energy technologies.

It is apparent from Table 1.5 that Saudi Arabia and the United Arabic Emirates are having relatively better experiences than other GCC countries in terms of the capacity to exploit and implement different renewable energy generation. However, it is apparent that the focus in GCC countries is currently on solar and wind energy. This can be explained according to the basic mechanisms involved in applying these types of technologies and, as stated above, the geographical positioning, which gives them greater opportunities to benefit from high solar irradiation. Moreover, the extraordinary decline in the price of PV systems is another important factor to consider when comparing solar photovoltaic technology and other renewable technologies.

Table 1.4 Renewable Energy Targets in GCC States (Modified from El-katiri and Husain, 2014)

Country	Renewable Energy Targets
Bahrain	5% by 2020
Kuwait	1% of electricity generation by 2015; 10% by 2020; 15% by 2030 of the country electricity demand.
Oman	10% of electricity generation by 2020
Qatar	At least 2% of electricity generated from solar energy sources by 2020
Saudi Arabia	50% of electricity from non-hydrocarbon resources by 2032: 54GW from renewables (of which: 41GW from PV and CSP, 9GW wind, 3GW waste-to-energy, 1GW geothermal), 17.6GW from nuclear.
UAE	Dubai: 5% of electricity by 2030 Abu Dhabi: 7 % of electricity generation capacity by 2020

Table 1.5 Summary of existing renewable energy projects in the GCC countries (Abdmouleh et al., 2015)

Existing projects	
Saudi Arabia	• In 2010, Realization of 10 MW of the King Abdullah Initiative for desalination plant using solar-generated energy resulted in two solar plants in Al-Khafji and Al-Oyainah. • In 2011, commissioning of 500 kW pilot solar plant by the Saudi Electricity Company on the Farasan Islands, which is expandable to 6-8 MW. • In 2012, Commissioning of a solar thermal plant in an area of about 36,300 m^2, in addition to the Saudi Aramco King Abdullah Petroleum Studies and Research Center (KAPSARC) solar park in Riyadh expanded from 3.5 MW to 5.3 MW.
United Arabic Emirates	• Installation of 10 MW PV plant at Masdar City in Abu Dhabi. • 4 small-scale solar PV projects: 1 MW rooftop installation on the Masdar Institute; 291 kW PV array at the Yas Marina circuit; 204 kW PV parking shade at Masdar City; and 200 kW mounted on the Presidential Sea Palace rooftop. • 100 MW Shams 1 CSP plant, located in Madinat Zayed in Abu Dhabi, extended over an area of 2.5 km • Solar PV in Al Qarneed Island (0.75 MW) and Marawah Island (0.49 MW). • The first wind project in the GCC under construction in Sir Bani Yas Island of 30 MW capacity and will be connected to the Abu Dhabi power grid to supply 10% of Dubai's electricity needs. • The first geothermal project in Masdar City with two wells being drilled.
Qatar	• Solar testing facility located at Qatar Science and Technology Park (QSTP) in order to work on studies about solar power, air conditioning and lighting technologies suited to Qatar's buildings and climate. • Tarsheed campaign organized by Qatar General Electricity & Water Corporation (KAHRAMAA) to reduce electricity consumption. The new laws require the installation of water and electricity meters in all new buildings, as well as improving the minimum standards fir insulation in the buildings. • Opening of Qatar Solar Energy (QSE) in 2014 one of the largest vertically integrated PV module production facilities in the Middle East and North Africa (MENA) region. The 300 MW facility, located in the Doha industrial zone of Qatar, is one of the steps to achieve the goals of Qatar National Vision 2030.
Kuwait	R&D RE demonstration projects in solar pond, passive heating and cooling and PV were implemented before the Gulf War 1990. Among the current implemented projects, were: • Two projects on solar cooling. • Numerous PV systems in street lighting, traffic signs, and communication. • Thermal energy storage project to be used during peak load. • 151 kW installed solar power capacity.
Bahrain	• In 2007, installation of two 225 kW wind turbines at the Bahrain World Trade Centre providing an estimated 11-15% of the building's electricity needs. • In 2012, launching of a 5 MW solar PV project with a joint venture between BAPCO, NOGA and two U.S.-based firms, Caspian Energy Holdings and Petra Solar. • Two mobile solar plants produced by the University of Bahrain's engineering faculty, one for desalination of water, and a 1.4 kW/100 W hybrid solar/wind power generation system, as well as an experimental solar water heating system. A solar water heating system installed at Aluminium Bahrain. • A solar panel factory in Bahrain in co-operation with a Dutch company.
Oman	• In 2011, award of 7 MW solar thermal project to Glass Point Solar by Petroleum Development Oman, which aims to produce 11 tons/h of high pressure steam that will be used to extract 33,000 barrels of oil and to provide 24 h heating.

In addition, clear and flexible regulations will facilitate the processes of such types of projects in terms of time and cost which are the most important criteria which taken into account for the investors.

The primary aim of this study is to investigate the feasibility of using solar photovoltaic systems (PV) in Kuwait. The study will cover all of the allowed not-military/non-restricted sites in Kuwait, including the six Kuwaiti governorates (Al-Asimah, Al-Ahmadi, Al-Farwaniyah, Al-Jahrah, Hawalli, and Mubarak al-Kabir). In order to reuse the sites, which cannot be used for construction purposes in their natural conditions, the study will include landfill sites.

The strategy for selecting sites had to account for Kuwaiti laws, which prevent working in certain places for various reasons. For example, there are sites dedicated to the Ministry of Oil and the Ministry of Defence. In addition, the solar intensity values of different areas in Kuwait needed to be taken into account, as the study will investigate the effects of environmental and climatic conditions on the efficiency of photovoltaic (PV) systems. Although some research has already been carried out in Kuwait and GCC countries on photovoltaic (PV) energy, no study has yet investigated and analysed the effects of external loads on both the ground (soil layers) and solar tracker. The effects of using different tracking systems (fixed, single-axis, and dual-axis tracking systems) will also be investigated as the effects of using these types of solar trackers have not been examined in the GCC countries and particularly in Kuwait. The effect of using single-axis and dual axis tracking systems will be investigated in this thesis by means of the performance parameters, environmental and economic evaluation studies.

1.2 Location and Climate of Kuwait

Kuwait is a GCC country located in the Middle East, and has a population of approximately 3.96 million (Kuwaitis represent 1.24 million (31%)) (Public Authority for Civil Information (Paci), 2015). The country is situated in the north-western region of the Arabian Gulf. Some studies refer the Gulf as the Persian Gulf. In this research, it will be considered as the Arabian Gulf, and it is surrounded by Iraq on its north-west borders, and Saudi Arabia on its south and south-west borders. Kuwait lies between a latitude 28.30° and 30.05° of the North, and a longitude 46.33° and 48.30° of the East (Figure 1.7). The total area of Kuwait is around 17,600 square kilometres. It has nine islands: Failaka, Bubiyan, Miskan, Warbah, Auhah, Umm al Maradim, Umm an Namil, Kubbar, and Qaruh.

Due to its geographical location, Kuwait is characterised by a hot and arid desert climate. The temperature is within the range of 25°C to 45°C in the summer (May - September) and 3°C to 18°C in the winter (October - April); the extreme temperatures measured in summer and winter are 53°c and -3°c, respectively. The average annual total rainfall is around 118mm, and the minimum and maximum measured values are 25mm and 336mm, respectively (KISR, 2015). The main wind direction in Kuwait is north-westerly, with winds blowing from this direction for around 60% of the year. North-western winds come from the desert regions of Syria, Jordan, and Iraq before reaching Kuwait, and are characterised as hot and dry during the summer. The south-eastern winds are usually responsible for the extreme dust storms experienced in the region, which can significantly decrease visibility.

Dust storms are considered one of the main characteristics of the climate in Kuwait; they are expected to occur because of low topographic relief, scanty vegetation, light-textured topsoil, and recurring strong and turbulent winds (Al-dousari and Al-awadhi, 2012). Figure 1.8 shows the monthly average number of dust storm days in Kuwait between 2000 and 2010 and it is clear that dust storms occur more frequently between April and August. The efficiency of the solar modules is highly affected by dust particles as the accumulated dust particles will directly influence the amounts of received solar irradiation.

The ground in Kuwait slopes gradually from sea level in the east of the Arabian Gulf coastline to the west and south-west. The elevation of the south-western corner reaches 300 metres above sea level.

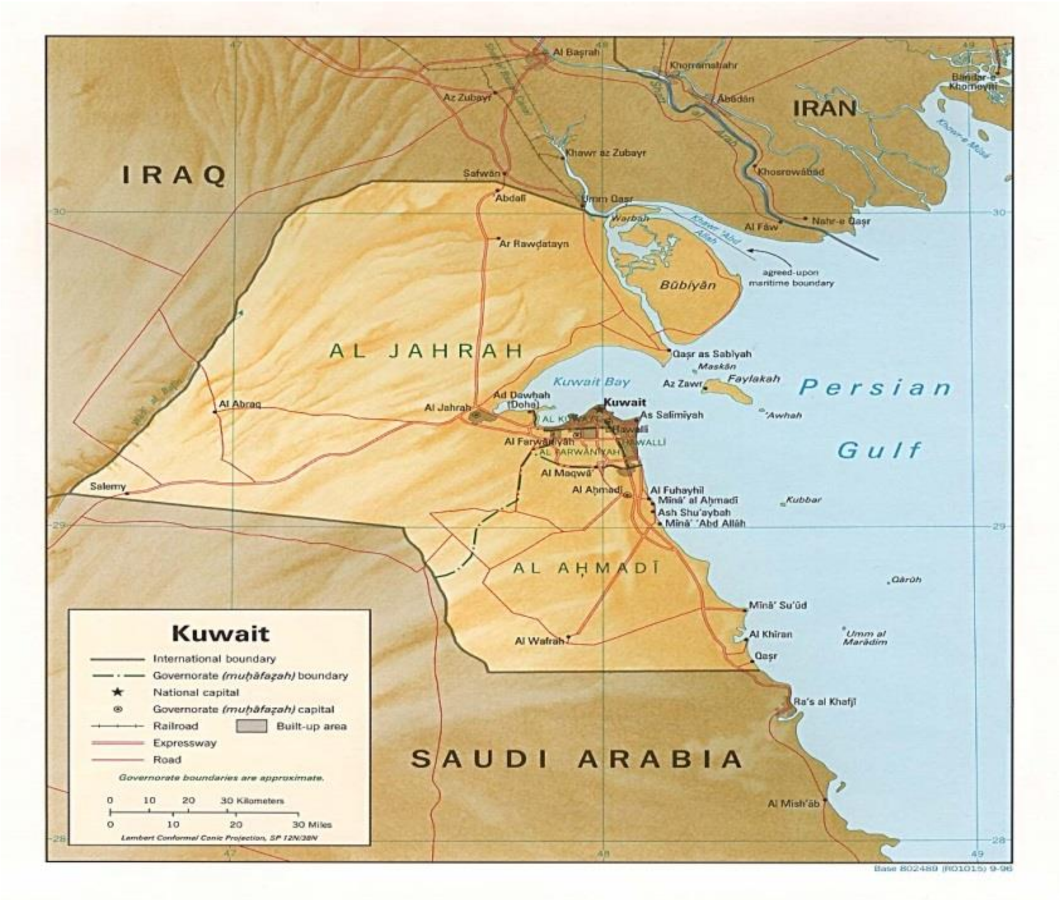


Figure 1.7 Map of Kuwait (The University of Texas at Austin, 2014)

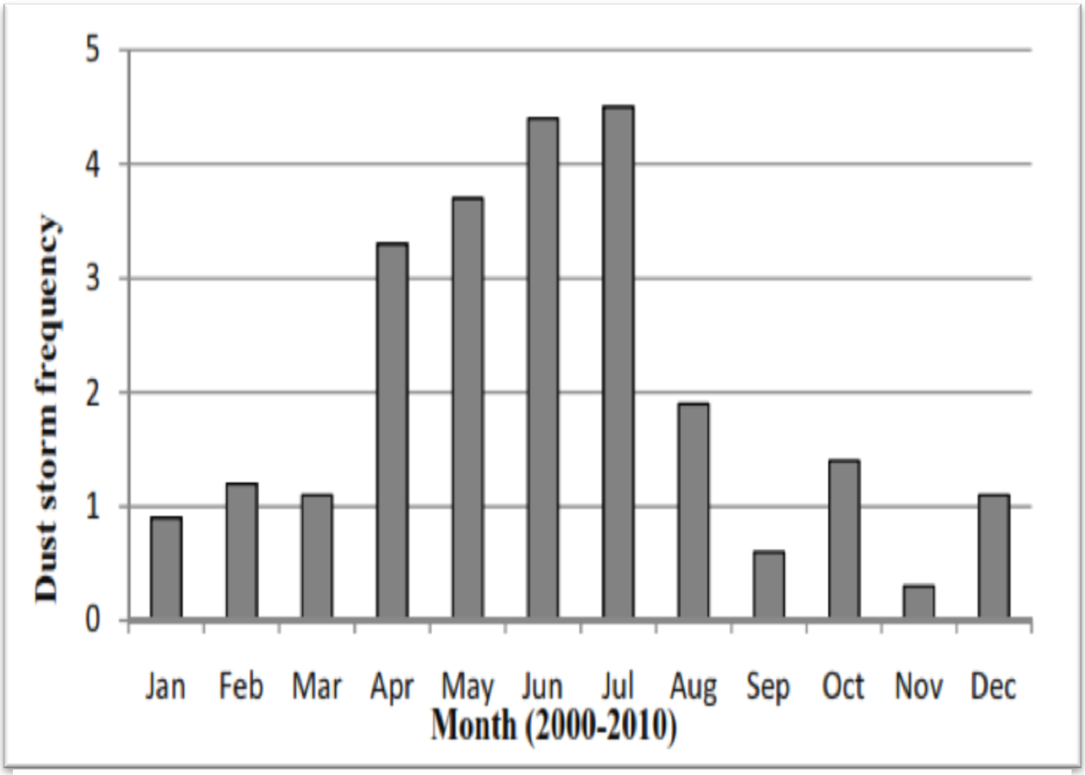


Figure 1.8 Average number of dust storm days per month in Kuwait (2000-2010) (Al-dousari and Al-awadhi, 2012)

1.3 Electricity Demand in Kuwait

Kuwait is one of the biggest oil producers in the world, and has the largest amount of oil reserves which is approximately equal to 102 billion barrels (U.S. Energy Administration, 2014). The main two resources used to generate electricity in Kuwaiti power plants are oil and natural gas. In Kuwait, the Ministry of Electricity and Water (MEW) is responsible for producing, transmitting, and distributing electricity and water. The electricity generation plants depend on both of these resources, which are controlled by the Kuwait Petroleum Corporation (KPC), which is responsible for preparing and outfitting oil to the electricity generation plants. The generation technologies used are based on 55% reheated steam, 20% non-reheated steam, and 25% open cycle gas turbines (Wood and Alsayegh, 2014).

One of the most important needs in Kuwaiti daily life is water, which is not readily available in terms of natural resources. Kuwait is classified as a poor country in terms of the availability of natural water resources, ranking 180th in the world (Darwish et al., 2008). The main water resources in Kuwait are fresh and brackish groundwater, desalinated seawater, and treated wastewater.

Wastewater is treated in wastewater plants in Kuwait, and approximately 40% of the treated water is reclaimed and used for irrigation, while the rest is discharged into the sea (Hamoda, 2001). The country is largely dependent on desalinated water; its desalination capacity is about 450 MIGD (million imperial gallons per day) using a multi-stage flash (MSF) system to produce steam that drives electric generators (Wood and Alsayegh, 2014).

The demand for electricity is increasing at a significant rate in Kuwait, especially over the last decade, which can be seen from Figure 1.9. The percentage increase in electricity consumption from 2006 to 2015 was approximately 43%, which is considered a significant increase over a relatively short period. The rate of electricity consumption in Kuwait varies throughout the year; in the summer (from May to September), electricity consumption reaches high levels, approximately double that of winter. Figure 1.10 shows the typical load profile of electricity consumption in Kuwait.

According to the latest projection profile of electricity and water demand (Figure 1.11) produced by the Ministry of Electricity and Water (MEW), there will be an approximately 230% increase (from a 2014 load of approximately 12 GW, to 28 GW in 2030), due to the expected additional loads of new residential, infrastructure, and industrial projects (Wood and Alsayegh, 2014).

In conclusion, a continuous increase in electricity consumption and predicted electricity demands has led Kuwait to reach a critical situation, the resolution of which must be carefully approached.

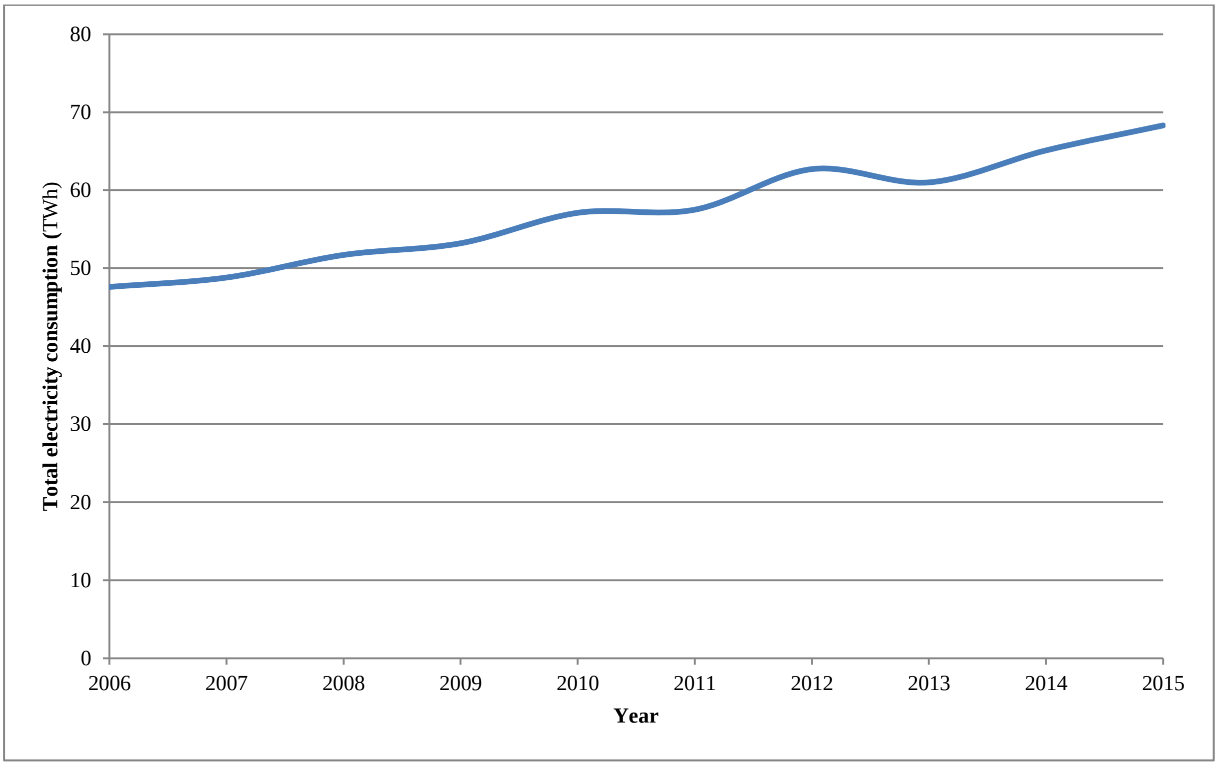


Figure 1.9 Total electricity consumption in Kuwait from 2006 to 2015 (data taken from BP Statistical Review, 2017)

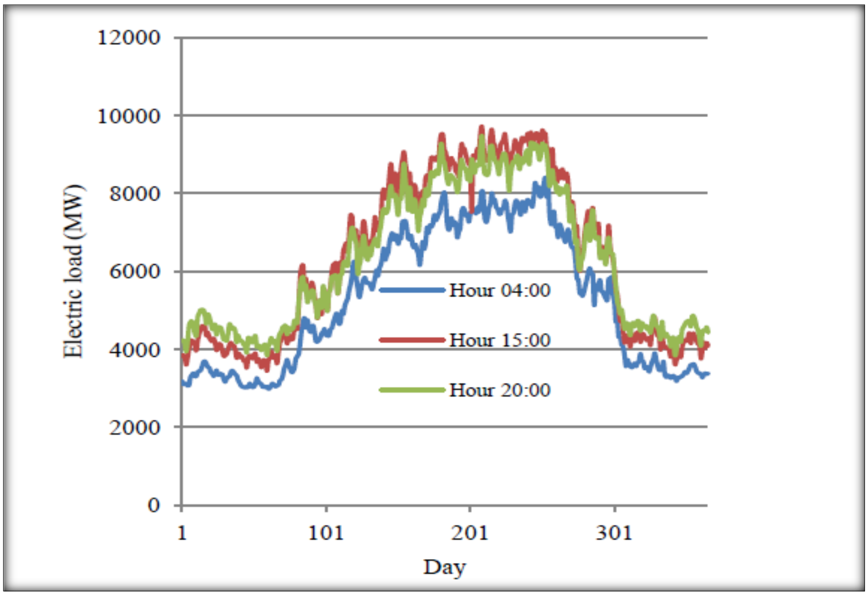


Figure 1.10 Typical load profile in Kuwait (example of 2008 load profile) (Wood and Alsayegh, 2014).

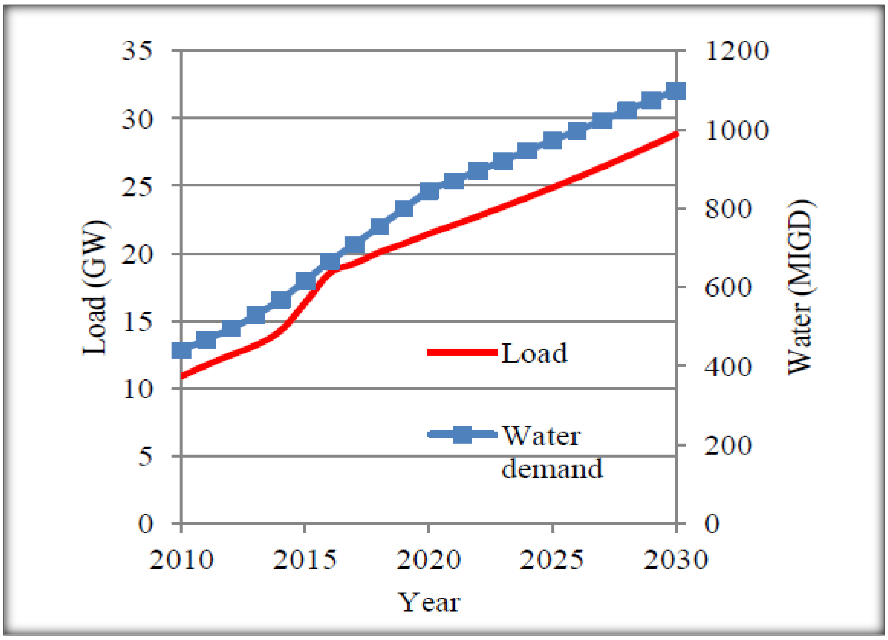


Figure 1.11 Projection profile of electricity and water demand in Kuwait (Wood and Alsayegh, 2014).

1.4 Current State of Renewable Energy in Kuwait

As stated in the background chapter, the continuing high energy demand, specifically in terms of electricity consumption, will soon lead the country to a critical situation. In order to satisfy the high demand of electricity, Kuwait will face significant challenges in terms of economic and environment issues.

The decision taken by the Kuwaiti government to be generating 15% of its total electricity need from renewable sources by 2030 is an extremely important step, and provides a benchmark and time scale for the future of renewable energy use in Kuwait. In addition to oil and natural gas, it has been identified that Gulf countries, including Kuwait, also have access to renewable, sources such as wind and solar (El-katiri, 2014). It should be highlighted here that the geographical location of Kuwait means it has high potential to take advantage of free and clean energy resources, such as wind and solar energy. As stated in the background and introduction, the high amounts of solar irradiation and the relatively long daylight hours encourage the implementation of solar energy. Likewise, the high wind speed, especially in desert areas, is another important factor that supports the use of wind energy in Kuwait.

As the suggestion to implement renewable energy in Kuwait is a relatively new one, wind and solar energy are the predominant energy resources currently under discussion, and other renewable energy sources, such as geothermal energy, have not yet been properly evaluated. This can be observed from the lack of relevant research and literature in these fields, where most of the research that has been conducted in Kuwait focuses only on solar and wind energy. Currently, this can be attributed to the lack of experience and basic information and data available on renewable energies in Kuwait, as stakeholders have hitherto been uninterested and discouraging of the renewable energy field. Table 1.6 lists the installed and upcoming RE projects in Kuwait; it can be seen that the focus is on implementing solar and wind technologies. It can be obversed also that the Shagaya Energy Park is considered as the most important projects as it include different solar and wind energy and is set to be constructed in two phases, in which the first phase a 70 MW capacity will be done and at the second phase a 2000 MW capacity will be reached in 2030.

Al Abdaliya Solar Plant is considered one of the most important RE projects in Kuwait and the GCC countries as it is aimed at applying concentrated solar photovoltaic (CPV) technology, which is considered the most advanced solar technology. However, this project has encountered many problems that have obstructed its implementation. The project has been postponed many times, and a new bid date is expected to be announced (Thienpont, 2017).

In fact, any installed and upcoming projects are based on relatively old plans, designed to enhance the use of renewable energy in Kuwait. For this reason they do not satisfy the minimum requirements for implementing efficient RE projects. For example, these projects do not include the use of tracking systems, which will have a significant effect on the amounts of electricity produced and the amount of GHG emissions avoided, as will be seen in Chapters 4 and 5. In addition, the use of tracking systems will have a direct impact on the cost of the project, as will be shown in Chapter 6.

On the other hand, the majority of the installed and upcoming projects were conducted based on relatively weak feasibility studies, which did not take into account accurate metrological data in Kuwait. This can be attributed to the lack of information and a related database detailing these technologies. One of the advantages of this research is that it will serve as a solid reference point for any future works concerning RE energy in Kuwait.

Table 1.6 Installed and upcoming RE projects in Kuwait

Project	**Energy type**	**Location**	**Capacity**	**Status**
Salmi Mini-Wind Farm	Wind	Salmi (West of Kuwait City)	2.4 MW	Completed in 2013
Shagaya Energy Park (Phase 1)	Wind, solar (thermal and photovoltaic)	Shagaya	70 MW	Completed in 2016
Shagaya Energy Park (Phase 2)	Wind, solar (thermal and photovoltaic)	Shagaya	1000 MW	Expected to complete by 2020
Shagaya Energy Park (Phase 3)	Wind, solar (thermal and photovoltaic)	Shagaya	2000 MW	Expected to complete by 2030
Al Abdaliya Solar Plant	Concentrated Solar Power	Al Abdaliya desert, south west Kabad region	280 MW	Postponed

1.5 Problem Statement and Proposed Solution

Kuwait, which is considered a rich country, has an economy that is mainly dependent on oil export revenues. Gross domestic product (GDP) and export revenues represent approximately 60% and 94%, respectively, of the nation’s total annual budget (EIA, 2014). As stated in the background and introduction to this chapter, the high increase in demand for electricity has been largely due to social and economic development, rapid population growth, and a high value gross domestic product (GDP). These factors are the primary reasons for the high electricity consumption rates in Kuwait and other GCC countries. In Kuwait, frequent electrical blackouts during the summer months is a key challenge facing the government. The Kuwaiti government is under significant pressure from parliament to resolve this issue, because the Ministry of Electricity and Water (MEW) is the sole utility provider responsible for the generation and distribution of electrical power in the country.

It is generally believed that constructing more new conventional power plants is not an appropriate way to overcome the problems in Kuwait, due to the significant variation in electrical demand between summer and winter, which is estimated as 50% and 60% (Al-Otaibi et al., 2015). In addition, constructing new conventional electricity plants will place a huge strain on the national budget, as well as generating environmental pollutants in the form of increased CO_2 emissions. International community pressure, represented by the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol, is another factor that must be taken into account. As a result, seeking a renewable energy source has become an essential task for the nation. The preference of the Kuwait government is towards using renewable energy, and this was announced by the Amir of Kuwait, Sheikh Sabah Al Ahmad Al Sabah, at the United Nations 18th Conference for Climate Change in 2012. He stated that 15% of the total energy generated in Kuwait will be derived from renewable energy sources by the end of 2030.

Finally, in terms of the diversity of energy sources, seeking alternative sources is a key strategic move for any successful country in order to preserve their natural resources, such as oil, for future generations, and to benefit from these resources in light of the high price of oil, instead of using them to generate electricity whilst there are alternative options available, such as wind and solar energy.

Solar photovoltaic energy was chosen as the renewable energy source to be examined in this study because Kuwait has a high solar energy potential. Kuwait has approximately nine hours of sunshine a day, on average, and annual solar irradiation of approximately 2100 kW/m^2/year (Ramadhan and Naseeb, 2011). This value is excellent when compared with other leading countries in solar technology such as Germany (1040 kW/m^2/year) (Sonnenenergie, 2008). The low levels of rainfall and cloud cover, as well as the large area of uninhabited desert, are also important factors affecting the use of solar photovoltaic systems. In addition, the significant price declination in PV system components, and in particular the solar modules, which represent approximately 60% of the total system cost (Feldman et al., 2012), will increase the success chances of such projects.

Solar photovoltaic energy is based on a simple mechanism that converts sunlight into electricity using solar cells; it is a promising energy source across the globe, as it is dependent on a free, clean, and sustainable fuel: sunlight. The proposed solution to the stated problems is to use solar photovoltaic systems as an alternative source of electricity generation in Kuwait, in order to satisfy the increased demand for electricity instead of constructing more conventional plants.

Utilisation of solar photovoltaic systems is likely to result in many economic and environmental benefits for the country, including:

- Reduced pressure on limited resources (oil and natural gas).
- Avoiding dependency on certain sources of energy.
- Reduced air pollution resulting from burning oil or natural gas to generate electricity in conventional power plants.
- Taking advantage of high oil prices by selling oil instead of using it in power plants to generate electricity.
- Exploitation of high solar irradiation and climate conditions in Kuwait.
- Using sites that are unsuitable for building, such as landfills.
- Economic opportunities to invest in clean and free energy.

If the proposed implementation proves successful, then it will contribute significantly to understanding the feasibility of utilising photovoltaic (PV) energy in Kuwait, not only from an economic perspective, but from an engineering perspective, by considering the ground (soil) and its behaviour under specific loads (wind and solar structure).

In terms of sustainability of land use, the sites which cannot be used for construction is another important issue; the efficient use of the sites will play an important role in preserving different areas for other works. For example, the reuse of landfill sites to generate renewable energy will enable other areas to be used for construction purposes, which is particularly important for Kuwait, which has a rapidly growing population rate (3.3%) and a remarkable increase in housing demand (Alotaibi, 2011).

In addition, in Kuwait and other GCC countries there will be a solid base of relevant and detailed information, which will provide a valuable reference for decision-makers and researchers. This can then be used to better understand the applications of solar energy, as well as providing the results for loads following the installation of photovoltaic systems, such as for the mounting structure and solar modules.

1.6 Research Aim and Objectives

The aim of this research is to assess the feasibility of using solar photovoltaic (PV) systems in Kuwait as a promising renewable energy source.

In order to achieve this, the following objectives have been set:

1. To review the state of photovoltaic (PV) energy in the Middle East, particularly in GCC countries (with a particular focus on Kuwait).
2. To assess & investigate the performance parameters of the proposed PV systems.
3. To assess the economic effects & benefits of PV systems.
4. To assess the impact of the PV systems on the environment.
5. To ensure the proposed PV systems is structurally safe under different surrounding loads and surrounding conditions.
6. To make recommendations regarding the feasibility of photovoltaic (PV) energy generation and use in Kuwait.

1.7 Organisation of the Thesis

In this thesis, the detailed work carried out for the study will be presented in eight chapters. The current chapter has provided detailed background information on the need for renewable energy in the world, and in particular in GCC countries and Kuwait. The rationale for the research and background details has been presented. The problem to be addressed has been identified, and the proposed solution outlined. The study aim and objectives have been delineated, and the forthcoming contents of this thesis presented. The nature of the electricity demand in Kuwait and the main problems related to the use of fossil fuels, as well as the proposed solution (PV) and its expected impacts have been outlined.

Chapter two will review the common renewable energy sources, and introduce previous studies of solar photovoltaic energy, including a discussion of the most common evaluation criteria used in feasibility studies of solar photovoltaic energy.

Chapter three will describe the methodology used in this research. It will explain the strategic methods that have been implemented in the site selection process, and the data acquisition phase. The main feasibility elements (performance, environmental, and economic, as well as numerical modelling) considered in this research will be presented.

Chapter four will focus on a performance parameters evaluation of the proposed PV systems in Kuwait. The results obtained will then be presented and discussed in detail.

Chapter five will consist of an environmental evaluation study, including a Life Cycle Assessment (LCA) as well as an explanation of the environmental benefits of utilising PV systems in Kuwait.

An economic evaluation of using PV systems in Kuwait will be presented in Chapter six. An economic assessment, cost-benefit analysis, and the cost of the CO_2 saved by implementing PV systems in Kuwait will be presented and discussed in this chapter.
Chapter seven will describe the numerical modelling of the proposed solar tracker. The analysis and discussion of the results will be presented in this chapter.

Finally, the conclusions drawn from the study findings, and recommendations for further research will be given in Chapter eight.

Chapter 2 – Literature Review

2.1 Introduction

This chapter talks about renewable energy, explaining why its use is increasingly being considered essential. It also identifies the most common types of renewable energy: wind, hydro, geothermal, biomass, and solar in Section 2.2. A review of photovoltaic (PV) technology & research in this area is conducted in section 2.3, providing information about the PV system, modules, inverter and balance of system (BOS). Section 2.4 presents previous work on photovoltaic System in the Middle East. The commonly used evaluation indices in implementing PV Systems are introduced in Section 2.5. The conclusions are presented in Section 2.6.

2.2 Renewable Energy

Renewable energy resources are required to effectively deal with high global energy demand. This demand is a result of fast population growth and economic development, as well as increased greenhouse emissions, which are caused by a high consumption of fossil fuels. Furthermore, renewable energy is considered a clean, free, and sustainable part of a country's energy policy.

In the 1990s, there were significant changes in energy policy worldwide due to economic, environmental, security, and social concerns, as well as energy regulation. These changes greatly contributed to encouraging the use of renewable energy sources (Beck et al., 2004). Renewable energy is expected to play a major role in providing sustainable energy to the large numbers of people in developing countries who have no current capacity to utilize clean energy (Painuly, 2001). Moreover, renewable energy such as solar and wind can be used as important alternatives to fossil fuels, to overcome environmental problems (Komor, 2004).

The use of renewable energy is growing remarkably. In 2010, around 16.6% of the world's total energy consumption was derived from renewable energy sources. This represents an increase of 22% between 2000 and 2010, and a further increase by more than 42% is expected during the period 2010 to 2020 (Panwar et al., 2011). Three of the world's leading countries responsible for renewable energy generation are Denmark, Germany, and the United Kingdom. These countries provide a good example of the policy design and are responsible for the proper use of regulations, which play an important role in achieving successful goals (Lipp, 2007).

Renewable technologies differ in terms of economic feasibility and technical use, and they are highly dependent on the environment and the location in which they are to be implemented (Gross et al., 2003). The most common renewable energies, such as wind, hydro, geothermal, biomass, and solar, are presented in the next section.

2.2.1 Wind Energy

Wind is a renewable energy source that is used to generate electricity. Turbines harness power from the wind by converting kinetic energy into mechanical energy. The wind power market has increased yearly by an average of 28% from 2001 to 2011 (Zhao et al., 2013). At the end of 2016, the entire installed wind power capacity was 12.49% higher than at the close of 2015. In 2016, more than 90 countries used wind power, and global annual installed wind capacity was more than 54.600 MW at the close of 2016 (Global Wind Energy Council (GWEC), 2016).

According to the GWEC, almost 486.75 GW of installed wind capacity is located in Asia, whereas Europe had 161.33 GW and North America had 97.61 GW of wind power installed at the end of 2016. Global wind power capacities have been calculated as follows: Asia (41.84%), Europe (33.14%), and North America (20.05%). These percentages indicate that Asia’s wind power usage is increasing at a rapid pace that might place it in the top rank of global use of the energy source.

China, the United States, Germany, India, and Spain are the top five countries in terms of total capacity or energy generation (REN21, 2014). At the end of 2016, they contributed more than 72.5% of the installed wind power capacity worldwide. Table 2.1 demonstrates the installed capacity and share of global wind capacity of these countries in 2016. The table shows that China used the highest capacity of wind power by an amount of 169 GW, which represents about 34.7% of global wind power usage.

The largest offshore wind farm in the world is Walney Wind Farm in the United Kingdom, which has a capacity of approximately 367 MW. China has two offshore wind farms with a total capacity of 232 MW, and aims to install 30 GW offshore wind farms by 2020 (IRENA, 2012).

Table 2.1 Installed capacity and share of global wind power in 2016 (data taken from GWEC, 2016).

Country	**Wind power capacity (GW)**	**% Share of global wind power**
China	169	34.7
United States	82,184	16.9
Germany	50,018	10.3
India	28,700	5.9
Spain	23,074	4.7

2.2.2 Hydro Energy

Hydro energy is a source of renewable energy, which depends on the movement of water through turbines, as when water runs through turbines at the site of a dam. At the end of 2016, global hydroelectricity energy production was about 3500 TWh, contributing about 16.4% of the world's electricity and 71% of the world's renewable electricity (Word Energy COUNCIL, 2016). There are around 160 countries worldwide that use this technology to produce electricity (Word Energy Council, 2016). Word Energy Council states that the total global hydropower energy was around 1,064 GW in 2016. Table 2.2 clearly demonstrates that China has the highest global hydrostatic power usage, with an amount of 1,126 TWh (26%). In addition, it can be observed that four countries combined (China, USA, Brazil, and Canada) comprise approximately 48% of the world's total use.

Table 2.2 Hydroelectric generation status in 2016 (data taken from Word Energy Council, 2016)

country	**Production (TWh)**
China	1,126
USA	250
Brazil	382
Canada	376
India	120
Russia	160

2.2.3 Geothermal Energy

Geothermal energy is a renewable resource drawn from the Earth's natural heat, in which steam taken from below the Earth's surface runs turbines that generate electricity. Geothermal energy piles are another commonly used technique in geothermal technology. it is basically rely on the fact that ground temperatures at shallow depths below the earth surface is constant throughout the year and therefore steel piles could be used as a heat exchangers (Faizal et al., 2016).

In 2013, the total global capacity of geothermal energy use was approximately 11.765 GW, and it is expected to reach 20 GW in 2024 (Pazheri et al., 2014). The countries with the highest installed geothermal power capacities are the United States, the Philippines, Indonesia, Mexico, Italy, New Zealand, Iceland, and Japan (Figure 2.1). It can be observed that the United States uses the largest amount, at around 3.389 GW (28.88%), and the above countries combined (excluding the USA) contribute around 7.19 GW (61.44%) of the world's total capacity, while the combined geothermal energy capacities of all eight countries contribute around 10.579 GW (89.92%) of global capacity.

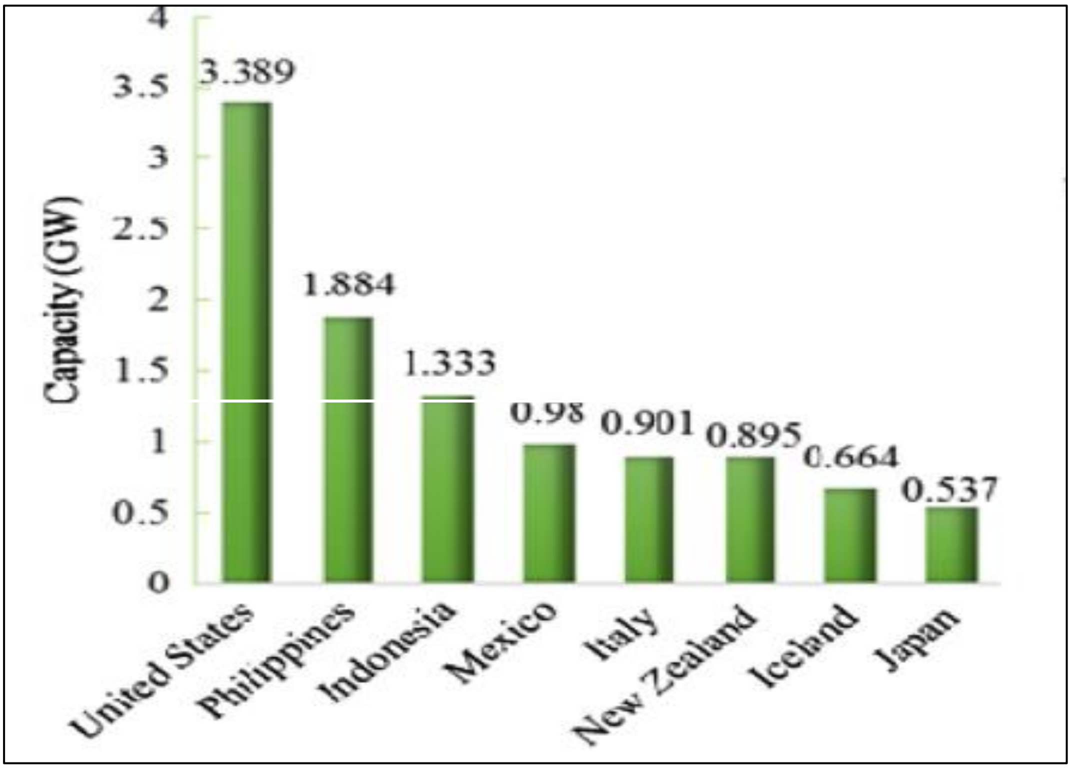


Figure 2.1 Global geothermal power status (Pazheri et al., 2014)

2.2.4 Biomass Energy

Biomass energy is ranked number four in the sources of world energy demand. It is produced by burning biomass resources to generate heat. The most common materials used to produce biomass energy are wood products, crops, dried vegetation, and some rubbish (Figure 2.2). It is estimated that most of the current biomass demand is used for heating and cooling purposes, while the resource makes up approximately 10% of overall energy supply worldwide. Over the last two decades biomass energy has become a widely used renewable source of energy due to its low costs. It makes up around 15% of the world's total energy supply (35% in developing countries) for cooking and heating purposes (Pazheri et al., 2014). In 2012, the largest biomass plant in the world was constructed in Poland, with a total capacity of 200 MW, and about 410 MW biomass power generation has been installed in the United States.

According to REN21 (2012), the global operating biomass capacity was around 72 GW at the end of 2011, with most global biomass plants existing in Europe and in North and South American countries. On average, around 90% of biomass power is produced from solid biomass fuels with that figure being slightly lower (80%) for European biomass energy (IRENA, 2012). Figure 2.3 shows global biomass power capacity at the end of 2011 and it can be seen that Europe has the highest amount (26.2 GW).

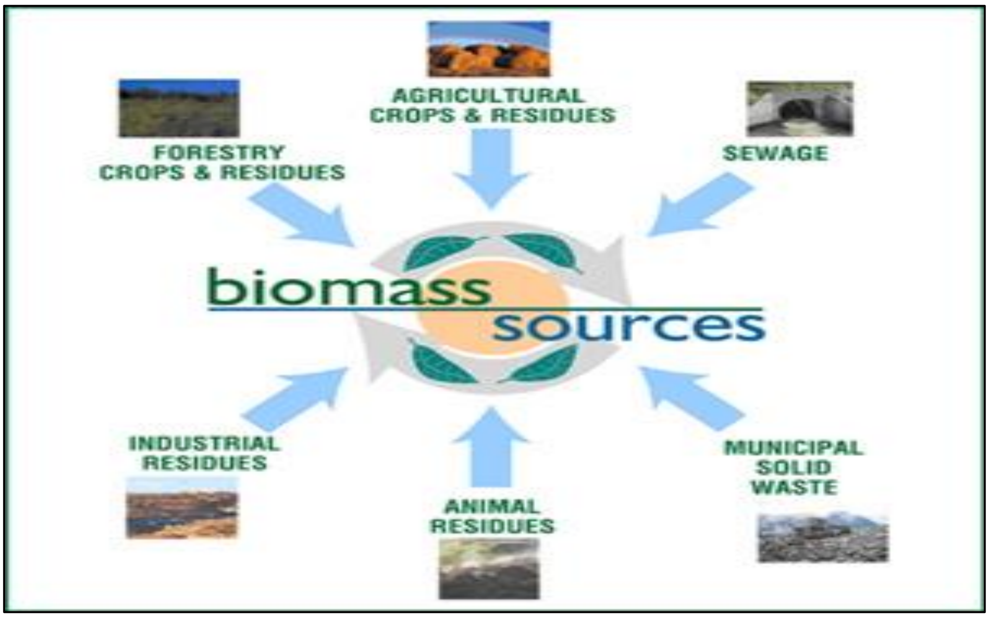


Figure 2.2 Biomass Sources (Zafar, 2015)

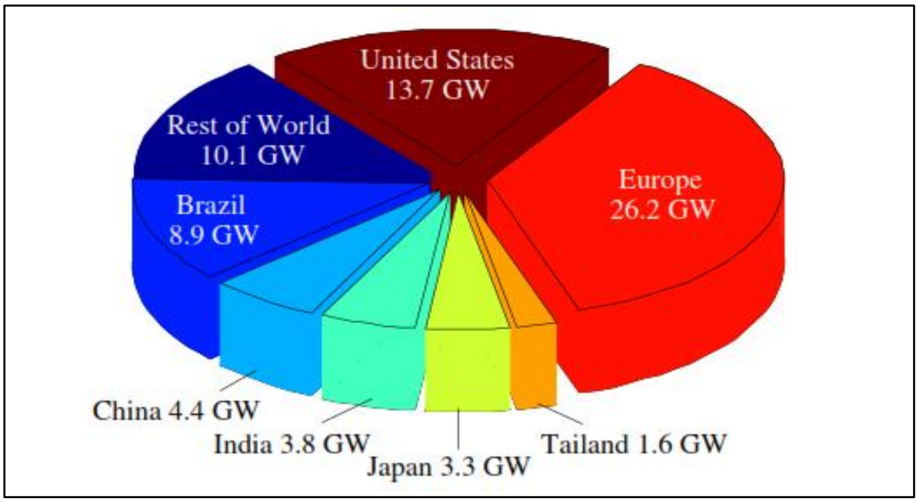


Figure 2.3 Global biomass power capacity in 2011 (Pazher et al., 2014).

2.2.5 Solar Energy

Solar energy is a free and clean renewable source of energy that is generally considered environmentally friendly. It is based on collecting energy from the sun's radiation to generate electricity, either by a solar photovoltaic (PV) systems– in which solar panels are used to collect solar radiation and convert it directly to electricity – or by using a concentrated solar power system (CSP), where solar radiation is collected and then concentrated to heat a liquid used to produce electricity.

Electricity production using solar energy is increasing rapidly in every region around the globe. It is estimated that global demand for CSP systems will be around 7% and 25% by the years 2030 and 2050, respectively (Pavlovic et al., 2012). The United States of America, Spain, the United Arab Emirates, India, and China are the top five countries for installed capacity (REN21, 2012).

Photovoltaic is one of the fastest developing technologies, with a growth rate of 35%-40% per year, and the global cumulative installed capacity of PV plants in 2013 was 138.9 GW. European countries have the biggest amount of installed capacity and China has the largest amount of PV cell production (Green, 2007; Tyagi et al., 2013).

In the last decades, the installed capacity of solar plants has increased at a very high rate (Figure 2.4). In 2012, Europe had the largest amount of installed photovoltaic (PV) systems at around 17 GW, while the rest of the world had approximately 13.9 GW.

It is estimated that the cumulative capacity installed in Europe in 2012 reached more than 70 GW (European Photovoltaic Industry Association (EPIA), 2013). Table 2.3 lists the top 10 grid-connected countries with PV installed in 2011 and 2012. From this, it is clear that China increased its installed capacity significantly, by 127%: from 2.2 GW in 2011 to 5 GW in 2012.

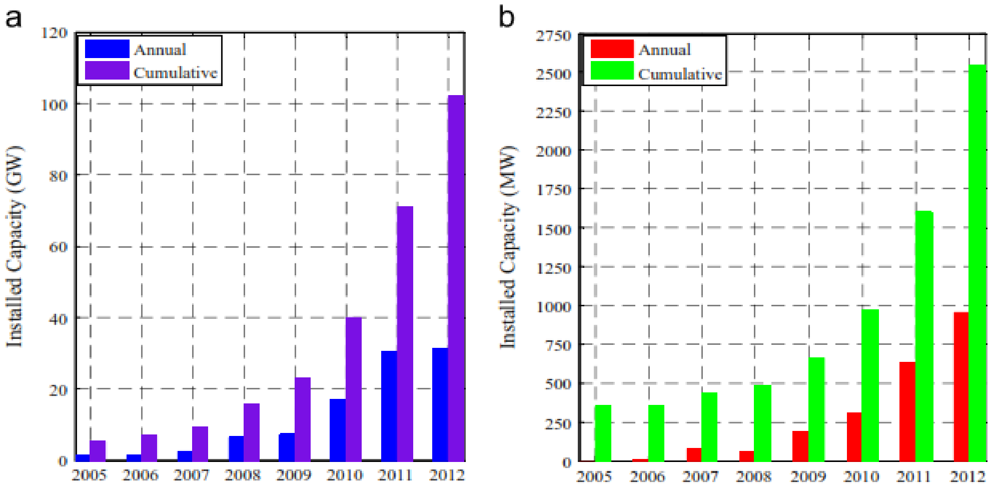


Figure 2.4 Global annual and cumulative installed capacities of solar plants (2005-2012). (a) PV plants and (b) CSP plants (Pazheri et al., 2014).

Table 2.3 Top 10 grid-connected PV installed countries in 2011 and 2012 (Pazheri et al., 2014)

countries	**Installed capacities (GW)**	
	2011	**2012**
Germany	7.484	7.604
China	2.2	5
Italy	9.284	3.438
USA	1.855	3.346
Japan	1.296	2
France	1.671	1.079

2.2.6 Types of Renewable Energy in GCC Countries

Besides the fact that implementing renewable energies as an alternative source for producing energy will reduce GHG emissions, the use of renewable energies is considered as an important step toward creating a solid economic growth for any country using free and sustainable resources (Abdmouleh et al. , 2015).

Although the GCC countries have started applying renewable energies, there is a clear variation in the level of the adoption of renewable energy technologies between these countries. This variation in implementing renewable energy technologies in GCC countries is mainly attributed to the policy transfer methods applied in each country (Atalay et al. , 2016). Despite that the GCC countries are characterized by harsh climate weather and vulnerable to high temperature in summer and frequent dust storms, which is negatively affecting the performance of such renewable technologies such as solar and wind technologies, the GCC countries are keen to investing in renewable energies (Abdmouleh et al. , 2015).

As stated in Chapter 1, due to the geographic locations of the GCC countries and willingness to invest in renewable technologies to gain environmental and economic benefits, these would positively increase the chances of successes of such types of technologies. However, it can be seen that the focus is primary on only two main technologies (solar energy and wind energy). These technologies have been widely utilised in all GCC countries and that could be explained to their high potential in GCC countries. The geographic locations of the GCC countries give them high potential to gain energy from solar and wind energy which is estimated around 6 kWh/m^2/day for solar irradiation and approximately more than 1,400 h/year of wind (Alnaser and Alnaser, 2009).

In Kuwait, there is a high potential to utilise the Concentrated Solar Power (CSP) and Photovoltaic Systems (PV systems) due to the high amounts received of solar irradiation which have been estimated as 2,100 kWh/m^2/year and 1,900 kWh/m^2/year for the direct normal irradiance and global horizontal irradiance, respectively (Bachellerie, 2013). However, it should be noted here that CSP technology requires high amounts of water for cooling purposes as well as cleaning mirrors; this would be considered as a main barrier of implementing this technology as Kuwait and other GCC countries suffer from the scarcity of water (Gastli, 2014).

On the other hand, Concentrated Photovoltaic (CPV) is considered one of the most advanced technologies in solar energy. CPV systems collect direct solar irradiation and concentrate it on solar cells using optical devices, such as lenses and mirrors (Khamooshi et al., 2014). A high level of efficiency (38.9%) has been achieved through the use of the CPV technology (Messenger and Abtahi, 2017). Although CPV systems have reached a high level of efficiency for converting solar irradiation into electricity, they are still considered expensive compared to PV systems. Moreover, the performance of such technology has not yet been examined in the context of GCC countries.

An important advantage of utilising CPV systems is that a high amount of solar irradiation can be focused onto a small area of the used solar cells; however, this type of technology requires a high amount of direct solar irradiation (minimum of 2000 kWh/m^2/year) in order to perform effectively (Messenger and Abtahi, 2017). Moreover, CPV systems are highly sensitive to high temperatures and dust particles, which cause a significant drop in system efficiency. This point is important to consider for hot and arid desert climates as occur in Kuwait and other GCC countries.

Overall, other renewable technologies, such as geothermal and hydropower, are not very well investigated, as there is a lack of basic information about these technologies, as is easily realised from the dearth of literature. As mentioned previously, the high solar irradiation in Kuwait (2100 kW/m^2/year), relatively long hours of sunshine (nine hours per day), low level of rainfall and cloud, combined with the fall in the price of PV systems, would be considered a main motivating factor when utilising PV systems in Kuwait.

The focus of this research will be on investigating the use of photovoltaic technology as an alternative option to meet the rising demand for electricity in Kuwait. This research will be a benchmark for any future work concerning PV systems in Kuwait and other GCC countries and it will also inform on-going research into wind energy.

2.3 Photovoltaic (PV) Technology

2.3.1 Introduction

There is no doubt that continued growth of electricity demand worldwide will cause a variety of serious problems. For example, it will increase the use of energy resources such as fossil fuels, which will cause high amounts of greenhouse emissions (such as carbon dioxide) and increase the complexity of environmental pollutants that threaten the world in many different ways, such as global warming.

Recently, a global focus has emerged on the efficacy of using renewable technologies to generate electricity instead of conventional power plants, or in parallel with them to satisfy energy requirements. PV energy is one of the most promising technologies and has grown at a remarkable rate. Table 2.4 shows the advantages and disadvantages of using photovoltaic systems. The technology depends on sunlight which the PV panels convert into electricity (Sonnenenergie, 2008).

The sun – the source of solar energy – provides energy in the form of radiation. Due to the long distance between the Earth and the Sun, only a small proportion of the Sun's radiation hits the Earth's surface. However, it is estimated that the amount of energy that reaches the Earth’s surface is about 10,000 times the world’s energy consumption. Therefore, it is clear that only a tiny amount (around 0.01%) of the energy from sunlight would be needed to meet global energy demands (Sonnenenergie, 2008).

Table 2.4 Advantages and disadvantages of using photovoltaic systems (Duffie and Beckman, 2013; Messenger and Abtahi, 2017; Sonnenenergie, 2008)

Advantages	**Disadvantages**
Environmentally friendly	Efficiency is highly affected by climate conditions
No noise	High initial costs
Operates even in cloudy weather	Large area needed for large scale applications
Long lifetime	Additional appliances are required (inverter, battery)
Minimal maintenance requirements	Cannot operate without sunlight

Solar irradiance (sunlight) which reaches the Earth's surface is comprised of two shortwave radiations, Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI) (Figure 2.5). The total amount of shortwave radiation received is called Global Horizontal Irradiance (GHI). The GHI, which is the sum of DNI and DHI, is the most important parameter in photovoltaic technology when calculating PV electricity, while Direct Normal Irradiance (DNI) is most important in concentrated solar power (CSP) and concentrated photovoltaic systems (CPV). It is generally accepted that DNI reaches the Earth's horizontal surface without any loss, while DHI reaches the Earth's surface after scattering or absorption by air molecules, aerosol particles, cloud particles, or other particles.

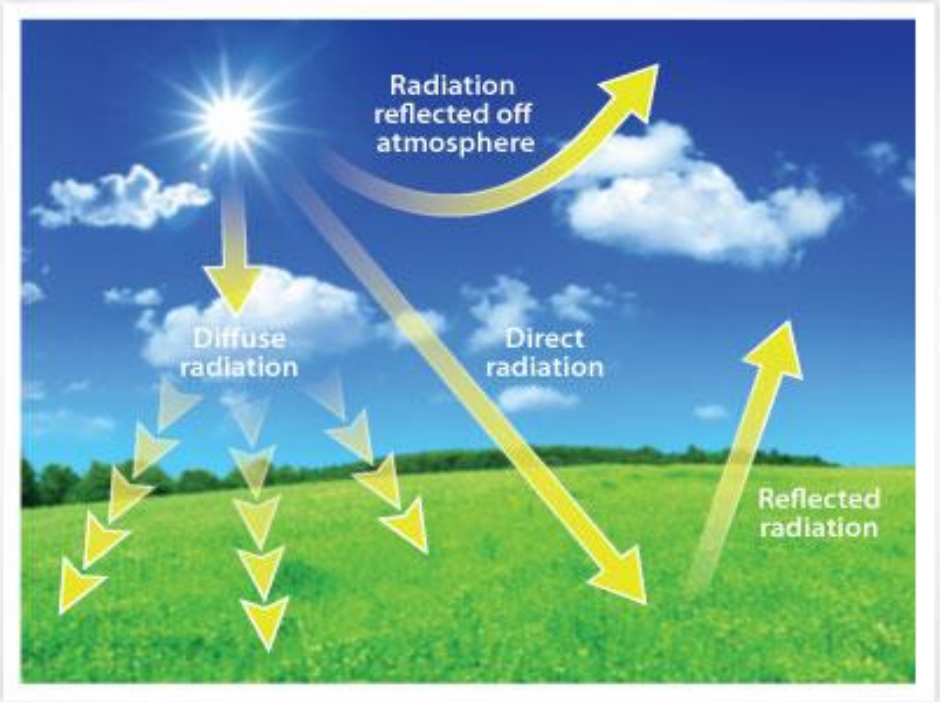


Figure 2.5 Solar Irradiance from sun (National Vet Content, 2015)

PV technology consists of three different systems: stand-alone, grid-connected, and hybrid (Figure 2.6). It is classified based on the method of use and implementation. In stand-alone systems, additional storage systems (batteries) are needed, while grid-connected systems do not require batteries because the electricity generated is simply feeding into the general grid or loads directly. Hybrid systems are implemented when the PV technology is supported by an additional power source, such as wind or a diesel generator.

In cold weather countries, most electricity consumption occurs in the evening and especially in winter, whereas hot weather countries consume most electricity in the morning and afternoon, especially in summer. The peak energy production of grid-connected systems occurs at the same time as peak demand for hot countries.

Kuwait is characteristic of a hot weather country, thus this study proposes that the grid-connected system would be implemented. This kind of systems is considered as cost-effectiveness as it feeds the grid with produced electricity directly, in other words, there is no need to use storages systems (batteries) and that will save a lot of money. The basic components for all the PV types are PV modules, an inverter and a balance of system (BOS) (Figure 2.7).

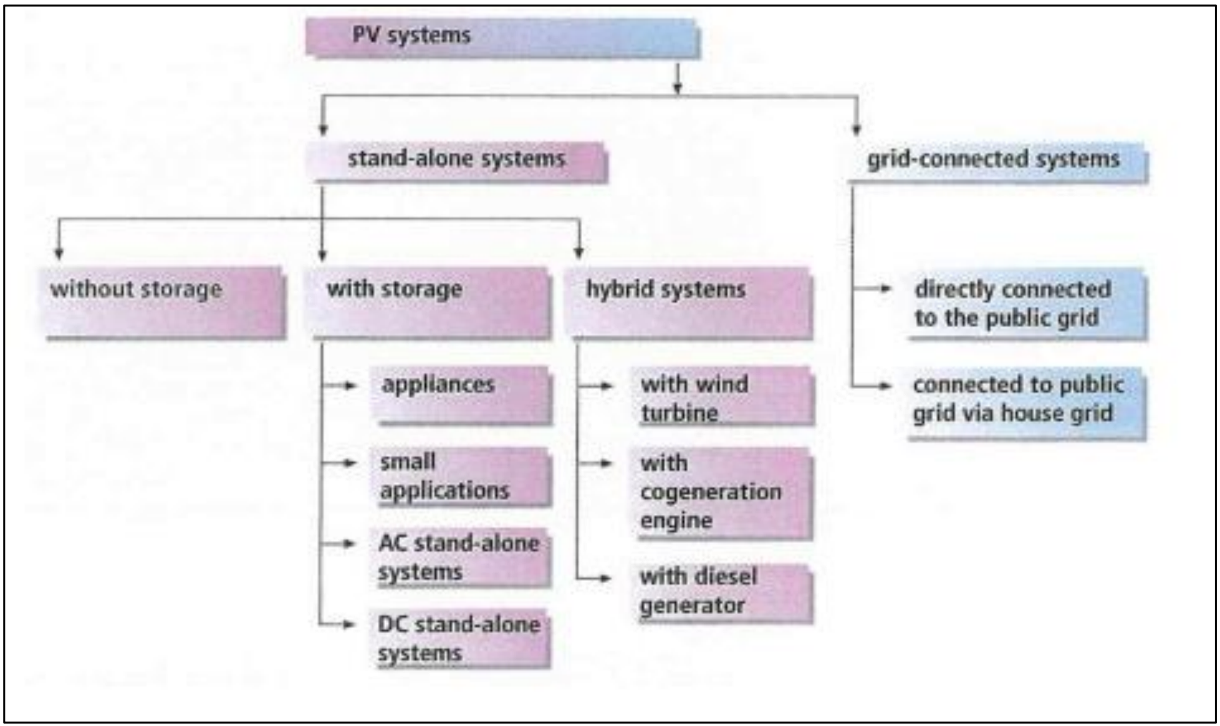


Figure 2.6 Types of PV systems (Sonnenenergie, 2008)

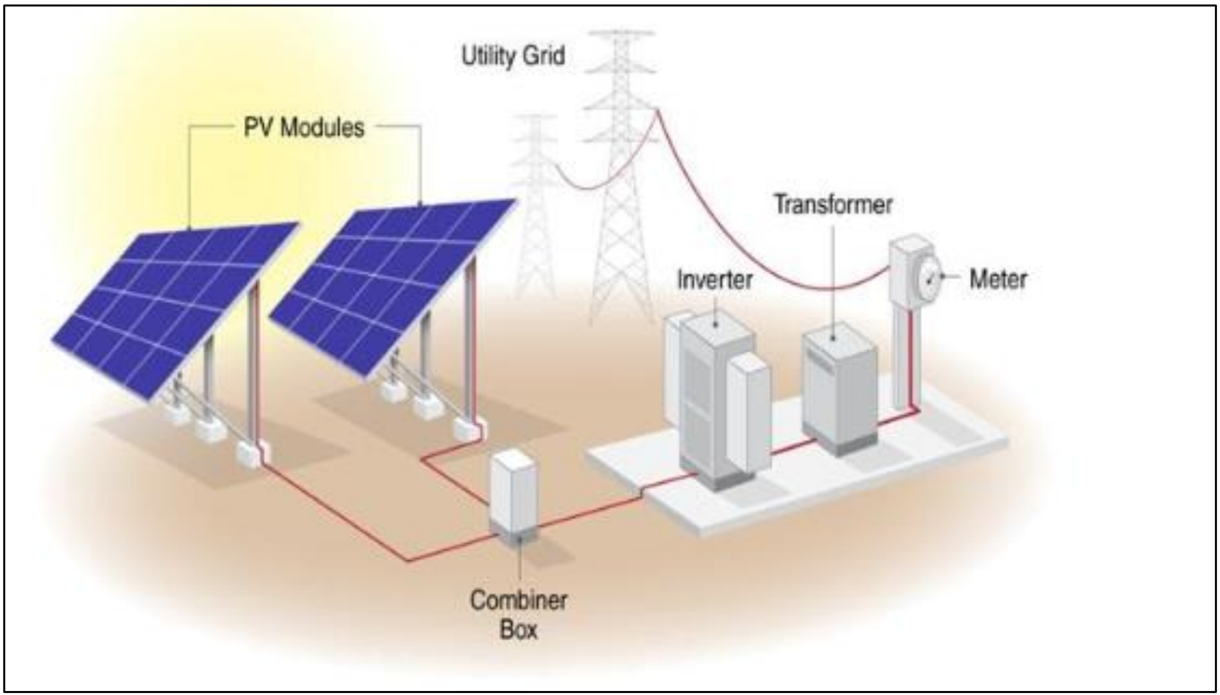


Figure 2.7 Basic components of PV systems (Olis et al., 2013)

2.3.2 System Components

2.3.2.1 PV Modules

PV panels (also known as PV modules) are the most important element in PV technology, as they receive the solar radiation and convert it to electricity. In the most standard production design, each panel consists of 36 cells. One of the main characteristics of PV modules is their efficiency. This is calculated as the ratio between the total electricity generated and the amount of irradiation on the modules' surface in standard test conditions (STC). Here, the temperature of a module is 25°C, the irradiation is 1000 W/m^2, and air mass (AM) is equal to 1.5 (Wirth, 2013).

Crystalline silicon (mono-crystalline or poly-crystalline) and thin film are the most common materials used in PV technology in different fields (commercial and utility-scale projects) (Olis et al., 2013). The efficiency of crystalline silicon PV modules varies between 12% and 19%, and is significantly affected by several parameters such as temperature and shade (Mekhilef et al., 2011; Nagae et al., 2006; Sanchez Reinoso et al., 2010). The efficiency of a thin-film solar module, which is formed from amorphous silicon, is lower than that of crystalline cells, at around 6% to 12% (Olis et al., 2013). Table 2.5 shows current commercial module efficiency.

The standard warranties for most PV modules are 80% of the system's power production for 25 years. After this, the PV modules will continue generating electricity but at lower performance values (Olis et al., 2013).

Table 2.5 Commercial module efficiency (Boxwell, 2015; Duffie and Beckman, 2013; Messenger and Abtahi, 2017; Sonnenenergie, 2008).

Technology	**Commercial Module Efficiency**
Crystalline Silicon	
Polyrystalline silicon	13-18%
Monocrystalline silicon	15-24%
Thin film	
Cadmium Telluride (CdTe)	8%
Amorphous Silicon (a-Si)	6%
Alloys of copper indium gallium diselenide (CIGS)	8%
Concentrated Photovoltaic (CPV)	20-43%

2.3.2.2 Inverter

As mentioned previously, a solar module is the main component in the photovoltaic system because it generates electricity by converting the received solar irradiation into direct current (DC). Most electricity used in buildings or even the connected grids is an alternating current (AC). As a result, electricity generated by solar modules must be converted from DC to AC, and the inverter is responsible for this operation.

Inverters are a vital part of photovoltaic systems and have three important functions. Firstly, the conversion from DC to AC. Secondly, inverters enable solar modules to harness all the available amount of solar radiation by using the maximum power point tracking technique (MPPT). This technique is used to allocate the point, at the voltage-current graph, at which the PV system produces the maximum power (Reza et al. , 2013). Thirdly, in line with safety standard UL 1741 and system intersection standard IEEE 1547 (Underwriters Laboratories INC, 2010), it is required that all inverters used for grid connection must disconnect from the grid if the AC line voltage or frequency values are not within the standard range limits (Ted, 2011).

2.3.2.3 Balance of System (BOS)

The third component of the photovoltaic system is a balance of system (BOS), which includes a mounting system and all technical and electrical parts. The mounting system, a structure holding the PV modules, is used to install and orientate the PV modules in the optimal direction in order to obtain the largest amount of energy from the Sun. It can be installed on a fixed-tilt or tracking system (Olis et al., 2013).

A tracking system is generally used to increase the amount of solar radiation received annually, and it is estimated that PV modules can obtain 30%-40% more solar irradiation than fixed tilt mounting systems (Bayod-Rujula et al., 2011). In other words, tracking systems will enable solar modules to be kept perpendicular to the solar irradiation as the sun location is varying throughout the day (Eldin et al., 2016). A 30% increase of the produced energy have been achieved as result of applying dual-axis tracking systems in a study conducted by Eke and Senturk (2012). However, sun-tracking systems require bigger and deeper footings because they are heavier than fixed tracking mounted systems (Sampson, 2009).

Moreover, the initial and running cost of such tracking systems is another important factor which should be taken into account. This is mainly due to the basic principle of tracking systems that relies on the movement of solar modules to follow the optimum position as well as the frequent maintenance of the solar trackers, particularly the moving parts.

There are two main different tracking systems; a single-axis tracking system in which the solar tracker could have vertical or horizontal rotation in one direction, or the dual-axis tracking systems, which rotate in two directions (see Figure 2.8).

In this research, the utilisation of single-axis and dual-axis solar trackers will be considered and an investigation of their effectiveness on the performance of the proposed PV systems will be conducted in terms of performance, environmental and economic evaluations, in Chapters 5 and 6. Furthermore, the behaviour of these trackers against the external loads will be investigated by means of numerical modelling in Chapter 7.

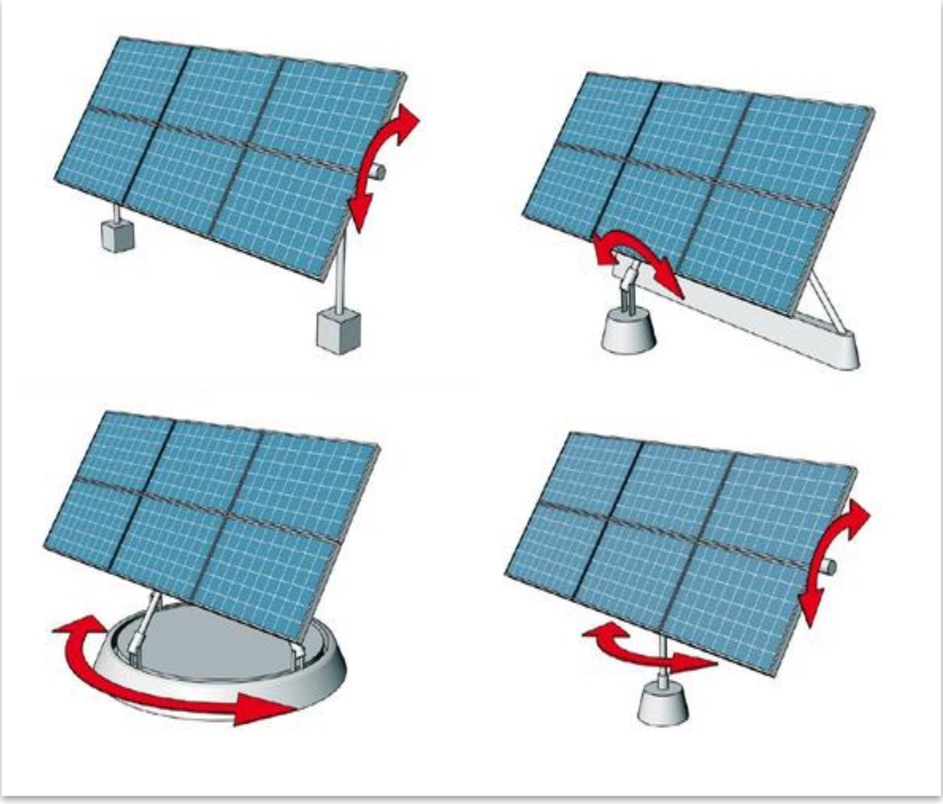


Figure 2.8 Different tracking systems (Nithya, 2017)

2.3.3 Factors Affecting Module Performance

The most important characteristic of the modules used in photovoltaic systems is their efficiency. Despite the fast growth and development of photovoltaic technology, focus remains on increasing the efficiency of solar modules in terms of manufacturing materials and design parameters. However, there are other important factors (Figure 2.9) that must be taken into account. Location, climate, type of tracking system and ground properties are elements that directly affect solar module efficiency. Selecting an appropriate location for a photovoltaic system is an important step towards harnessing high levels of solar radiation, which increases the chances of creating energy. It is highly recommended that the selected location of the proposed PV systems should not have a history of environmental disaster, such as flooding, high winds, snow, and extreme temperatures. Marion et al. (2014) studied the energy output of PV modules for three different locations (Florida, Oregon, and Colorado). They found that there is a remarkable variation in energy production caused by site differences. Climate conditions such as temperature, wind, humidity, and dust are the most common influential elements.

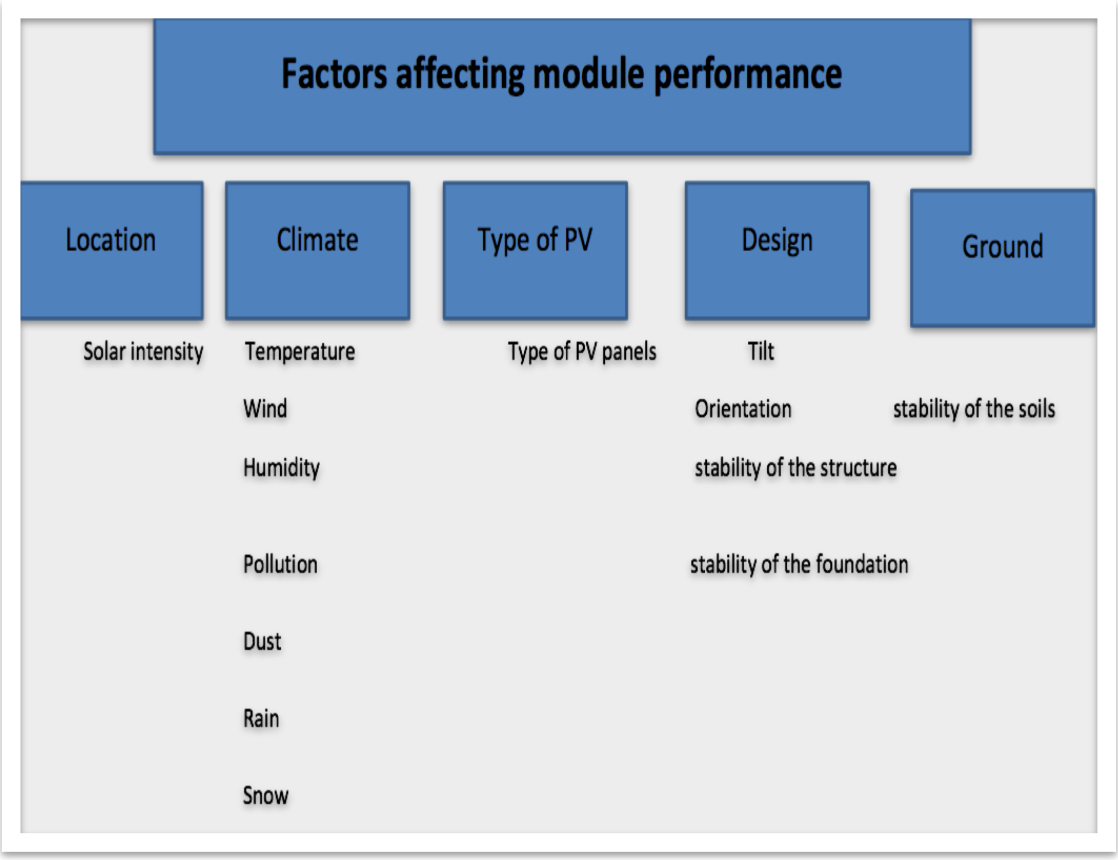


Figure 2.9 Factors affecting module Performance

Kaldellis et al. (2014) studied the impact of temperature and wind speed on the efficiency of PV installations in Greece. They found that temperature has a significant influence on the process whereby PV modules convert the received solar radiation into electricity. Solar module performance decreases as temperature increases. Thus, the efficiency of PV modules depends on the operating temperature (Dubey et al., 2013; Meneses-Rodríguez et al., 2005).

Dabou et al. (2016) investigated the performance of a 1.75 kW grid-connected PV system installed in Algeria. Data was collected over one year (2010), which was reported under different climatic conditions. They obtained information on the final yield, reference yield, performance ratio and system efficiency. Results showed that the lowest values of reference yield, array yield, and final yield were due to the low levels of solar radiation during sandstorms, and the lowest values of performance ratio and efficiency were due to high module temperature. Thus, changes in solar irradiance are caused by changes in the weather. Investigating the performance parameters of the PV systems will be a main part of this thesis and this will be explained in detail in Chapter 4.

Furthermore, a finite element thermal analysis of a solar photovoltaic module was conducted by Lee and Tay (2012). The highest temperature of the cells was 66.0°C under a solar irradiation of 1000 W/m^2 and PV efficiency was 12.2%, while it was 15% at the reference temperature of 25°C.

Photovoltaic systems are vulnerable to the wind, which will directly affect the efficiency of solar modules. Wind can impact the modules in different ways: high speed winds may increase dust deposits on solar panels, which would impede the ability of the panels to effectively receive the target amount of solar radiation and cause the efficiency of the solar system to be decreased. However, high speed winds may also be helpful in decreasing the humidity that would negatively affect the modules' efficiency (El-shobokshy and Hussein, 1993). This would be accounted for in this thesis by means of conducting a numerical modelling to examine the effects of different wind load magnitudes, blowing from different directions, on the proposed solar tracker. This would be shown in details in Chapter 7.

Sulaiman et al. (2011) studied the effects of dust on the performance of PV panels. They found that efficiency decreased by around 50% due to the accumulated dust on the surface of the modules. Al-Sabounchi et al. (2013) evaluated the design and performance of a photovoltaic system in Abu Dhabi, (UAE). The purpose of the study was mainly to assess the effects of temperature and dust on the photovoltaic system. The results showed that dust deposits on the top of the solar panels significantly reduce the efficiency of the solar system. It is generally accepted that the glass transmittance is directly affected by the accumulated dust on the solar panels and the plate tilt angle (Elminir et al., 2006).

Furthermore, Ndiaye et al. (2013) investigated the effects of dust on the performance of monocrystalline and polycrystalline PV modules installed at Dakar University in Senegal for one year without cleaning. The results demonstrate a loss in the output power of between 18% and 78% across solar modules.

In their research on the impact of accumulated dust on the surface of photovoltaic modules, El-shobokshy and Hussein (1993) used five types of dust with different physical properties (three limestone and two cement and carbon). They found that fine particles have a more pronounced effect than coarser ones in terms of reducing the efficiency of solar panels. Moreover, in the study, cement decreased the efficiency of the system when it was deposited onto the surface of photovoltaic panels. Finally, they found that carbon particles, which are produced by the combustion of diesel engines, have the most significant impact on module efficiency, because they are the smallest in diameter. Mani and Pillai (2010) reviewed the impact of dust on PV systems performance. They found that dust is an important factor that has direct effects of the PV systems efficiency. Moreover, they suggested applying appropriately a cleaning cycle for PV systems in order to deal with environmental conditions. Sulaiman et al. (2014) analysed the impacts the accumulation of dirt such as dust on the performance of solar photovoltaic panel. They found that significant reduction in the output performance of the solar modules have been obtained due to the obstruction of the light reaching the solar panels.

Al-Sabounchi et al. (2013) evaluated a 36 kW PV grid-connected system in Abu Dhabi. They studied the impact of ambient temperatures on power and energy production, conversion efficiency, consistency of voltage, and frequency and the impact of accumulated dust on the production of the system. Results showed that dust has a significant effect on system performance and a comprehensive cleaning programme should be established in order to avoid the accumulated effects of the dust.

A performance study of amorphous thin film and mono-Si technologies in Chile was conducted by Ferrada et al. (2015), who observed a significant difference in energy yield between the technologies during the summer, caused by dust accumulation, which impacted the performance ratio values.

Another concern is the effect of humidity (the water-vapour content of the air), when designing a PV system. Humidity on the module surface or in the atmosphere will affect the efficiency of solar modules by preventing solar radiation from reaching the modules in large amounts (Mekhilef et al., 2012). Ettah et al. (2012) investigated the effect of relative humidity on the performance of solar panels in Nigeria. They found that the efficiency of solar modules is significantly impacted by relative humidity. They also identified that at low relative humidity, the solar panel's efficiency is high, whereas it is low at high relative humidity.

2.4 Photovoltaic Systems in the Middle East

Photovoltaic systems are used globally and achieve encouraging results. Europe has the highest percentage of PV system usage. In order to have a better understanding of implementing PV systems in Kuwait, the focus of this study will be in the Middle Eastern countries with more focus on the GCC countries.

There is no doubt that the location of the Middle East countries provides a high potential and opportunities to implement the PV energy systems. In this regard, China is a good example in both manufacturing and utilizing large amounts of PV modules. China, one of the developing countries which is characterised by a large and strong economy, is suffering from environmental pollution resulting from the massive use of fossil fuels, for instance, large amounts of coal are consumed in order to satisfy its needs of energy (Gan, 1998; Liu and Wang, 2009; Wang et al., 2011).

Japan is also playing a vital role in the PV systems production field and a promising future of implementing PV systems is expected in coming years. It is characterised by using well-functioning PV systems by the means of industry and marketing for PV (Vasseur et al., 2013). A remarkable development and diffusion of PV solar energy have been seen in Japan. This could be attributed to applying a subsidy program which has significant effects by the means of implementing PV systems. According to the National Survey Report of PV Power , Japan is aiming to increase its annual installed capacity by 2020 (YAMAMOTO and IKKI, 2010).

Pakistan and Bangladesh represent a good example of the orientation of implementing PV systems in Asia in order to benefit from their geographical locations which give them more opportunity to collect a high amount of solar irradiation. Although Pakistan has insufficient experience in implementing PV systems, recently a significant development has been seen by means of a renewable energy policy and creating large scale power plants (Sher et al., 2015). In Bangladesh, the scarcity of electricity in the country is one of the main causes of any industrial development. However, the government has set up serious steps to use the renewable energy in generating electricity (Hil Baky et al., 2017).

As stated in the introduction Chapter, the GCC countries have also taken serious steps and procedures in utilising PV systems. However, the undertaken renewable energies projects are still under the normal required level. This would open a wide range of questions such as why the GCC countries are late and relatively not so highly interested or focused on the use of the renewable energies. In addition to the fact that these countries are rich in fossil fuels resources, there is relatively high support of the electricity and fuel cost to their citizens and residents (Al-maamary et al., 2017). This would be definitely considered as an important issue in this regard as the people would be busier in other daily life issues such as the political and social aspects more than energy issues such as the cost and the environmental effects.

For Kuwait, it should be emphasized here that after the Iraqi invasion in 1990, the political situation and the security of the country has been of high priority rather than other issues. It can be seen that the increased rate of illness and patients as well as the spread of very dangerous diseases, such as cancer, is being remarkably increased. This would be attributed to many factors; one of them is the air pollution (Nicolson, 1999).

It is clear that constructing more conventional power plants in order to satisfy the high demand of electricity as well as the huge numbers of cars in Kuwait as a result of high economic development and relatively low fuel prices are also contributing in increasing air pollution. There is no doubt that the fuel subsidy from the government in terms of low prices of fuels is definitely considered one of the main causes of a lot of problems such as air pollution. However, as the focus of this research is the use of PV systems to generate electricity in Kuwait, other issues such as economic and political /social issues whether directly or indirectly caused by excessive use of energy will not be discussed here.

As stated previously, the low prices of electricity resulting from the high governmental subsidy will not give any fair chance for investors by means of competition with conventional power plants. The scarcity and the high cost of land in Kuwait are also other important barriers as these types of projects require a large area of land. Limited awareness of the basic principles of this technology of the decision makers would also directly affect the relevant legislation and regulation related to the deployment and implementation of such renewable technologies in the country. In fact, GCC countries have begun with serious steps in developing their projects in the renewable energy field in order to benefit from abundant renewable energy resources such as solar and wind (Mondal et al., 2016).

In Saudi Arabia, the King Abdullah City for Atomic and Renewable Energy is a good forward step for the use of renewable energy such as solar energy. It provides important options for electricity generation and water desalination for the country; the King Abdullah City is aiming to produce 41 GW from solar energy (16 GW from photovoltaic energy)(Al-maamary et al., 2017).

In the United Arab of Emirates, there are ambitious and encouraging projects, such as Masdar City in Abu Dhabi. It is considered as a good example for the design of zero- carbon city (Lee et al., 2016). The Masdar City will be a good view for the use of renewable energy in the country and will be as a tangible development measure in the contribution of reducing the greenhouse emissions resulting from the burning of fossil fuels.

A significant advance and development has been noticed in Qatar. In terms of encouraging the implementing of solar energy, Qatar Science and Technology Park, a part of Qatar Foundation Research and Development, is providing good opportunities to investors as this project is basically considered as a free zone with zero taxes (Atalay et al., 2016).

Many solar energy targets have been set in Bahrain and Oman in order to benefit from the high solar irradiation in generating electricity (Mondal et al., 2016). The siting of large photovoltaic farms, using different PV technologies, in the Al-Batinah region of Oman was investigated by Gastli and Charabi (2010). Results showed that a photovoltaic system is an appropriate source of renewable energy in terms of technical performance. They found also that using the free land in in the country will help provide large amounts of electricity to satisfy the electric energy demand in Oman.

Kuwait has been involved in the renewable energy relatively earlier than the GCC countries and that was mainly activated by the purpose of creating the Kuwait Institute for Scientific Research (KISR).

As stated previously, the Iraqi invasion of Kuwait in 1990 was a main cause of the delaying of the development of all fields in the country such as the research in the renewable energy. The optimization of the electrical load pattern in Kuwait using grid-connected PV systems was investigated by Al-Hasan et al. (2004). They evaluated the performance of grid-connected photovoltaic systems in the Kuwait climate and found that the peak load matches the maximum solar irradiation allowed. They also identified this as a credible value which will encourage the use of photovoltaic systems in the state of Kuwait.

Al-Enezi et al. (2011) investigated the feasibility and potential of solar energy on the horizontal surface of the Kuwait Area. The findings of their research showed that Kuwait is facing a significant increase in the demand for electricity, but there is a lack of electrical energy and load peaking. Moreover, the country has an abundance of solar energy potential, and average daily global and monthly solar irradiation is around 3 kWh/m^2 in winter and 8 kWh/m^2 in summer.

As stated above, the high solar radiation amounts striking the country and the fact that high electricity demand coincide with the high production time of solar panels; these will provide high chance of successful of the implementation of the photovoltaic energy in Kuwait.

Overall, there have been some attempts and projects in the country to generate electricity using photovoltaic energy. Al-Shagaya project is mainly the most important step toward the use of renewable energy in Kuwait. The capacity of this project is 70 MW and the photovoltaic energy is accounting 10 MW (KISR, 2014a). However, this project is being implemented based on relatively old feasibility studies in which a lot of updated and new technological features are not included such as utilising tracking systems to increase the amount of produced energy.

2.5 Commonly Used Evaluation Indices in Implementing PV Systems

2.5.1 Introduction

In order to efficiently evaluate the feasibility of PV systems in Kuwait, this study will focus on the most important methods and criteria by which the PV systems are investigated. From a review of previous work and literature related to solar energy projects, the following studies will be conducted:

- Performance parameters study
- Environmental evaluation study
- Economic evaluation study

These are the most important elements used to help judge the feasibility of any proposed project in the PV system field. Furthermore, investigating the behaviour of the solar trackers and the ground against the external loads will be an important procedure in order to have a complete understanding of implementation of PV systems in Kuwait. The performance parameters evaluation of any proposed type of renewable energy is extremely important, in order to estimate or even predict the amount of energy that would be produced by implementing such technologies.

As mentioned in the background introduction, it is vital to consider the environmental pollution and global warming caused by fossil fuels when investigating the impacts of PV systems on the environment. The feasibility of any proposed technology for both private and government sectors cannot be determined without an economic evaluation study. Therefore, in this chapter, the literature review covers the relevant research in more detail. Finally, in order to establish a better understanding of implementing PV solar trackers, the previous research conducted in this field will be reviewed.

2.5.2 Performance Parameters of PV systems

The International Energy Agency (IEA) stated that the main components of the performance parameters of PV systems consist of the total energy generated by the PV system; Final Yield (YF); Reference Yield (YR); Performance Ratio (PR); Capacity Factor (CF); and system efficiency (Marion et al., 2005). YF (also known as the yield factor) is defined as the daily, monthly or yearly alternating current (AC) energy produced by the PV system, divided by the rated output power of the used PV system (Ayompe et al., 2011; Marion et al., 2005). It is given by:

$$YF = E_{AC} / P_{PV,\ rated} \qquad (2.1)$$

The ratio of total solar irradiation (H_t) in (kWh/m^2) to the reference irradiation G (1 kW/m^2) is known as YR (Ayompe et al., 2011; Marion et al., 2005). It is given by:

$$YR = (H_t)\ (kWh/m^2) / G\ (1\ kW/\ m^2) \tag{2.2}$$

Performance ratio (PR) is given as:

$$PR = YF / YR \tag{2.3}$$

CF is determined as the ratio of the annual energy output of the PV system to the rated power of the PV system (Ayompe et al., 2011). It is given as:

$$CF = E_{AC} / (P_{PV,\ rated} \times 8760) \tag{2.4}$$

Marion et al. (2005) observed that the final yield, reference yield, and performance ratio are the most commonly used performance parameters of grid-connected PV systems, and they are important measures when comparing different PV systems. The long term assessment of the PV systems is an important measure which will give the best understanding of the performance of any proposed system in the future. Ma et al. (2013) studied a 19.8 kW stand-alone PV system in Hong Kong and analysed its performance parameters. Results showed that long term assessment is vital for achieving a better understanding of system performance; it would also provide a useful framework for future studies and applications.

A performance ratio is an important measure of any proposed PV system as it provides an initial indication about the technical behaviour. A performance analysis study of a mini-grid-connected PV System was conducted by Cherfa et al. (2015). The average daily energy obtained was 30 kWh and the performance ratio ranged between 62% to 77%, while the yearly performance ratio was 71%, to 82% is the maximum value which could be achieved in May, June, and July, when the PV system is most efficient.

El Fathi et al. (2014) conducted a study of performance parameters in a 7.2 kW photovoltaic power plant, and discovered that the performance ratio of the PV system ranged from 33% to 70.2%. Thus, they concluded that performance ratio is significantly affected by the rate of energy demand during the day, as well as the state of battery charge. Ayompe et al. (2011) investigated the performance of a 1.72 kW PV system installed on the flat roof of a building in Dublin. Results showed that low final yield values were achieved due to poor solar insolation in winter, while the performance ratios ranged between 72.3% and 91.6%. The capacity factor ranged between 10.1% and 15.5%.

Al-Otaibi et al. (2015) evaluated the performance of 85.05 kW and 21.6 kW thin film, grid-connected PV systems on the rooftops of two schools. They determined that the performance ratio was maintained between 74% and 85%, and that the minimum monthly energy yield of the PV systems was about 104 kWh/kW. The average daily yield of the photovoltaic systems annually was 4.5 kWh/kW/day. In addition, the rooftops of the school buildings were identified as a good location because they are large, unused areas.

In India, a lot of research has been conducted in photovoltaic energy and the performance of PV systems has been investigated. Sharma and Chandel (2013) investigated the performance parameters of a 190 kW solar photovoltaic power plant using PVsyst software. The results of their investigation were encouraging. They found that the annual average performance ratio of the implemented systems is equal to 74% and the capacity factor is equal to 9.27%. Shukla et al. (2016) conducted a technical performance study of a 110 kW grid-connected photovoltaic system in India, in which performance ratio and energy yield were obtained for four different types of PV module. They found that the performance ratio of the PV systems varied between 70% and 88%, while the energy yield varied between 2.67 kWh/kW and 3.36 kWh/kW. Therefore, they proposed that all types of PV system are appropriate for use in tropical weather conditions with regard to annual energy yield.

Hajiah et al. (2012) also conducted an assessment of the electricity generated by a 100 kW PV grid-connected systems in two sites in Kuwait, Al-Wafra and Mutla. Results showed that the selected sites have high energy productivity with an annual capacity factor of 22.25% and 21.6%, respectively. Furthermore, the annual yield factors for both sites are 1861 and 1922.7 kWh/kW/year, respectively.

The orientation and the tilt angle of the solar panels are important parameters that directly affect the performance of the PV systems. Al Otaibi and Al Jandal (2011) assessed the local optimum tilt angle and the annual power output of four photovoltaic modules of different types. The study focused on the amount of power generated by photovoltaic systems in hot weather conditions in Kuwait, as well as the effect of using different tilt angles on system performance. Results indicated that the PV modules perform well in Kuwait’s climate.

Emziane and Al Ali (2015) evaluated the performance of rooftop PV systems in Abu Dhabi, using two different PV systems (multi-crystalline silicon and single-crystalline silicon solar modules). The multi-crystalline silicon modules achieved higher yield factors and lower efficacy, due to the use of different inclination angles and inverter types. Furthermore, a performance comparison study between low concentration and fixed angle PV systems was conducted by Famoso et al. (2015). They found that although the low concentration photovoltaic system performed better during the summer, the fixed angle system was more efficient during other months.

2.5.3 Environmental Evaluation

An environmental evaluation is an extremely important part of any proposed renewable project, as the main reason for implementing renewable energy is to help reduce the amount of emissions caused by fossil fuel resources. Reductions in greenhouse gases (GHGs) and the life-cycle assessment (LCA) are the most common methods used to evaluate PV systems from an environmental perspective. Several environmental studies have been conducted on PV systems using the LCA approach (Alsema, et al., 2006; Alsema, et al., 2005; Fthenakis and Kim, 2011; Hong et al., 2016; Kim et al., 2014; Stoppato, 2008).

Kim and Alsema (2008) researched the life-cycle of greenhouse gas emissions from four types of major commercial PV systems: multi crystalline silicon, mono crystalline silicon, ribbon silicon, and thin-film cadmium telluride, in Europe and the United States. They found that the pollutant emissions generated by PV systems are significantly less than that the ones generated by conventional power plants.

Fthenakis and Kim (2011) conducted a life-cycle analysis of a high concentration PV system using a tracker and lenses to receive more solar irradiation. Results showed that the emissions from PV systems are very small compared to emissions from conventional power plants. In addition, the environmental issues associated with silicon-based PV systems in Korea were examined by Kim et al. (2014). The LCA results, based on global warming potential (GWP) and fossil fuel consumption (FFC) values, indicated that single and multi-crystalline silicon module systems are the most suitable for use in Korea.

The impacts of implementing PV systems on the environment could be seen obviously by estimating the greenhouse emissions that would be avoided. Zhai et al. (2012) investigated the potential for avoiding emissions from photovoltaic electricity. The emissions avoided per solar PV capacity (g/W) for the selected states ranged from 670 to 1500 for CO_2, 0.01e7.80 for $SO_{2,}$ and 0.25e2.40 for NOx. The researchers concluded that more emissions could be avoided in the locations with a larger proportion of coal, higher emissions from existing fossil fuel plants, and a higher PV capacity factor.

The environmental impacts of PV systems used to generate electricity were evaluated by Alsema et al. (2006), who discovered that the potential of using the systems as clean energy is great, and the hazardous emissions from PV systems are caused during the manufacturing process. Furthermore, Adam and Apaydin (2016) investigated the possibility of using a 500 kWp solar PV system to reduce GHGs. They found that the reduction of the amount of CO_2 emissions was credible and proposed that a government subsidy is necessary to encourage the use of PV systems.

The environmental effects of multi crystalline silicon cells were explored by Hong et al. (2016). Results of the study showed that multi-crystal solar PV technologies have significantly fewer negative environmental impacts. The researchers recommend increasing the amount of renewable energy sourced used for producing electricity.

The life cycle assessment (LCA) is another important measure in any environmental evaluation study. It provides a complete assessment of the product from the beginning of the production stage and ends with recycling stage. Stoppato (2008) conducted a life-cycle assessment of photovoltaic electricity generation. He found that the transformation of metallic silicon into solar silicon and panel assembly are the most critical phases in the life-cycle analysis, which is due to the use of high amounts of energy.

Alsema et al. (2006) evaluated the environmental impacts of crystalline silicon photovoltaic module production and found that crystal solar PV systems are more competitive than the other energy technologies. They also found that the Energy Pay-Back Times for southern European locations are 1.7-2.7 years, and life-cycle CO_2 emissions are in the 30-45 g/kWh range.

Furthermore, a life-cycle assessment of multi-crystalline PV systems in China was performed by Fu et al.,(2015), who also discovered that the process of changing the metallic silicon into solar silicon is a vital stage in which more energy is used. Yu et al. (2013) conducted a cost benefit analysis of a newly constructed 10 MW solar photovoltaic power plant in China. They determined that 18,000 tons of CO_2 emissions could be saved each year. Although the LCOE of the photovoltaic energy is twice that of fossil fuel electricity, the use of photovoltaic energy will be increased in China in order to minimize CO_2 emissions.

It can be observed that the amounts of emissions that can be avoided by the implementing of PV systems and the amounts of GHG emission are the common and dominant criterions that have been investigated in the existing literature.

2.5.4 Economic Evaluation

One important aspect of assessing the feasibility of a photovoltaic system is financial assessment. Thus, an economic evaluation of the proposed PV system is an essential part of this thesis as it attempts to study the feasibility of using PV technology in Kuwait.

Encouraging the private sector in photovoltaic energy will create large opportunities of new jobs and will also provide alternative tools for producing electricity. Borah et al. (2014) evaluated the technical, financial, and institutional aspects of photovoltaic programmes in four common solar lighting technologies used in India, with regard to the social impact of these programmes on rural households. They found that private photovoltaic projects perform better than subsidy projects. In addition, they concluded that financial support, technical innovations, and training programmes are the main factors that encourage photovoltaic system projects.

A study of a 100 MW large-scale photovoltaic power generation (VLS-PV) system to be installed in the Sahara, Negev, Thar, Sonora, Great Sandy and Gobi deserts, was conducted by Kurokawa et al. (2002). They found that generation costs in the Sahara desert and the Gobi desert are 5.3 cent/kWh (0.041 £/kWh) and 6.4 cent/kWh (0.049 £/kWh), respectively, based on a PV module price of $1.0/W (0.77 £/W), system lifetime of 30 years, and an interest rate of 3%. They concluded that VLS-PV systems are economically feasible when there are high irradiation solar values and the cost of photovoltaic modules equals or is less than $1 per watt. It should be highlighted her that this study is relatively old; however, it gives an indication of the importance of applying large scale PV systems. In addition, it refers also to the installation cost of the PV systems and that is an important point. Recently, a significant decline in the installation costs that have been seen, would affect positively on the potential of using PV systems from an economic viewpoint. It is assumed that 1$ = 0.7768£ at the time of writing this thesis.

In Saudi Arabia , The feasibility of the design and construction of a solar power plant using photovoltaic cells in Saudi Arabia was investigated by Al-Ammar and Al-Aotabi (2010).

They stated that the implementation of photovoltaic systems is crucial to meeting the increasing demands for electricity in Saudi Arabia as it would reduce fossil fuel consumption.

An analysis of energy production and an economical evaluation of a 5 MW installed capacity photovoltaic-based grid-connected power plant for electricity generation was conducted by Rehman et al.(2007). They found that global solar radiation varies between a minimum of 1.63 MWh/m^2/y and a maximum of 2.56 MWh/m^2/y for Tabuk and Bisha, respectively. The calculated duration of sunshine in Saudi Arabia was between 7.4 hours and 9.4 hours. The economic indicators of their study highlight that Bisha was a more appropriate site for a photovoltaic power plant than Tabuk. In addition, they found that around 8,182 tons of greenhouse gases can be saved per year through the use of photovoltaic technology.

A feasibility study of utilising stand-alone and grid-connected photovoltaic systems in the UAE was conducted by Allaham et al. (2015). They found that the payback time for the systems decreased by 14% and 15%, respectively, with an inflation rate in the electricity price equal to the general inflation rate in the country. They recommended the use of PV systems in the UAE to gain the benefits of using renewable energy from both an environmental and economic perspective. In addition, they stated that governmental incentives are essential due to the high initial cost of the PV systems.

An assessment of the potential benefits of implementing solar energy in the UAE was completed by Mokri et al. (2013). They focused on the production and consumption of the energy as well as the local operating conditions of solar installations. They reviewed the progress of solar energy in the UAE and concluded that although the price of generating electricity using photovoltaic systems is high compared with the electricity sold in the UAE, it is easy to encourage the use of this new technology by offering governmental incentives to use these systems, such as a feed-in tariff.

Some research has been conducted to investigate the feasibility of using PV systems in Kuwait. Ghoneim and Abdullah (1994) also studied the performance and economic feasibility of solar heating and cooling systems in Kuwait, using a conventional flat plate collector and modified flat plate collector (equipped with transparent insulation material). The results demonstrated a remarkable increase in the performance of the modified flat plate collector, caused by a reduction of the optimum collection area. Furthermore, they found that the cost of energy when using the modified flat plate collector is equal to around 64% of the energy cost when using conventional fuel systems.

Hasan and Sayigh (1996) conducted a cost and sensitivity analysis for a photovoltaic station in the state of Kuwait. They compared the cost of kWh generated from a PV station with the kWh generated from conventional units. They concluded that the capital (investment) cost of any proposed photovoltaic station should be less than that of conventional power plants. Abdullah et al. (2002) explored the feasibility of installing grid-connected PV systems (crystalline solar modules installed on the building roof) in Kuwait's climate. They concluded that the electricity tariff would have a significant impact on the photovoltaic system in terms of cost effectiveness.

The levelized cost of energy (LCOE) method which is the widely used measure when comparing between different electricity generation technologies as an evaluation tool. The economic feasibility and viability of implementing PV solar energy in Kuwait was studied by Ramadhan and Naseeb (2011). They found that the high levels of solar radiation in Kuwait are crucial to enhancing the use of solar panel systems in the country. Moreover, the cost of energy (LCOE) of a 1 MW station was determined to be approximately $0.20/kWh (0.15 £/kWh) (assuming the present price of $5/W (3.83 £/W) and 15% efficiency). Finally, they stated that the LCOE value $0.20/kWh (0.15 £/kWh) is feasible when the cost of oil is around $100/barrel (£76.68/barrel). Hajiah et al. (2012) also found in their study, an assessment of the electricity generated by a 100 kWp PV grid-connected systems in two sites in Kuwait that the levelized cost of energy (LCOE) is around 0.1 USD/kWh (0.77 £/kWh), which is similar to the amount of energy taken from the Ministry of Electricity and Water (MEW) in Kuwait.

It can be observed from most of the existing literature relevant to Kuwait that the investigation studies have been conducted based on the comparison criterion between the proposed PV systems in Kuwait and the conventional power plants in term of LCOE value. This can be attributed to the fact that the only available source of electricity is produced from the conventional plants. In addition, the country is relatively late in implementing different renewable energies; in other words, there is no available data of implemented projects in different renewable energies.

2.5.5 Numerical Modelling

Numerical modelling is vital for solving the complex problems in different engineering disciplines. It is generally considered an important part of most structural integrity research and is used in the design and analysis of the behaviour of different types of structures.

PV modules are secured by a mounting structure, and its type depends on the type of system designed (for example, a system sited on the roof of a building). In cases of a farm/park photovoltaic system in which a ground mounting structure is used, foundations are established to install the mounting structure in the ground. The support structure of the solar modules should be properly designed, with complete knowledge of the forces that the supports will be subjected to, such as wind. It is extremely important to understand the mechanism of transferring forces from the support structure to the foundations, and it can be assumed that the weight of the modules and the wind are the major forces that act on the supports for the solar modules (Annavarapu et al. , 2009).

The ground mounted system is an important part of the photovoltaic system because it is not only responsible for securing the solar modules, which represent approximately 50%-60% of the total cost of the system; it also keeps the whole structure stable. The stability of the structure of a photovoltaic system, whether it is a fixed tilt, single axis or dual axis tracker, is crucial to achieving the best possible system efficiency. This can be ensured by using an effective foundation that remains stable against environmental factors such as wind speed (Miller, 2009).

Selecting the appropriate foundations for photovoltaic systems relies on understanding environmental factors, such as wind speed, and the geotechnical properties of a site. Each of these factors should be taken into account when designing solar systems in order to avoid any possible failures (Miller, 2009).

Since there are no clear codes or standards used in the design of the solar PV structures and foundations, the improper design of a structure and foundations of a solar system will cause adverse conditions (excessive settlement or collapse of the support structure in a worst case scenario), thereby affecting the production and performance of the system used (Kibriya, 2013).

Driven piles, helical piles, earth-screws, and ballasted foundations (Figure 2.9) are the main types of foundations used. The selection of the foundation type used for any project depends on the site and the mechanical properties of the ground (Worden, 2014). Helical pile foundations and ballasted foundations, which are precast concrete or concrete poured in place, are used on sites that are characterized by cohesionless soil such as sand, while driven foundations are widely used on sites characterized by cohesive soils such as clay and dense sand (Worden, 2014). Earth-screws foundations are used when there is difficulty penetrating piles due to tough soils or rocks, and ballasted foundations is the preferred option in landfills. Therefore, site investigation is extremely important for selecting the appropriate type of foundation (Worden, 2014).

Steel piles are commonly used in solar panel systems, especially in large scale utility systems (5 MW or more), because the structures require a large amount of piles. For instance, a 10 MW solar PV system consists of around 5,000 piles in a typical design. Moreover, steel piles can be installed quickly (Kibriya, 2013). The most widely used steel piles have a diameter of 114mm to 125mm and an embedment depth of 2.75m to 3.5m, so they can be driven into soil or pre-drilled in cases of hard soils (Kibriya, 2013). The basic standard tests for deep foundations (steel piles) are ASTM D3689/D3689M (Standard Test Methods for Deep Foundations Under Static Axial Tensile Load), ASTM D1143/D1143M (Standard Test Methods for Deep Foundations Under Static Axial Compressive Load) and ASTM D3966/D3966M (Standard Test Methods for Deep Foundations Under Lateral Load) (ASTM, 2013), and they should be conducted in order to achieve a successful design criteria.

The typical soil profile in Kuwait is mainly consisted of windblown dune sand in surface layers with varying depths up to 7 m, underlined by fine to medium sand deposits known as Gatch, locally name for cemented sand and at depths below this, approximately 80 to 100 m depth of limestone bedrock (Al-Sanad and Shaqour, 1991; Ismael and Jeragh, 1986; Ismael et al., 1986). The majority of soil in Kuwait is is within SP to SM classification system (poorly graded sand to silty sand) according to the Unified Soil Classification System (Ismael et al., 1986).

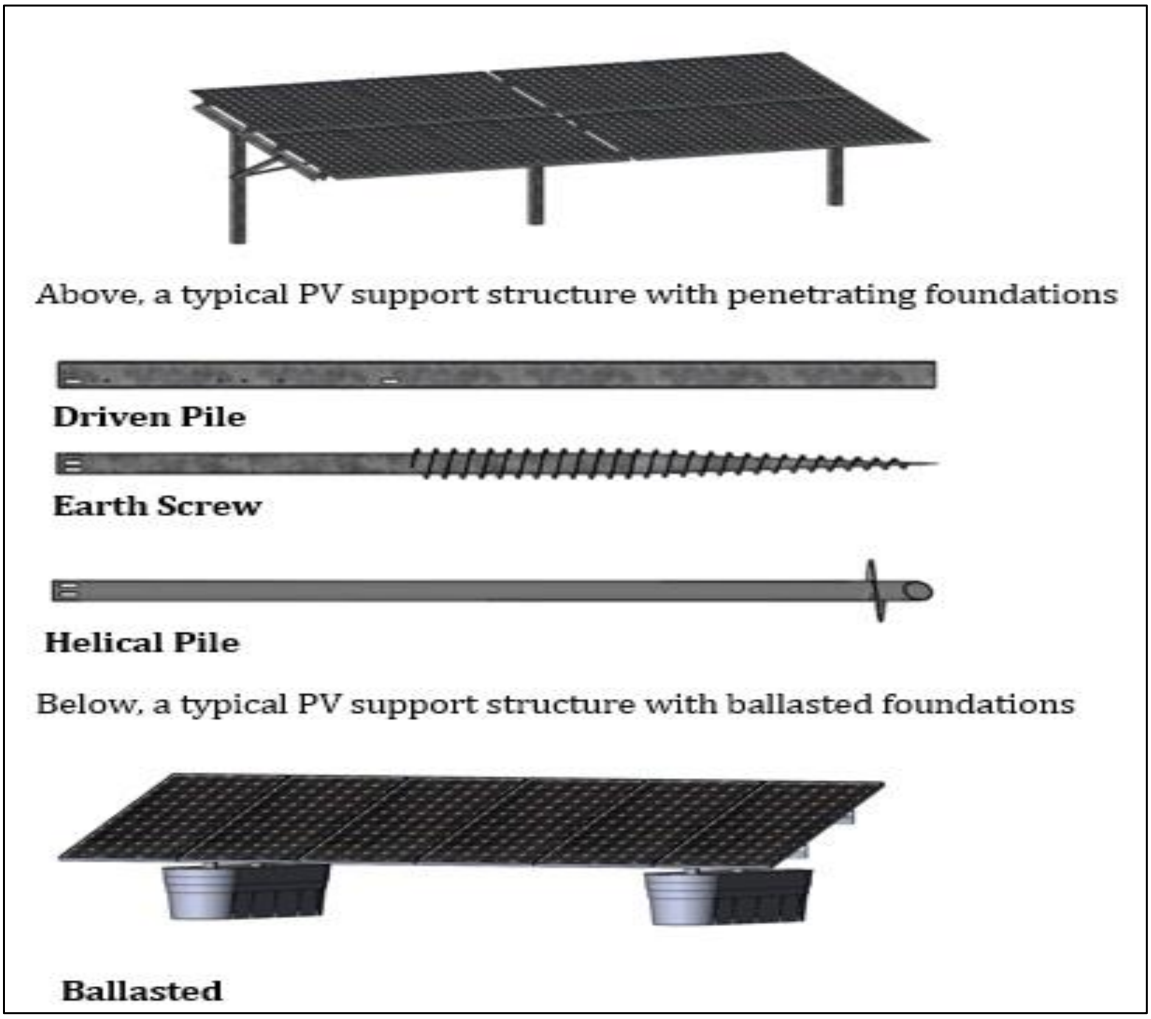


Figure 2.9 Types of PV foundation (Worden, 2014)

Sprince and Pakrastinsh (1991) investigated the behaviour of helical screw piles in four different soils (fine sand, floating loam, sandy loam, and hard loam) using finite element software (Lira 9.2). They found that screw piles have different capacity values with different soil types and the capacity of the screw pile is directly proportional to the embedment depth of the screwed plate. Two helical pile load testing was conducted by Sakr (2011) in Canada. He stated that helical piles are an effective foundation system for solar plants due to the speed of installation and their high tensile capacities.

Recently, a concern has emerged to achieve the maximum efficiency of solar panels by modifying the design methods of the supporting structures (GadhaviAkash and Kundaliya, 2015). A solar tracker is basically a system which is used to fit and orientate solar panels and thermal collectors to gain the maximum amount of the sunlight (Mohammad and Karim, 2012; Parmar et al., 2015). There are three main types of solar trackers and they are categorized according to their movements: fixed solar tracker, single-axis tracker, and dual-axis tracker (Gil et al. , 2009).

Most previous and current research in this field has been focused on increasing the performance of the solar panels, either by constructing highly efficient modules or reducing the losses caused by several reasons such as using improper tilt angles of the solar panels. The optimal tilt angle is a function of time. In other words, it is dependent on the movement of the sun. Thus, solar tracking systems have been designed to follow the sun in order to maintain an optimum tilt angle throughout the day.

Many researchers have investigated the effects of using solar trackers (Abdallah, 2004; Abu-Khader et al. , 2008; Dakkak and Babelli, 2012; Eke and Senturk, 2012; Koussa et al. , 2011; Helwa et al. , 2000). They have found that the effects can be clearly noticed when comparing the energy output obtained from fixed tracking system with the energy obtained from single-axis or dual-axis solar trackers. Furthermore, that the two-axis solar trackers have the highest increase in obtained energy compared to other solar tracking systems. In addition, it is generally accepted that the gained energy would be increased by approximately 30% when implementing dual-axis solar (Bayod-Rujula et al., 2011; Eldin et al., 2016). However, although a larger amount of energy can be produced by tracking systems compared with fixed mounting systems, solar trackers are considered expensive and require more maintenance.

In this thesis, the effect of using different tracking systems will be evaluated by technical performance. Economic and environmental evaluations will also be conducted to investigate the different tracking systems in five different sites in Kuwait.

From the existing literature, it can be observed that most researchers have focused on investigating the effects of wind load and self-weight of the solar tracker as main external loadings. Naik et al. (2013) analysed a solar panel supporting structure by using ANSYS software. They focused on analysing and optimizing the solar structure and found that, based on the initial analysis results that showed stresses and deflections in the support structure, optimization can be carried out in particular locations. In addition, they found that a weight reduction of around 14% can be achieved, which will have a positive impact on production and manufacturing costs. Mihailidis et al. (2009) conducted a study into solar panel support structures. The main tasks of the study were load calculation, analysing the structure, and identifying critical structural points. They concluded that solar support structures should be tested to withstand wind load even when they are properly designed. Moreover, they recommended that analysis of the aerodynamic loads should be carried out for many wind directions. The design and stability of a supporting structure in India subjected to wind force was assessed by Mathew et al. (2013). They concluded that a reaction force created by the weight of the structure itself is a key element in terms of the stability of the whole structure.

The effects of self-weight and wind load on structural deformation were studied by Cao et al. (2013). They considered two different wind speeds blowing from different directions. Results indicated that there was no failure in the structure and that displacement of solar modules is affected by the elevation angles of the solar tracker. Aly and Bitsuamlak (2013) performed a study to investigate the impact of wind loads on ground-mounted solar panels. They found that the model size does not affect the mean loads, whereas the peak loads are significantly affected by the geometric scale. Baetu et al. (2013) created a numerical model in order to analyse the effect of the wind on solar panels. They applied computational fluid dynamics and used different wind directions. They found that the amount of stress on the solar panels is influenced by the wind direction. In their study, the highest pressure occurred at an angle of 180°.

Stathopoulos et al. (2014) investigated the distribution of wind pressure on the solar panels of stand-alone PV systems sited on the roof of a building. A wind direction of 135° had a significant effect on the pressure coefficients. The researchers also found that building height has a slight impact on the load created, and the highest load is created at the corners of the solar panels. Giorges et al.(2014) created a numerical model of wind loads on residential roof-mounted PV arrays. They investigated the wind-induced pressure on the solar panels. Complex flow types were obtained through changes in wind angles. They also found that the clearance between the solar panels and the roof has significantly impacts the induced pressure on the solar panels.

Recently, as the need of using tracking systems has increased in order to maximise the produced energy by the solar panels, studies have begun investigating the behaviour of single-axis and dual-axis tracking systems. The conducted studies, in this regard, are not so different as they still considering the wind load and the self-weight as the primary loads. However, using different inclination angles and using different direction in which the wind load is blowing the surfaces of the solar panels has become essential in order to evaluate the effects of the external loads.

Ferroudji et al. (2013) modelled a two-axis solar tracker using finite element software. They used a 130 km/h wind speed and demonstrated that the maximum stress is equal to 74.43

MPa and the maximum settlement of the structure is 1.2mm. A design and analysis study of a dual axis solar tracker was conducted by Bezawada et al. (2014). Results showed that a 15% higher yield can be achieved as a result of using the dual-axis tracker, and the wind loads are the most important parameters to be taken into account when designing solar trackers.

Solar tracker is just like any construction in which it is vulnerable to failure or destruction when it is exposed to excessive loading. In order to avoid failure of the solar trackers, it is important to have more knowledge about the behaviour of the solar trackers when it is loaded by external forces such as wind. In other words, determining the maximum induced stresses and strains will provide important information about the weak areas at the solar trackers. Lates (2008) conducted a mechanical behaviour study of a solar tracking system. He looked at the critical position of the system using the finite elements method. Results showed that the rotational joints of the structures are critical sites, where the maximum stresses have occurred.

As the direction of the solar tracker is changing during the day to follow the sun in order to maintain the optimal orientation to harvest the highest solar irradiation, it is necessary to investigate the behaviour of the solar tracker using different wind directions. A wind load analysis of a dual-axis solar tracker was conducted by Vellcu and Lates (2014). They evaluated the stresses on the solar trackers based on different wind load directions. They recommended that the materials of any proposed solar trackers should be designed based on the strength criteria.

In this research, numerical modelling through finite element methods will be utilised to investigate the behaviour of solar trackers in Kuwait, with fixed, single-axis and dual-axis tracking systems, against the external loadings. The effect of different wind magnitudes and directions will be considered. In addition, different tilt angles will be investigated with different wind directions.

2.6 Conclusions

The solar modules are highly influenced by climatic conditions, such as temperature. Thus, the high temperature in summer and frequent dust storms in Kuwait are extremely important variables which need to be assessed. Results are likely to recommend frequent cleaning to avoid the deposition of dust particles on the surfaces of the PV modules.

It can be concluded that solar module efficiency is greatly affected by the climate conditions in a proposed location. Hence, it is vital to consider the metrological data from any proposed to determine the most appropriate location. In addition, from an economic perspective, this would avoid the need for a lot of maintenance work, such as frequent surface cleaning of the solar modules.

It was found from the literature review that the majority of the conducted works and research in Kuwait based on the following assumptions:

- Using only one constant value for solar irradiation throughout the whole year.
- Using empirical equations, with inaccurate assumptions, to calculate the energy produced by PV systems.
- Using one source of data for the metrological data.

It was also found that the performance parameters of the PV systems, environmental and economic evaluations are the most important investigative elements of any feasibility study in solar energy field.

Chapter 3 – Methodology

3.1 Introduction

This chapter describes the methods and techniques used to investigate the feasibility of using solar photovoltaic systems (PV) in Kuwait. As stated in the introduction chapter, there is a growing need to use renewable energy sources instead of fossil fuels such as oil and natural gas in order to satisfy the high energy demand. Environmental concerns related to global warming support the switch to renewable energy such as wind and solar energy.

The stakeholders in this case are the people involved in the solar energy field, who can also act as important reference points or sources of information that may be missing or unclear. With regard to stakeholders, it is important to highlight the fact that solar energy is not an independent discipline, such as civil or mechanical engineering; that is, the science behind and use of solar energy is not taught as a comprehensive curriculum spanning two to four-years like structural or geotechnical engineering which is taught as a complete programme. The study of solar energy is multi-disciplinary and comprises fundamental science and engineering principles together principles of physics and electrical engineering (Gevorkian, 2014).

In order for the researcher to gain a better understanding of the research area, as part of the PhD plan, it was agreed with the supervisor that the researcher follows a parallel programme that mostly comprises attendance at relevant courses and conferences, as follows:

- Renewable Energy Management & Finance course at the University of London.
- Solar Photovoltaic course at the University of London.
- International Conference on Energy Research & Development (ICERD – 6).
- Participating in relevant conferences and journals.

The objectives of this research study will be determined on the basis of the findings of the literature review and the information gained at the conferences and courses outlined above. In addition, this research will consider the outcomes of the following studies in order to judge the feasibility of using PV systems in Kuwait (see Figure 3.1):

- Performance evaluation study.
- Environmental evaluation study.
- Economic evaluation study.
- Numerical modelling study.

Section 3.2, introduces the site selection process which consisted of three stages, namely: Stage 1 that involved the selection of all available sites on the map and, Stage 2 and 3 which involved the screening out and final selection process, respectively. The selected (proposed) sites are listed in Section 3.3, the data collection process is presented in Section 3.4 and the technical evaluation is presented in Section 3.5. The environmental and economic evaluations are presented in Sections 3.6 and 3.7, respectively, while Section 3.8 presents the numerical modelling.

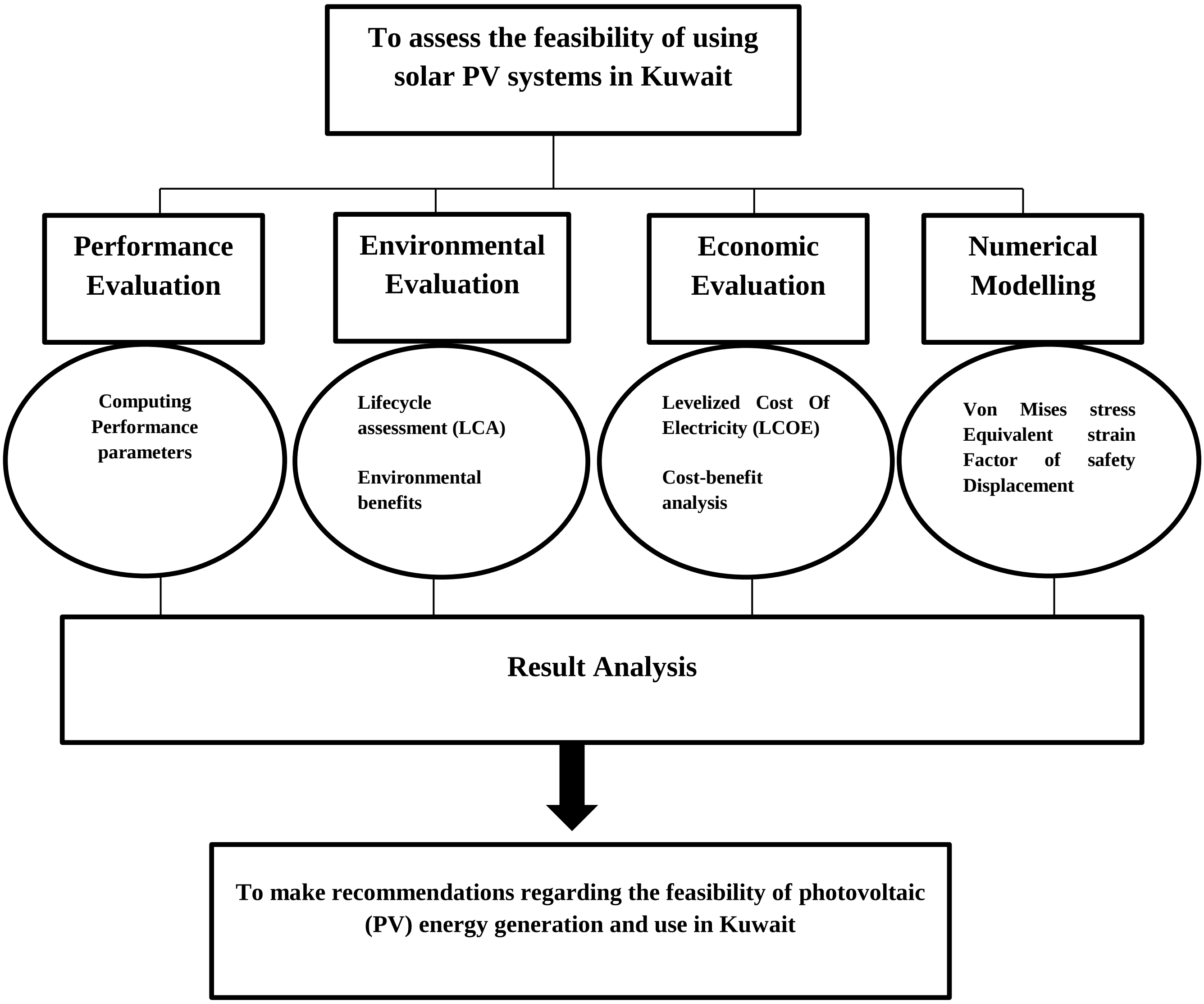


Figure 3.1 The main feasibility elements used in this research

3.2 Site Selection Process

According to the literature site selection is the most important step when it comes to setting up solar systems. The feasibility of PV systems is highly dependent upon the location of the site. Feasibility can be evaluated in different ways, including on the basis of solar resources and climate conditions of the selected location.

The main objective of the site selection process for the purposes of this thesis is to identify all the suitable and available sites in Kuwait and assess them in terms of productivity and cost effectiveness. The site selection process (Figure 3.2) is divided into the three stages described below.

3.2.1 Site Selection – Stage 1

The first stage was to select all available sites in Kuwait (that is sites that are not being used for anything in particular) using the map of the state of Kuwait. The initial goal was to include the most suitable sites even if there was some doubt about their availability; this could be checked out as part of the next task.

Kuwait consists of six governorates (Figure 3.3) and nine islands (Figure 3.4). The governorates are Jahra (11,230 Km^2), Al Asimah (200 Km^2), Farwaniya (190 Km^2), Hawalli (80 Km^2), Mubarak Al-Kabeer (100 Km^2) and Ahmadi (5,120 Km^2). The islands are Failaka (48 Km^2), Bubiyan (683 Km^2), Miskan (around 1.21 Km^2), Warbah (37 Km^2), Auhah (4 Km^2), Umm al Maradim, Umm an Namil, Kubbar (29 Km^2) and Qaruh. Failaka, Bubiyan and Warbah represent around 4.4% of the total area of the country and this large area could be investigated for the setting up of photovoltaic systems. Field visits confirmed that there are a good number of available sites within the Kuwait governorates, such as in Jahra and Al-Ahmadi. Dump sites (landfills) and the islands were also included in the study.

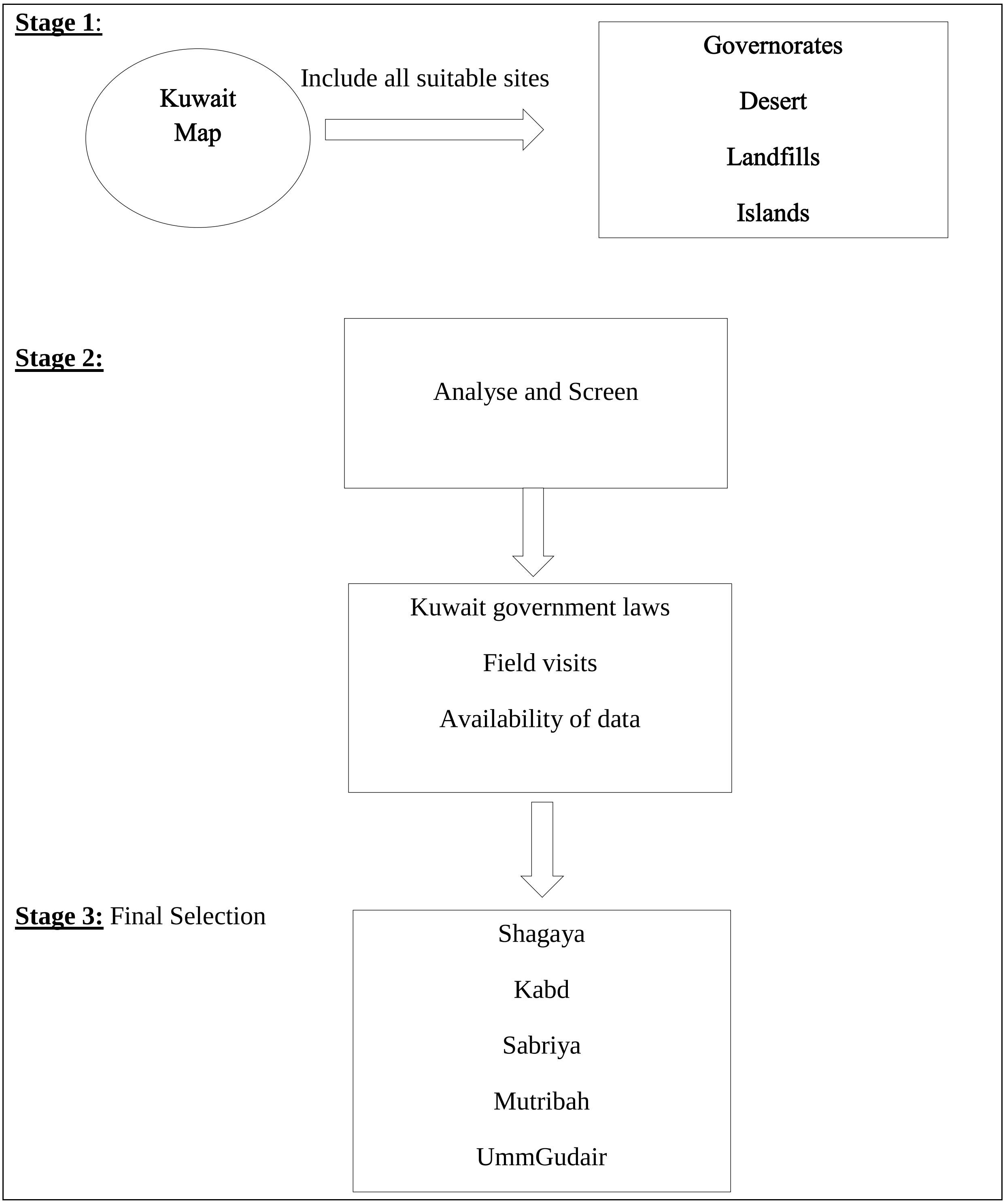


Figure 3.2 Site selection process

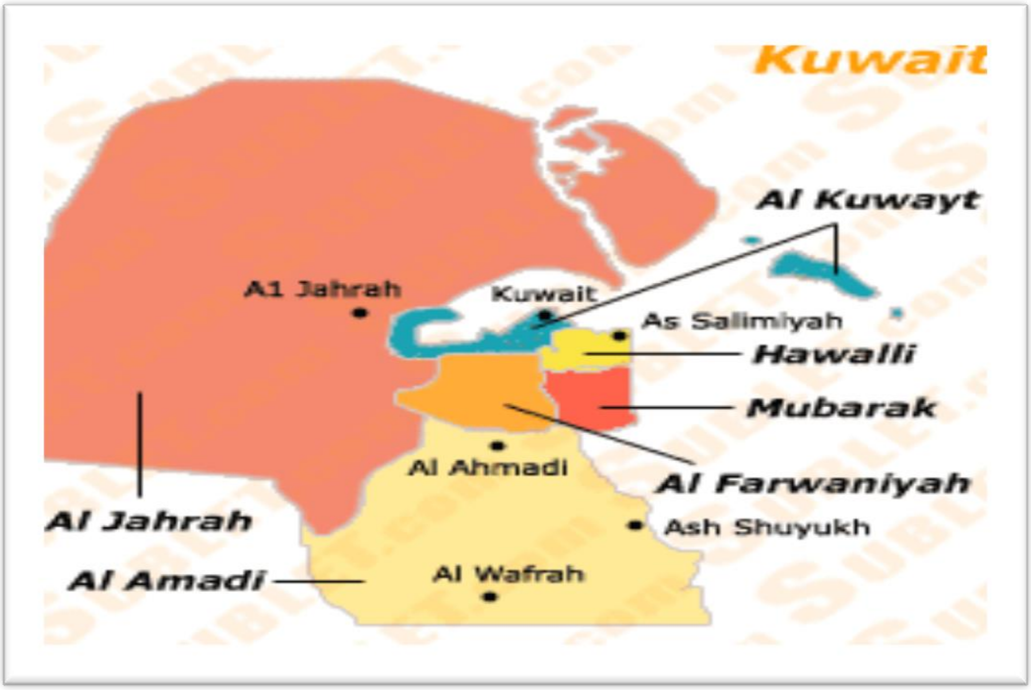


Figure 3.3 Kuwait governorates (Sunbelt, 2014)

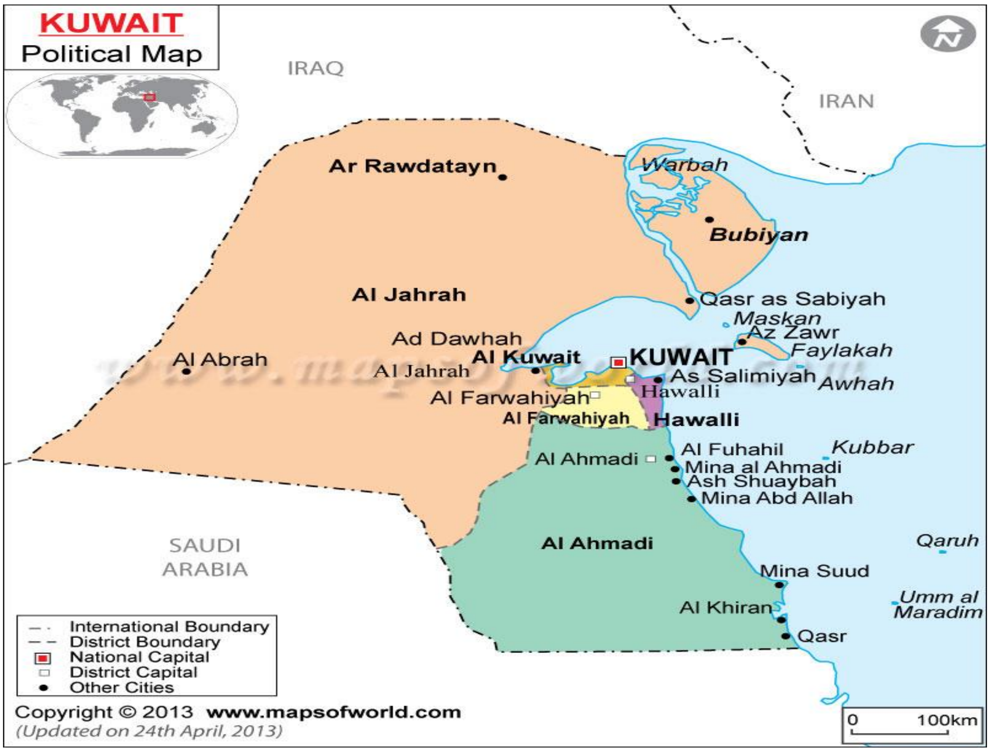


Figure 3.4 Kuwait islands (Maps of World, 2014)

3.2.2 Site Selection – Stage 2

Since Kuwait is a relatively small country, the effect of solar radiation is not a primary factor to be taken into account in the selection of the site; however, it is taken into account in this research when assessing sites in terms of annual production in order to have more detailed results which may be used in future or even for different purposes. The second step was to analyse and screen out the selected sites based on the following factors:

- **Kuwait Government Laws**

Certain Kuwaiti laws do not allow construction or the use of any land without permission from the relevant ministry. Some sites cannot be developed, such as, for examples sites near land allocated to the Defence Ministry, Oil Ministry and Dewan Al-Ameri sites. Therefore, this is a key factor of consideration in the selection of a site even when it is the most appropriate site for a solar energy installation. This results in a number of free (unused) sites not being available for potential projects.

The biggest Kuwaiti islands, Failaka (48 Km^2) and Bubiyan (683 Km^2), are initially chosen as potential sites for a photovoltaic solar system.

Although there are no clear laws preventing the use of Kuwaiti islands for renewable energy projects, the political situation in the country renders the use of these islands for these types of projects a sensitive issue. This is because, following Kuwait’s liberation from the Iraqi invasion of 1990, these islands retained the status of protected areas and can only be used for military purposes.

- **Field visits**

An important part of the engineering process is to obtain a complete set of data and information from maps, reports and field visits. The field visit (as part of the site selection exercise) is an important task because the given data and maps may not be fully up-to-date. Some changes on the ground might not be easily captured on a map or even in updated reports. The field visit included visits to private companies that are interested in solar energy. Following an intensive survey and visits to companies and people interested in solar energy, in both the private and the government sector, it was found that:

- Since Kuwait is a small country with a high rate of population growth (about 3.3%) (Alotaibi, 2011), there is a need for new residential areas, preferably at or close to the city centre.
- Large projects will lead to the renewal and construction of new highways and bridges to solve or minimise traffic problems, and sometimes there is a need to partially or completely remove some existing buildings (whether new or old) in order to carry out on-going and long-term projects.

Therefore, it can be concluded that it would be wiser not to site the solar energy installation within the Kuwaiti governorates. In addition, it was found that the best way to use solar energy in governorates in Kuwait is to use small scale solar panels, where the solar panels are put on the roofs of buildings.

• Landfill in Kuwait

It was established from literature review and field visits that landfills in Kuwait are used only for the dumping of waste. In other words, there is no evidence that they can or have been used for other purposes, such as renewable energy projects that would capitalise on their relatively large areas.

In Kuwait, sites earmarked for landfilling are not selected using engineering methods or even on the basis of long-term strategic goals; they are usually sand and aggregate quarries that can be filled in. Landfill is the main disposal system used in Kuwait, although prior to 1970, burning dumps were the most commonly used method to dispose of waste (Koushki et al., 2004). In 1970 the government started to use particular sites (dumping sites) as landfills. The daily average municipal waste production per capita is around 1.4 kg/person, which is high when compared to other countries (AL-Meshan and Mahrous, 2002).

The landfill sites selected were mostly quarries from which sand and gravel was extracted to be used in construction projects. Such quarries could be from 5m to 18m deep and could be found anywhere, not necessarily far away from residential areas. Kuwait has 16 landfill or dumping sites making up a total area of 29.5 Km^2, which is around 0.166 % of the total area of the state of Kuwait (AL-Fares et al., 2010); Table 3.2 shows the landfill sites in Kuwait. The landfill sites are distributed across the six governorates of the state (Figure 3.5). Only three of the sites, al Jahra, the Ring Road and the Meena Abdullah site, are still in operation; the rest are closed. The total area of the closed sites adds up to 8.35 Km^2 (28.12 %) while the total area of the sites which are still in operation adds up 21.35 Km^2 (71.88 %) (Figure 3.6). These sites do not satisfy the minimum requirements of environmental standards for site design and site selection. In conclusion, given the general lack of data on the soil properties of landfills and the lack of engineering designs, the Landfill will not be included in this study.

Table 3.1 Landfill sites in Kuwait

Serial	**Site Name**	**Waste Type**	**Start year**	**End Year**	**Status**	**Depth (m)**	**Area (km²)**
1	Kabd	Animal Waste + Household Waste	1999	2001	Closed	NA	0.37
2	Al Qurain	Construction Waste	1975	1985	Closed	Up to 20	0.7
3	Jleeb Al Shuyoukh	Construction Waste + Household Waste + Liquid Waste	1970	1993	Closed	>15	5.498
4	East Sulaibiya	Construction Waste	-	-	Closed	-	0.17
5	Sabhan Military	Construction Waste + Household Waste	1984	1991	Closed	Up to 20	1.798
6	Sabhan	Construction Waste	1980	1986	Closed	Up to 13	0.499
7	Al Egaila	Construction Waste	NA	NA	Closed	NA	0.11
8	Al-Shuaiba	Construction Waste + Liquid Waste	1982	2005	Closed	Up to 15	0.13
9	Al Yarmouk	Construction Waste	NA	2004	Closed	Up to 10	0.5
10	Al Wafra	Construction Waste	NA	NA	Closed	NA	0.2
11	Failaka	Construction Waste + Household Waste	NA	1990	Closed	NA	2.71
12	Al Jahra	Construction Waste + Liquid Waste	1986	Till date	Open	>15	1.983
13	Al-Sulaibiyah	Construction Waste + Liquid Waste	1982	2005	Closed	Up to 15	2.76
14	Seventh Road (N)	Construction Waste + Liquid Waste	1986	2005	Closed	Up to 15	5.91
15	Seventh Road (N)	Construction Waste + Liquid Waste	1992	Till date	Open	>15	4.475
16	Mina Abdullah	Construction Waste + Liquid Waste	1992	Till date	Open	>15	1.896

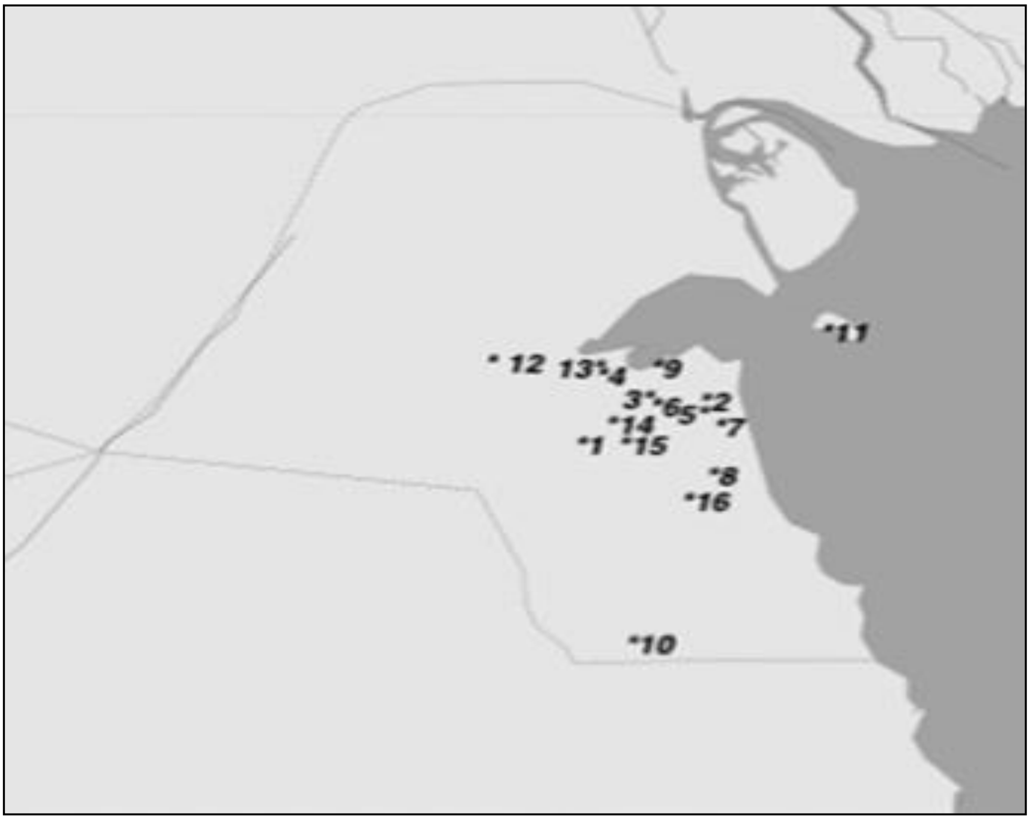


Figure 3.5 Dumping site locations in Kuwait (AL-Fares et al., 2010)

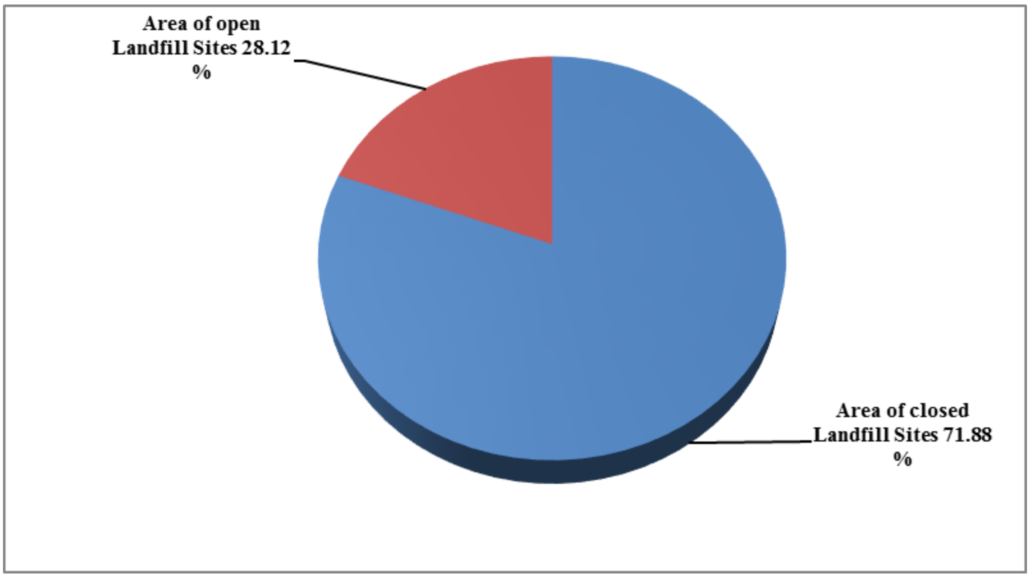


Figure 3.6 Percentage of open and closed landfills in Kuwait

• **Availability of Data**

When selecting a site for any proposed project, having access to the full set of data about the site, in addition to relevant legislation and any other information obtained on the site visits, is extremely important as it saves considerable time and effort. The lack of data, for any reason, could be a main cause of hindrance as it could lead to a waste of time, increased costs and even exclusion of the most appropriate sites.

Data is a major component of any research study, as it aids the investigation, whether this be experimentation in the field or the lab or numerical investigation. Data provides the solid foundation on which to design engineering works. After selecting the proposed sites in Stage 2, obtaining the required data for each site, such as solar irradiation, became essential. In other words, the availability of site data is extremely important in order to start the study and obtain the results to meet the proposed objectives.

3.2.3 Proposed (Selected) Sites

As a result of the site selection process carried out in Stages 1 to 3, the following sites were selected: Shagaya, Kabd, Sabria, Mutribah and Umm Gudair. The location of the selected sites are listed in Table 3.3. Figure 3.7 shows the selected sites on the Kuwait solar map. Incidentally, the sites selected represent the different regions in Kuwait, specifically: the Mutribah site represents the northern part of the country; the Umm Gudair site represents the southern part; and, the Shagaya and Kabd sites represent the western and eastern parts of Kuwait, respectively. In addition, the Sabria site is the closest to the biggest Kuwaiti islands (Failaka and Bubiyan) and, as such, could be considered to best represent these islands.

Table 3.2 Selected sites

Site Name	**Latitude (N)**	**Longitude (E)**
Shagaya	29.2°	47.1°
Kabd	29.2°	47.7°
Sabria	29.6°	47.9°
Mutribah	29.9°	47.4°
Umm Gudair	28.7°	47.8°

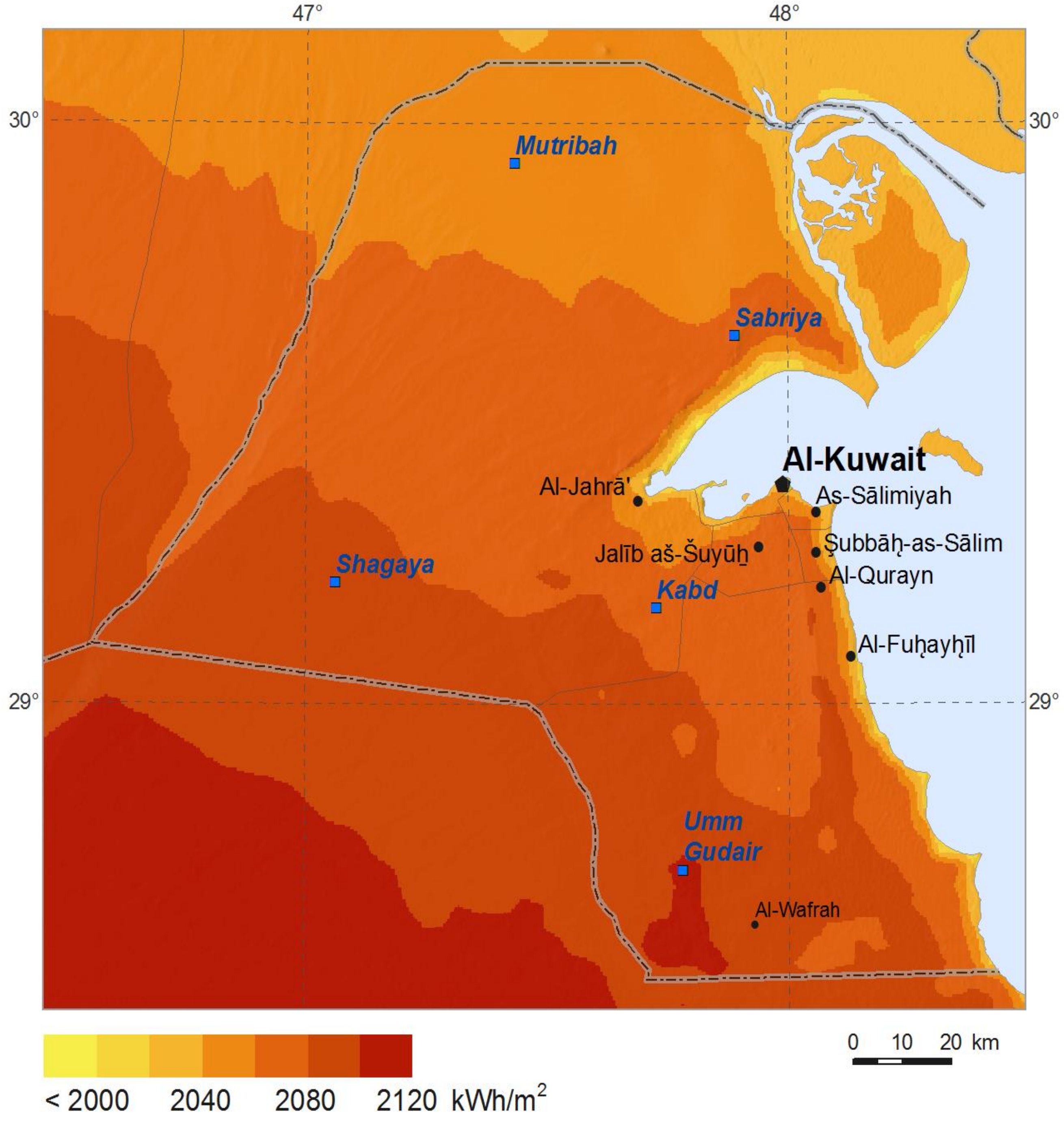


Figure 3.7 Selected sites on the Kuwait solar map (KISR, 2014b)

3.3 Data Collection

3.3.1 Introduction

The next step after selecting the proposed sites is data collection. It is important to generate all of the required data for each site in order to determine the research tasks and objectives within the planned methodology in order to achieve the objectives of this study. For the purposes of this study three types of data, namely, meteorological, geotechnical and structural, were collected.

3.3.2 Meteorological Data

In order to perform a simulation study of the performance of the PV systems by means of generating electricity by the solar modules, the meteorological data, PV solar modules, and inverters will be the main input data that would be used.

The meteorological data for the proposed sites were collected from KISR (Kuwait Institute for Scientific Research) and were used to assess the sites, that is to calculate relevant parameters and values (monthly and annual electricity production rate, performance ratio, capacity factor, and the amount of CO_2 savings). This data included basic meteorological data used in analysing and designing photovoltaic systems, such as solar irradiance, temperature and wind speed. The meteorological data used in this study pertained to the five sites identified in the selection stage in different locations in Kuwait, namely Shagaya, Kabd, Sabriya, Mutribah and Umm Gudair. The available data comprised satellite data for the five sites over long periods ranging from 1994 to 2012. Ground station data for one complete year (September 2012 to August 2013) were also collected. The ground station data was used to validate the use of the satellite data. This data are the only available data in Kuwait.

3.3.3 Structural and Geotechnical Data

For the purposes of this study a Si-poly model (S255P60 Professional) PV module made in Germany by Centro Solar and Sunny Central 630CP-JP inverters manufactured by SMA Solar Technology AG were used. These particular solar modules and inverters were chosen as they are suited to the hot desert climate in Kuwait (Rashed, 2014). Moreover, they are used for experimentation in a small scale project at top roof of the Water and Electricity Ministry as they are heavy duty, durable and have a high-performance (Rashed, 2014). The dimensions and material properties of the solar modules are shown in Table 3.4.

Table 3.3 Dimensions and material properties of the Si-poly model S255P60 Professional solar modules (Centro Solar, 2014).

Weight	20 kg
Module width	1,660 mm
Module height	990 mm
Frame thickness	40 mm
Material	Copper
Front side material	Structured low-iron glass (antireflex)
Rear side material	White foil
Frame material	Anodised aluminium

There are many factors involved in the processes of selecting a solar tracker type, for instance, the power station size, location and land area. There is a range of solar trackers on the market manufactured by different companies across the world. Most manufacturing companies focus on the design stage and the stability of the solar structure against external loads, such as wind. In addition to these external loads, one important factor to be taken into consideration when choosing a solar tracker type is Kuwait's extremely hot weather climate (characterised by the desert climate). Therefore, the Patriot Solar Group's ground mount solar tracker, which is known for its durability and ability to work in such harsh environments, was chosen for use in this study.

As previously stated, the behaviour of the dual-axis solar tracker and ground against the external loads will be investigated and therefore data pertaining to the ground properties (soil layers) will be used in the study of the proposed PV systems. Information on basic soil properties, such as unit weight, and some advanced geotechnical properties such as the cohesion, will be required.

The Shagaya site, located at the South West of the Kuwaiti capital, is the only site out of the selected sites for which geotechnical data is available and, therefore, was selected as the site on which to conduct the numerical modelling study of the proposed PV solar tracker.

The Gulf Inspection International Company, a private company, carried out investigations and soil tests on the Shagaya site in 2013. The detailed results of this investigation were provided by KISR in a report on ground investigation works for the Shagaya Renewable Energy Power Plant KUWAIT.

3.4 Performance Parameters Evaluation

A performance parameters evaluation will be conducted to determine the performance parameters of the proposed sites in the selected sites. The International Energy Agency (IEA) has identified the following performance parameters for photovoltaic systems (Marion et al., 2005):

- total energy generated by the PV system;
- final yield (YF);
- reference yield (YR);
- performance ratio (PR);
- capacity factor (CF); and
- system efficiency.

The most effective way to obtain the performance parameters of the proposed sites is through the use of simulation software. There are several simulation software tools that are widely used to simulate renewable energy systems, the most commonly used for PV systems being RETScreen, PV F-Chart, Solar Design Tool, INSEL, TRNSYS, NREL Solar Advisor Model (SAM). The choice of software to be used depends on the purpose of the study; for instance, the TRNSYS software is most suitable for energy simulations (Frontini et al., 2013). The Solar Advisor Model (SAM) is another recommended software tool which is widely used in different renewable energy projects. SAM software is a commonly used program in solar energy fields for both grid-connected and stand-alone systems (Frontini et al., 2013; Kandasamy et al., 2013; Lee et al., 2011; Siraki and Pillay, 2010). For the purposes of this research, however, it is not the ideal choice as it is not uploaded with Kuwaiti metrological data. Moreover, the single-axis and dual-axis tracking systems that are an integral part of this study are not easy to simulate in this program.

Although SAM software allows the user to enter metrological data, this requires a special data format, called a typical meteorological year (TMY) data. TMY data represents the metrological data for a period of 30 years or more for a specific location on a reasonable annual data set, including the type of data that is mostly used by building designers and in other renewable energy conversion systems (Wilcox and Marion, 2008).

After contacting the relevant ministries and organisations in the state of Kuwait, the researcher was only able to identify one site with a TMY file, is Kuwait's international airport, which is not relevant to this study.

PVsyst software is used only on photovoltaic applications and, as such, is more focused on photovoltaic energy principles (Mermoud, 1995). It will be used in this study as it allows the user to import data. In addition, it has a valuable online database that is updated with all the related specifications of the modules and inverters on the market produced by different companies across the world. After obtaining the results from the PVsyst program, the performance of the PV system for each site will be assessed according to the parameters set and the effect of using single-axis and dual-axis tracking systems will also be investigated.

The monthly data relating to each selected site will be compared on the basis of the energy output and performance ratio. In addition, an annual base analysis will also be conducted based on the performance parameters to obtain a more effective analysis and enable comparison of the results with similar results reported in the literature.

3.5 Environmental Evaluation

As stated in the literature review and the introduction, the increased rate of use of fossil fuels is a serious danger that threatens the future of the human race. This danger is manifested in different ways, for example, global warming. Global warming is attributed to the high amounts of greenhouse gases (GHG) that are emitted as result of using fossil fuels, such as oil and natural gas, to generate electricity. The environmental evaluation study will be conducted at all the proposed sites and the influence of using single-axis and dual-axis tracking systems will also be evaluated.

It is evident in the literature review that the most commonly used method in environmental studies is the life cycle assessment (LCA) method. According to this method, any product, such as the solar modules for the PV systems which are being considered in this study, is assessed on the basis of its life cycle. In other words, the assessment will include all the life stages of the product, starting from the point of acquisition of the material and ending at the recycling stage. All the energy used in the life cycle will be estimated including the energy used in installation, maintenance and even recycling. This will give a detailed, accurate and complete picture about the role of PV systems in environment pollution.

It should be emphasised here that, although PV systems are known as being environmentally friendly technology as no emissions are emitted when this technology is implemented, a large amount of emissions is emitted in the production stage which uses a large amount of energy for instance, in refining and purifying the silicon material used in PV systems.

The evaluation study will be conducted in two ways; first, the LCA will be conducted which will evaluate PV systems in terms of the Energy Payback Time (EPBT), the energy yield ratio (EYR) and the GHG emissions rate. At this stage, the total energy used in the life cycle of the PV system will be estimated together with the total amount of emissions generated. The evaluation indices (EPBT, EYR and GHG emissions rate) will be calculated based on the annual produced energy which will be obtained from the performance parameters study. Second, in order to gain a better understanding of the environmental benefits of using PV systems, the amount of avoidable GHGs as a result of implementing PV systems in Kuwait will be estimated together with the effect of using different tracking systems.

3.6 Economic Evaluation

An economic evaluation study of the proposed sites will be conducted to meet another main objective of this research. Various methods are used to evaluate the feasibility of renewable energy projects, such as payback time (PBT), accounting rate of return (ARR), net present value (NPV), and levelized cost of electricity (LCOE).

PBT is the time that the project will take to cover the cost of the investment. It is a simple and easy method to apply. However, it does not take into account the time value of the money and revenues after including payback time. ARR is the ratio between the average profits and the initial investment. It is also considered an easy to use method, but once again it does not include the effect of time value.

NPV is a widely used method on which the decision of accepting or rejecting the proposed projects can be based. It is simply the summation of all cash flow values including the initial investment cost. A positive NPV value (NPV>0) means the proposed project may be accepted, while a negative NPV value (NPV<0) means the project should be rejected.

The levelized cost of electricity (LCOE) is another common method used to compare different techniques and technologies for producing electricity, such as comparing the cost of electricity generated by a renewable technology and conventional power plants (Bakhshi and Sadeh, 2016). LCOE is an important measure that can be used in evaluating the financial aspect of many energy generation technologies. A lot of solar technology projects are economically evaluated based on the LCOE methodology, which focuses on the lifetime of generated energy and the total cost of the installed system (Branker et al., 2011). The main inputs of LCOE are the installation cost, and operations and maintenance (OM) costs. It is generally agreed that photovoltaic solar module efficiency and the levels of solar radiations at the installation site are the most important factors of PV technology (Smestad, 2008).

In this study the LCOE method will be used in investigate the proposed PV systems in Kuwait. An economic evaluation of the proposed sites will be conducted to investigate the feasibility of using PV systems in Kuwait. In order to effectively evaluate the proposed PV systems by the means of a complete study from economic perspectives, the focus will be applied on the following stages:

- An economic assessment of implementing PV systems;
- Cost-benefit analysis; and
- Cost of CO_2 saved.

The economic assessment of the implementation of PV systems in Kuwait will be conducted by determining the LCOE for each individual site using different tracking systems. The results obtained will be compared with the LCOE values of conventional power plants in the State of Kuwait. In this comparison, the key parameter of the comparison between the proposed PV systems and the conventional power plants will be considered to be 0.12 $/kWh (0.09 £/kWh).

In addition, as stated in the literature review, in order to overcome the uncertainty and the lack of the data related to Kuwait to be used by generated using the LCOE method, a sensitivity analysis of the most important factors involved in the LCOE calculations, such as the installation costs, interest rates, and the lifetime of PV system components, will be conducted.

A cost-benefit analysis of using the proposed PV systems will be carried out to determine the amount of money that would be saved by using PV systems to generate electricity instead of using conventional power plants. In this study, the effect of oil price fluctuation will be considered by assuming a wide range of oil prices, from \$20 (£15.34) to \$100 (£76.68) per barrel.

Finally, the amount of CO_2 emissions avoided as a result of using PV systems at the proposed sites will be determined in monetary terms to add value to the economic analysis of the use of PV systems.

3.7 Numerical Modelling

The numerical modelling of the proposed solar trackers is an important objective in this research as it will support and complement the previous methods used to assess the feasibility of using PV systems in Kuwait. Moreover, the numerical modelling will be conducted to investigate the behaviour of the solar tracker and the ground will significantly address a gap in the knowledge identified in the literature review.

Numerical modelling using the finite element method will investigate the use of a fixed, single-axis and dual-axis solar tracker in Kuwait. The process will help check the stability of the solar tracker against its self-weight and the wind load. The effects of the wind load from different directions will be taken into account.

It should be highlighted here that another important reason for carrying out numerical modelling in this research is the fact that the efficiency of the solar modules is dependent upon the orientation and tilting angle of the solar modules, and thus, any changes to either caused by unexpected soil settlement due to stresses and strain on the soil particles can have an impact on their efficiency. Therefore, the study of the behaviour of the solar tracker and the ground as a whole model is very helpful in order to increase the efficiency of the solar modules.

It bears pointing out here that previous research did not generally include the ground (soil layers) when analysing and designing the solar tracker structure against external loads including wind load.

The basic principle behind the use of solar trackers is to increase the efficiency of the solar modules by tracking sunlight. In other words, the solar modules should be positioned towards sunlight in order to receive the highest amount of solar radiation. Thus, the sunlight is tracked by changing the solar tracker elevation (inclination angle) and orientation position. It is clear that the movement of the solar tracker and the wind load are the main parameters in this study and there is no clear correlation between them. Moreover, the thermal loads from high temperature are included in this study.

In this study, in order to study the effects of aerodynamic loads and self-weight of the tracker, equivalent stress, displacement, equivalent strain and factor of safety will be determined. The effects of inclination angles of the solar tracker and of different wind directions will be also investigated.

Selecting the appropriate software is an extremely important step in order to meet the predetermined goals and objectives of any proposed study. There is no doubt that the purpose of the study is the most important measure to select the software; however, in large scale studies with changing variables or objectives.

It is very useful to use the software that has the highest reliability and is flexible enough to cater for any unexpected changes even in the objectives or the main aim of the proposed study. In this research, the numerical modelling study will be conducted based on the finite elements method (FEM) using COMSOL Multiphysics software.

This software is commonly considered to be one of the most robust and effective finite elements programs in benchmark studies (Hickey and Gottsmann, 2014), which can be used to solve multi-physics problems. Moreover, it allows the user to import geometry from other software. One additional important advantage of using COMSOL Multiphysics software is the ability to use more analytical or constitutive equations; in other words, the user can add or change the mathematical equations.

Stability analysis is an important aspect of geotechnical engineering analysis. In addition, solar trackers must be able to withstand wind loads. This 3 D soil-structure interaction study will place a great deal of emphasis on the stability of the soil and the proposed foundations as the solar modules efficiency is highly affected by the inclination angle and the orientation of the solar tracker.

It is generally accepted in the geotechnical engineering scientific field that soil behaviour is not linear and, therefore, effective modelling of the soil behaviour by means of selecting the best constitutive model was an important step in this study. Table 3.5 lists the common constitutive models that are used in numerical modelling applications (El-Hamalawi, 2002).

In order to investigate the behaviour of both the PV solar tracker and the soil against the external loads, the following parameters, which are the commonly used parameters, will be considered (Ferroudji et al., 2014):

- von Mises stress;
- equivalent strain;
- factor of safety (FOS); and
- displacement.

Table 3.4 Constitutive Models

Model	**Description**
Linear-Elastic Relationship	- simple. - based upon Hooke's theory.
Elastic-Plastic Relationships	Defines two stress states - the elastic domain - the material yield surface.
Tresca Yield Criterion	- Suited for metals yield criterion. - States that the onset of yielding occurs when the maximum shear stress in the material reaches a critical value.
Von Mises Yield Criterion	- Suited for modelling the behaviour of metals yield criterion - States that plastic yielding occurs when the second deviator stress reaches a critical value.
Mohr-Coloumb Yield Criterion	- Suited for materials soils and concrete whose behaviour is highly dependent upon the hydrostatic pressure within the material.
Drucker Prager Yield Criterion	- The Drucker-Prager yield surface forms a smooth approximation of the Mohr-Coulomb criterion making a pressure sensitivity modification to the previously discussed Von Mises surface.

Chapter 4 – Performance Parameters of Photovoltaic Systems in Kuwait

4.1 Introduction

The performance of solar modules depends on the type of technology employed (i.e. the efficiency of the modules) and is also considerably influenced by environmental conditions, e.g. temperature and dust (Fuentealba et al., 2015).

As stated in the introduction chapter, Kuwait has a desert climate, which is primarily dry and hot in summer and cold in winter, with some humidity and instances of dusty weather during the year. This type of weather influences the performance of the solar modules, in particular the very hot conditions during the summer months, when the temperature varies between 25^{o}C and 45^{o}C in the shade, which in the sun can reach higher values. These effects can clearly established in a technical manner by determining energy output throughout the year.

The performance assessment is an important criterion, investigating the performance of any proposed photovoltaic (PV) system in accordance with all relevant input data, e.g. the metrological data of the proposed site. Such technical assessments are generally conducted through the use of performance parameters.

In feasibility studies of PV systems, inaccurate data is primarily attributed to the measurement of the values of solar irradiation and electrical power (Fuentealba et al., 2015). These errors were therefore taken into consideration during the current research, enabling the acquisition of accurate data, i.e. Section 4.2, in which two sources of data were used: (1) satellite data for the long term study and (2) ground station data for a single year.

This chapter discusses the performance parameters investigating the potential use of PV systems to generate electricity in Kuwait. The study focussed on five different sites in Kuwait, obtaining relevant data and using two sources of data for validation purposes. Commercial software (PVsyst) was employed to analyse data (e.g. metrological data and additional input parameters) and compute the performance parameters.

An investigation was also undertaken into the effect of using single-axis and dual-axis PV systems on the performance parameters. Firstly, Section 4.2 introduces the selected sites and metrological data in which the study is applied; secondly, Section 4.3 outlines the proposed

PV system; thirdly, Section 4.4 outlines the performance parameters; fourthly Section 4.5 discusses the results: and finally, the conclusions are discussed in Section 4.6.

4.2 Selected Sites and Metrological Data

As stated in Section 3.2, the proposed sites for implementing PV systems in Kuwait were selected through the site selection process undertaken in Chapter 3. Five different sites were selected to conduct the performance parameters of the proposed systems: (1) Shagaya; (2) Kabd; (3) Sabria; (4) Mutribah; and (5) Umm Gudair (Figure 3.6). The location and elevation of the selected sites are listed in Table 4.1.

Table 4.1 Location and elevation of the selected sites

Site Name	**Latitude (N)**	**Longitude (E)**	**Elevation (m)**
Shagaya	29.2^0	47.1^0	240
Kabd	29.2^0	47.7^0	76
Sabria	29.6^0	47.9^0	74
Mutribah	29.9^0	47.4^0	88
Umm Gudair	28.7^0	47.8^0	201

As stated in Section 3.5, PVsyst, PC software package for the design and analysis of PV systems, will used to compute the performance parameters of the PV systems at the selected sites. Many researches in photovoltaic energy field have been conducted using PVsyst software (Kumar and Sudhakar, 2015). PVsyst is basically simulation software that is commonly used in feasibility studies to evaluate the performance of any proposed PV system. This software is supplemented by a metrological database in numerous parts of the world, such as global irradiation, wind speed, and temperature (Muñoz et al., 2016). Moreover, one important advantage of this software is that personal data can be imported as well.

The simulation processes passes through simple procedures; starting with defining the location and metrological input data for the proposed site, the orientation and the type of tracking systems and the type of proposed solar modules and inverters (SolarEdge, 2016).The key data inputs required by this software to estimate the energy production from the proposed sites are: (1) meteorological data; (2) location; (3) PV module type; (4) inverter type; and (5) the electrical and mechanical specifications of the PV modules. Inverters are required to perform the design and the analysis process of the proposed PV systems.

It is important to emphasise that solar irradiation values are not constant throughout the year, but change as a result of the sun's declination over both a single day and due to seasonal variation. The literature review identified that a considerable proportion of previous research, and in particular that focussed on Kuwait, has employed a constant solar radiation, termed the average solar radiation. However, using an average value of the solar irradiation throughout the year can lead to highly inaccurate results, leading to inappropriate decisions.

Therefore, this aspect was addressed by acquiring the solar irradiation data for each site on a daily basis. The meteorological data for the proposed sites were collected from KISR, and used in assessing the sites by calculating the performance parameters. This included basic meteorological data employed in analysing and designing PV systems, e.g. solar irradiance, temperature and wind speed.

The data employed consisted of satellite data for all the selected sites over the long term, i.e. from 1994 to 2012. There was also a collection of ground station data for one complete year (i.e. September 2012 to August 2013). Each of the meteorological ground stations is based on a 10 m tower, consisting of four wind speed cup-type sensors at 1, 4, 6, and 8 m heights to derive the wind speed profile (KISR, 2014). In addition, a combined wind speed and direction sensor at a height of 10 m was employed, along with one solar radiation sensor (pyranometer), with an uncertainty of 5% (Figure 4.1). A pyranometer is a common measurement tool of global solar irradiation, placed horizontally over a flat surface, in order to receive solar radiation from all directions (Lysko, 2006).

In this current study, the ground station data validates the use of the satellite data. Tables 4.2-4.6 demonstrate the average daily and monthly solar irradiation of the ground stations for Shagaya, Kabd, Sabriya, Mutribah, and Umm Gudair from September 2012 to August 2013. The average annual solar irradiation for the ground and satellite data are listed in Tables 4.7 and 4.8, respectively. The data employed is relatively matching, and therefore provide an effective indication of the quality of the collected data (Table 4.9).

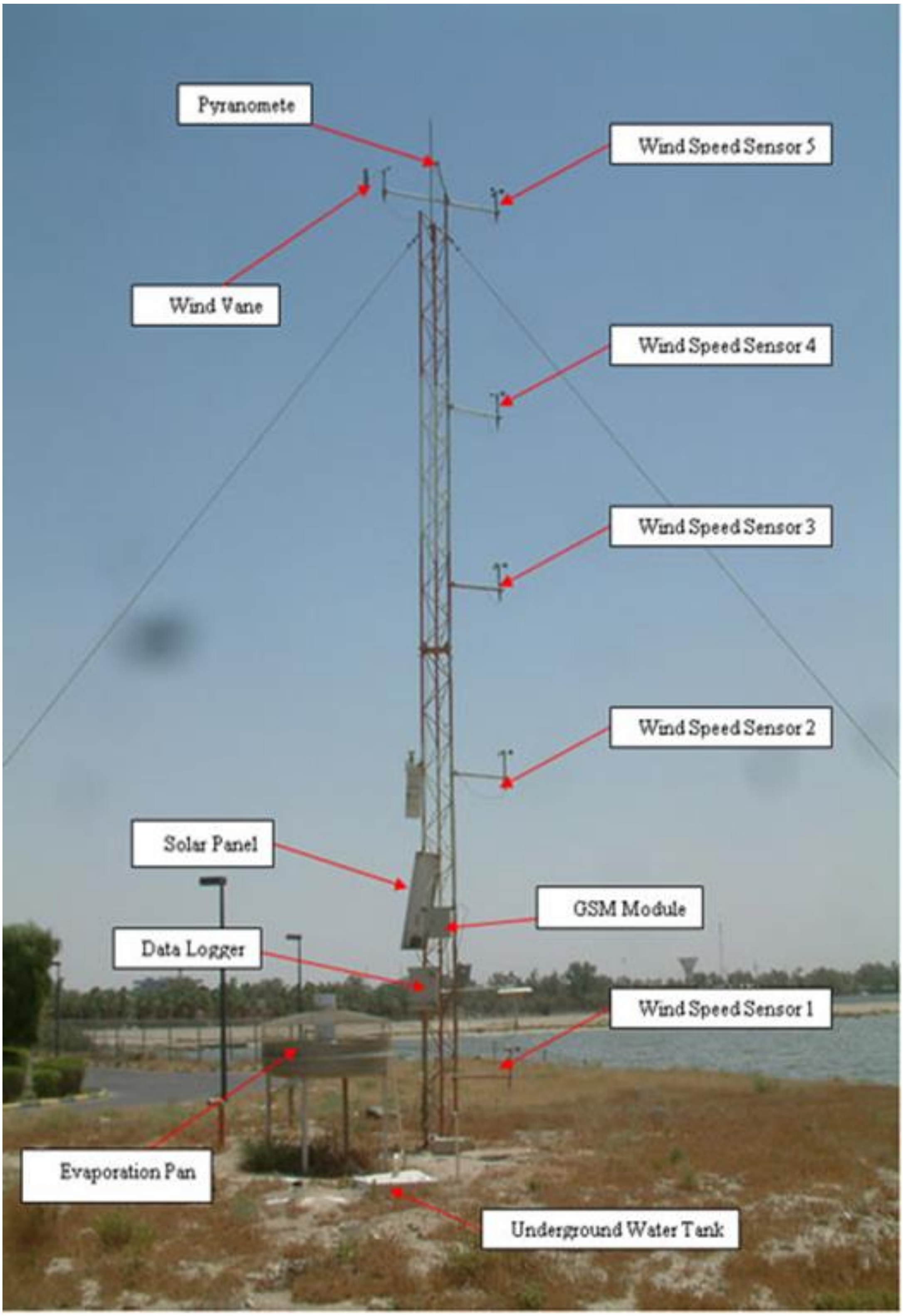


Figure 4.1 A typical meteorological station (KISR, 2014b)

Table 4.2 The average daily and monthly data for Shagaya from September 2012 to August 2013. The data was collected from KISR.

Month	**Average daily solar irradiation (kWh/m^2)**	**Average monthly solar irradiation (kWh/m^2)**
September	6.728	201.83
October	5.156	159.83
November	3.77	113.11
December	3.198	99.14
January	3.545	109.89
February	4.849	135.77
March	5.772	178.92
April	6.775	203.26
May	7.572	234.72
June	8.08	242.39
July	8.123	251.81
August	7.652	237.20

Table 4.3 The average daily and monthly data for Kabd from September 2012 to August 2013. The data was collected from KISR.

Month	**Average daily solar irradiation (kWh/m^2)**	**Average monthly solar irradiation (kWh/m^2)**
September	6.426	192.77
October	4.970	154.06
November	3.633	109.00
December	3.051	94.57
January	3.449	106.93
February	4.787	134.04
March	5.694	176.53
April	6.506	195.18
May	7.248	224.68
June	7.817	234.50
July	7.832	242.81
August	7.345	227.70

Table 4.4 The average daily and monthly data for Mutribah from September 2012 to August 2013. The data was collected from KISR.

Month	Average daily solar irradiation (kWh/m^2)	Average monthly solar irradiation (kWh/m^2)
September	6.485	194.56
October	4.819	149.38
November	3.509	105.26
December	2.960	91.75
January	3.344	103.65
February	4.597	128.73
March	5.510	170.80
April	6.404	192.11
May	7.278	225.62
June	7.940	238.19
July	7.904	245.03
August	7.441	230.68

Table 4.5 The average daily and monthly data for Sabreya from September 2012 to August 2013. The data was collected from KISR.

Month	Average daily solar irradiation (kWh/m^2)	Average monthly solar irradiation (kWh/m^2)
September	6.496	194.89
October	4.952	153.52
November	3.530	105.91
December	3.049	94.51
January	3.296	102.19
February	4.672	130.81
March	5.539	171.71
April	6.569	197.06
May	7.256	224.94
June	7.843	235.28
July	7.887	244.50
August	7.441	230.68

Table 4.6 The average daily and monthly data for UmmGhdair, from September 2012 to August 2013. The data was collected from KISR.

Month	**Average daily solar irradiation (kWh/m^2)**	**Average monthly solar irradiation (kWh/m^2)**
September	6.728	201.83
October	5.337	165.44
November	3.970	119.10
December	3.378	104.71
January	3.744	116.05
February	5.046	141.29
March	5.939	184.10
April	6.684	200.51
May	7.470	231.56
June	7.824	234.72
July	7.734	239.75
August	7.668	237.71

Table 4.7 Average annual solar irradiation of the ground stations for Shagaya, Kabd, Sabriya, Mutribah, and Umm Gudair, from September 2012 to August 2013. The data was provided by the Kuwait Institute for Scientific Research.

Site	**Solar irradiation ($kWh/m^2/year$)**
Umm Ghdair	2176.8
Shagaya	2167.9
Kabd	2092.8
Sabreya	2086
Mutribah	2075.8

Table 4.8 Average annual solar irradiation of the satellite data for Shagaya, Kabd, Sabriya, Mutribah, and Umm Gudair. The data was collected from KISR.

Site	**Solar irradiation (kWh/m^2/year)**
Umm Ghdair	2123.4
Shagaya	2054
Kabd	2119.5
Sabreya	2072.7
Mutribah	2059

Table 4.9 Solar irradiation (kWh/m^2/year) for satellite data and ground station data for Shagaya, Kabd, Sabriya, Mutribah and Umm Gudair. The data was collected from KISR.

Site	**Ground Stations**	**Satellite data**	**% (Satellite/Ground)**
Umm Ghdair	2176.8	2123.4	97.55
Shagaya	2167.9	2054	94.75
Kabd	2092.8	2119.5	101.28
Sabreya	2086	2072.7	99.36
Mutribah	2075.8	2059	99.19

The potential use of PV systems on the proposed sites can be initially determined from the solar irradiation data of each site. Figures 4.2 to 4.6 show the monthly solar irradiation of the proposed sites, which varies between 91.75 and 251.81 kWh/m^2 throughout the year. The minimum value was recorded in December at the Mutribah site, and the maximum value was recorded in July at the Shagaya site.

In general, high rates of solar irradiation were reported between June and August. This is the peak of summer in Kuwait, during which there is sunlight for a considerable proportion of each day, giving the solar modules the most effective opportunity to harvest a higher amount of solar irradiation. The opposite is true for the period between November and February, during which days are relatively short. Thus, the variation in daily solar irradiation is attributable the earth's rotation around its axis every twenty-four hours, while the data also reveals monthly variations in solar irradiation, and between summer and winter, due to the variation in hours of sunshine.

The location of the proposed site (i.e. the country) needs to be taken into consideration, including whether it is situated in the northern or southern hemisphere. This is due to the earth revolving round the sun in 365 days, leading to a variance in the hours of sunshine, and thus the inclination and orientation of the solar modules are affected by the sun's movement, both during a single day and an entire year. This ensures the vital role of solar tracking systems, including methods of maximising the amount of solar irradiation received. The importance of implementing solar trackers is discussed below, during the comparison of the amount of energy received by both fixed and tracking PV systems. At the same time, the variation in the recorded data of the selected sites (i.e. from site to site) is considered normal, as the selected sites are distributed in different locations in the country, i.e. this variation in data is fairly limited.

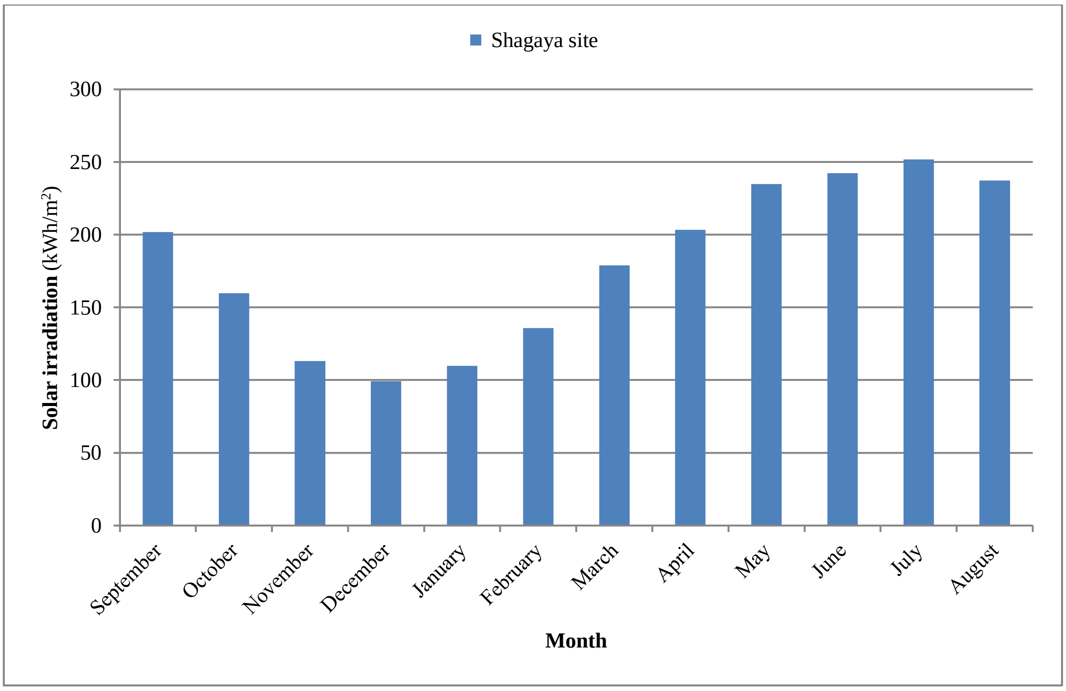


Figure 4.2 Solar irradiation for the Shagaya site

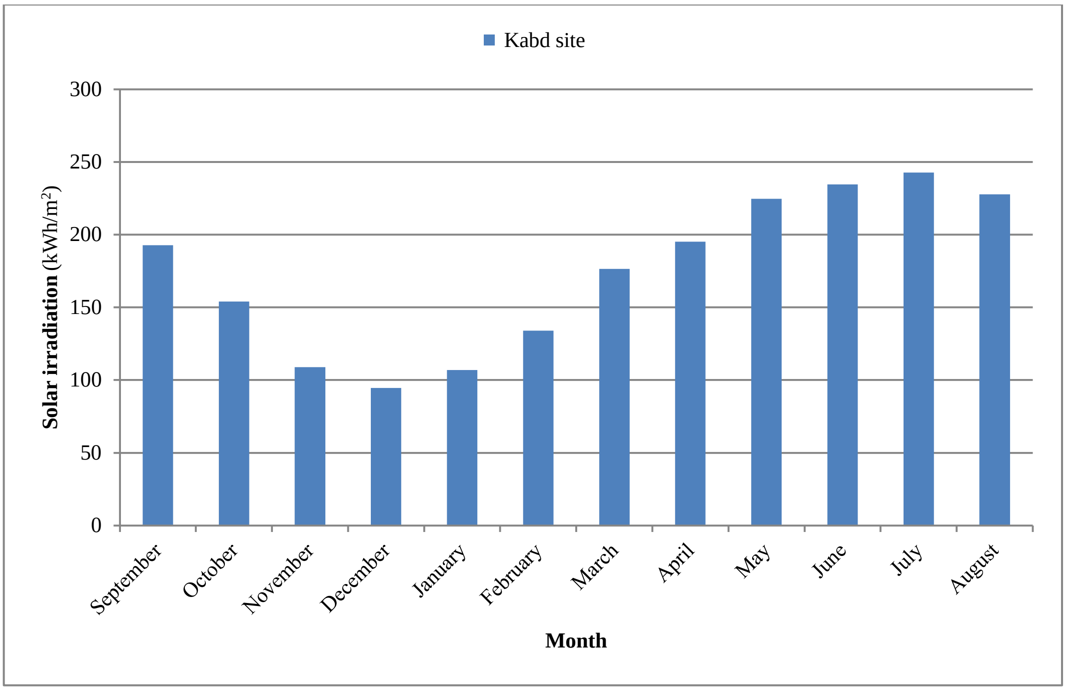


Figure 4.3 Solar irradiation for the Kabd site

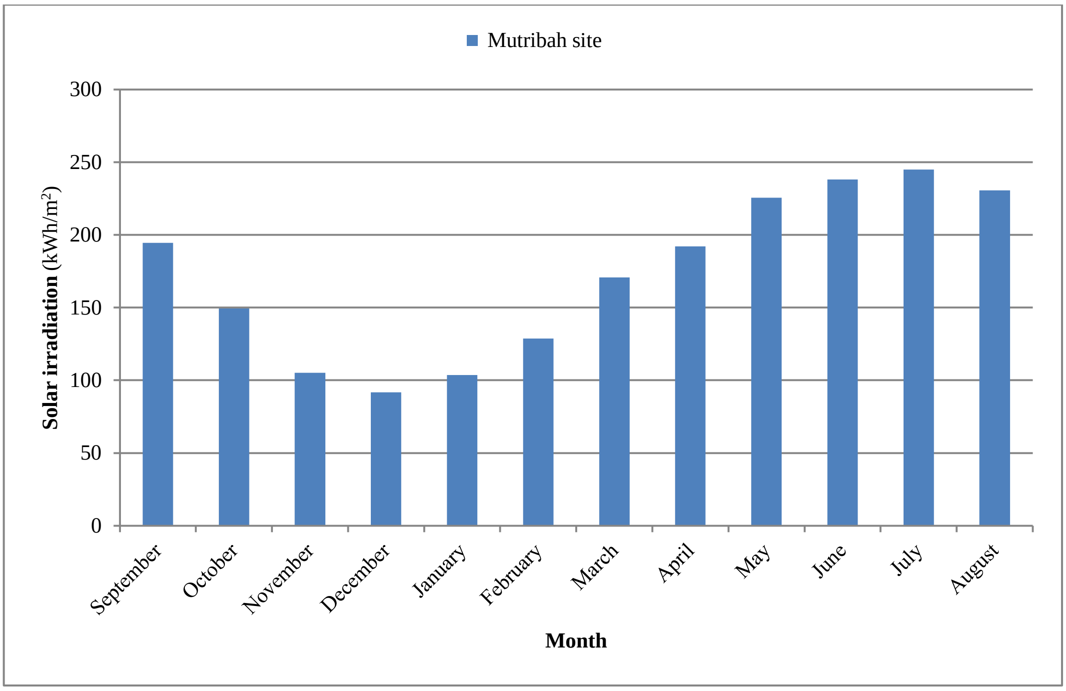


Figure 4.4 Solar irradiation for the Mutribah site

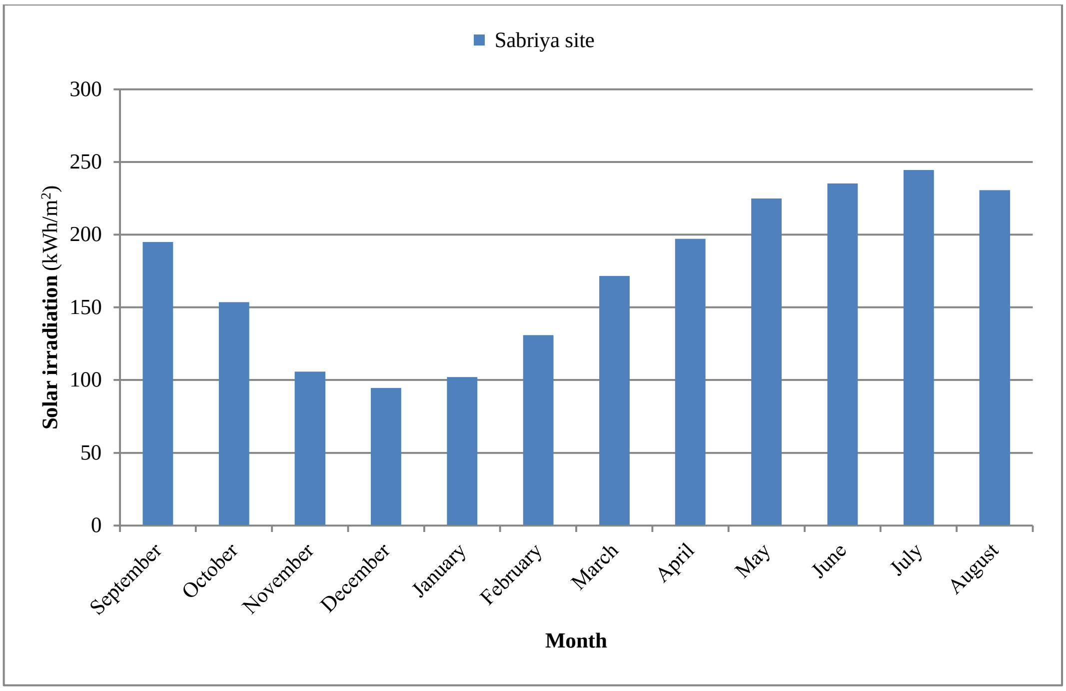


Figure 4.5 Solar irradiation for the Sabreya site

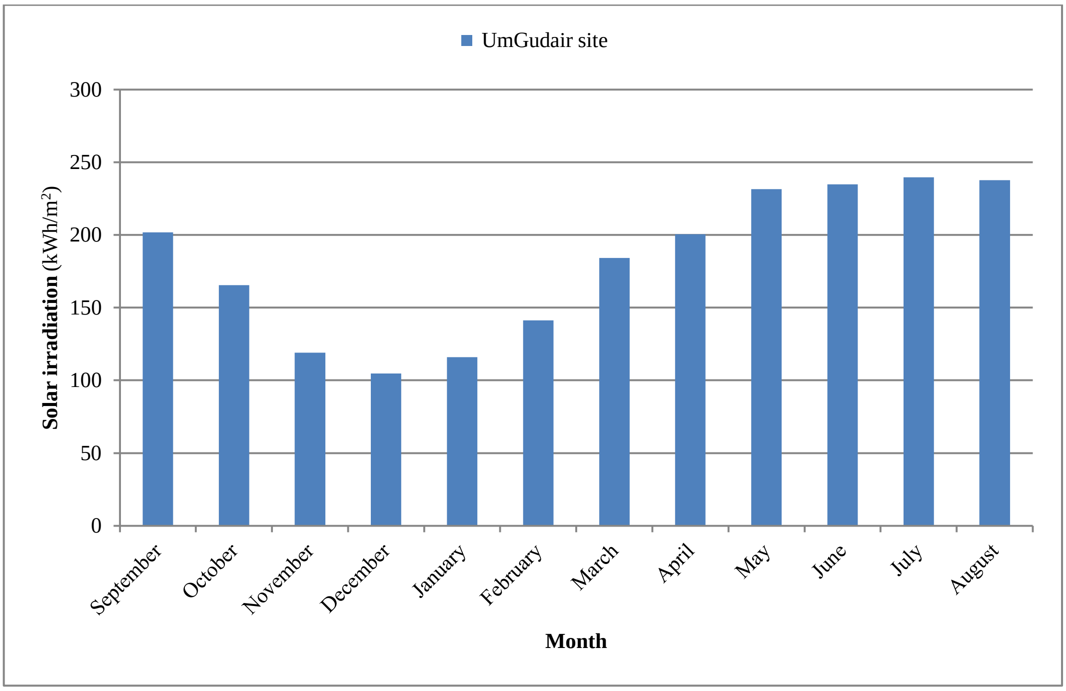


Figure 4.6 Solar irradiation for the UmGudair site

4.3 The Proposed PV System

The selected sites are located in open areas, where there is no indication of projects being undertaken by either private or government sectors in the near future. Therefore, this study considers the most effective option to be large-scale PV systems. In addition, large-scale capacity systems (i.e. generally larger than 5 MW) tend to be the most effective systems in terms of long-term investment and environmental benefits. However, the most common disadvantages of large scales PV systems include the need for a considerable amount of land and a relatively high degree of investment. This is addressed in the current study by locating the selected PV sites in uninhabited open areas, at a sufficient distance from residential and commercial areas.

The energy produced by PV systems is highly influenced by the technical specifications of the systems applied, e.g. PV modules and inverters; climate conditions; and the type of mounting structure (Aste and Del Pero, 2010). As stated in the literature review, the solar modules convert the sunlight into electricity (DC), and therefore the efficiency of the solar modules is taken with great interest weather in the production stage of these modules or the power production stage. However, it is important to emphasise that the efficiency value of the any single module is computed at the standard test conditions (STC). This needs to be considered when designing a new PV system, in which the main base output consists of the amount of electricity required. The subsequent design step consists of the selection of the type of PV modules, as this determines their number, as well as the configuration of the proposed PV system.

In this present study, a 100 MW grid connected power station is proposed for all selected sites, with each power station divided into eight arrays, of 12.5 MW for each array. A PV module type Si-poly model (S255P60 Professional) and Inverter type Sunny Central 630CP-JP Manufacture (SMA) were used in this study. The PV module specifications and the design configuration for each array are provided in Table 4.10.

Table 4.10 Design array configuration and PV module specifications (Centro Solar, 2014; SMA, 2014)

Total number of PV modules	49020 modules In series: 20 modules; In parallel: 2451 strings
PV module type	Si-poly model (S255P60 Professional)
Maximum Power (P_{max})	255 W_p
Voltage at Maximum Power (V_{mpp})	29.87 V
Current at Maximum Power (I_{mpp})	8.54 A
Open Circuit Voltage (V_{oc})	37.69 V
Short Circuit Current (I_{sc})	8.99 A
Efficiency	15.50 %
Inverter Model	Sunny Central 630CP-JP Manufacture: SMA Solar Technology AG
Operating Voltage	500-850 V

4.4 Performance Parameters of the Proposed PV Systems

This section analyses the results for each single site, based on the results obtained from simulations using PVsyst software of the proposed PV systems, with different tracking systems. The main objective of this chapter is to determine the performance parameters of the proposed PV systems in the selected site, using different tracking systems.

As stated in Section 2.5.2, the International Energy Agency (IEA) stated that the main components of the performance parameters of PV systems consist of the total energy generated by the PV system; Final Yield (YF); Reference Yield (YR); Performance Ratio (PR); Capacity Factor (CF); and system efficiency (Marion et al., 2005).

The equations 2.1 to 2.5 were introduced in Section 2.5.2 to explain the performance parameters. These equations have been reproduced below:

$$YF = E_{AC} / P_{PV,\ rated} \tag{2.1}$$

$$YR = (H_t)\ (kWh/m^2) / G\ (1\ kW/\ m^2) \tag{2.2}$$

$$PR = YF / YR \tag{2.3}$$

$$CF = E_{AC} / (P_{PV,\ rated} \text{ x } 8760) \tag{2.4}$$

The performance parameters of the proposed PV system can be established by computing all performance parameters recommended by EIA, and comparing the results with separate results, i.e. from the literature. A detailed analysis will be undertaken of the performance parameters of each site, based on the above definitions and equations. The effect of using different tracking systems is discussed in the following section.

4.5 Results and Discussion

A crucial step in this research is the performance evaluation of the proposed PV systems in Kuwait. It forms the solid base of this research, which focuses on a detailed analysis of the feasibility of PV systems in Kuwait. Thus, the results of the performance evaluation clarify the need to continue seeking further feasibility components, including the economic and environmental parts previously selected for investigation. The environmental and economic evaluation studies are dependent on the performance evaluation study, and therefore the results of the technical study will form a primary input for both the environmental and economic evaluation studies. This is clarified in detail in the next chapters (i.e. chapters 5 and 6).

The feasibility study was undertaken in Kuwait, leading to considerable focus on selecting appropriate sites in which to undertake the study. It is important to ensure the selection of the most representative sites, in order to ensure effective coverage of the entire country. This is demonstrated in the site selection process contained in the methodology of this current research. At the same time, considerable focus has been placed on methods of acquiring the metrological data, i.e. the type and period. Two different sets of data were employed (i.e. satellite and ground station data) for validation purposes for all the selected sites. It is important to use high quality data for these types of renewable energy projects, in order to ensure accuracy and so obtain precise and realistic results. The main input data employed in the simulation software included the metrological data and the specifications of the proposed PV system components, e.g. solar modules and inverters.

It should also be noted that considerable effort was made to ensure a complete and robust performance evaluation study through the use of a preliminary stage. This study focussed on covering most of the identified gaps, or underestimated parameters, identified in the literature, as can be seen in: (1) the type of data collected; (2) the process of site selection (i.e. the selection of the most appropriate sites) and (3) the use of specialised software. The literature review identified that only a small number of authors have investigated the performance of the solar photovoltaic systems in Kuwait. This current study also identified a lack of investigation in Kuwait into the effect of using tracking systems with a complete technical view, which can be attributable to a lack of interest in the use of renewable energy.

The performance evaluation study was conducted by determining the performance parameters recommended by EIA. The investigation took place in two parts: (1) the first part was based on a monthly basis analysis, in which the most important two parameters for each site were computed, i.e. the monthly production and the performance ratio. (2) The second part focussed on an investigation undertaken on an annual basis, in which all the performance parameters were determined. The importance of the second part was subsequently identified when comparing the results with relevant works in the field of PV energy, in order to effectively evaluate the obtained results.

As noted in the literature review, one of the challenges negatively affecting or delaying utilising PV systems in Kuwait (and other countries with hot and arid climates) is the high summer temperatures in such regions. It should be further noted that, alongside the increase in temperature during the summer months, there is also an increase in the number of hours of sunshine, i.e. between nine hours in December and eleven hours in August (see Table 4.11.). This ensures additional sunshine hours for the production of energy.

Table 4.11 The monthly average duration of sunshine in Kuwait. (data taken from KISR, 2014b)

Month	Sunlight (hours)
January	8
February	8.55
March	9
April	8
May	10
June	10
July	10
August	11
September	10
October	10
November	8
December	7
Year	9.1

Any increase in production time (i.e. sunshine hours) will have positive results for large scale projects in terms of the total energy produced. A holistic analysis is important when evaluating such conditions with dependent variables, i.e. the efficiency of the solar modules is inversely proportional to the temperature. It is therefore important to balance both the expected advantages and disadvantages of the proposed project prior to decisions being taken in projects highly affected by several parameters.

A detailed study was conducted at the selected sites, based on a monthly data analysis for the energy output and the performance ratio. In addition, the annual basis analysis was also considered (i.e. by means of performance parameters), in order to obtain a more focused analysis and a comparison of the results with those found in the literature. The output energy and the performance ratio of each site, with different tracking systems, are listed in Tables 4.12 to 4.16. The monthly energy output for fixed tracking systems varies between 12001 and 16513 MWh, and between 13252 and 21978 MWh for single-axis tracking systems, and 14677 and 22540 MWh for dual-axis tracking systems.

The minimum energy output of the proposed fixed tracking systems was obtained at the Mutribah site, while the maximum value was observed at the UmGudair site. The minimum energy output values of single-axis and dual-axis tracking systems were obtained at the

Mutribah and Kabd sites, respectively, while both maximum obtained values of the energy output were observed at the Sabria site. The performance ratios for the proposed systems varied between 69.92% and 86.41% for the fixed proposed tracking systems and between 67.85% and 86.79% and 67.62% and 85.60% for the single-axis and dual-axis tracking systems, respectively. The minimum performance ratios were found at the Kabd site, and the maximum values at the Mutribah site.

Overall, the average energy output per month was equal to 14257 MWh for fixed tracking systems, with an average performance ratio of 78.17%. An average output energy of 17615 and 18608.5 MWh was also established, with an average performance ratio of 77.32% and 76.61% for both the single-axis and dual-axis tracking systems. This variation in the results obtained was not unexpected, as the selected sites were in different locations and subject to different metrological data.

Table 4.12 The energy output in MWh and the performance ratio in % for the Shagaya site.

Month	**Energy output** (MWh)			**Performance ratio (PR)** %		
	Fixed	**Single-axis**	**Dual-axis**	**Fixed**	**Single-axis**	**Dual-axis**
January	13301	15061	16489	86.03	86.41	85.17
February	13371	15723	16405	83.94	83.81	83.02
March	16148	20081	20400	81.56	81.56	81.53
April	14497	18611	18789	79.22	78.76	78.95
May	15199	19945	20399	76.38	75.75	75.80
June	15332	20522	21156	73.64	72.18	71.79
July	15676	20864	21390	72.51	71.04	70.76
August	15834	20740	20986	71.84	70.42	70.52
September	15857	20044	20195	73.65	72.81	72.75
October	14985	18165	18629	77.36	77.17	76.47
November	12327	13971	14994	82.51	82.67	81.53
December	12511	14109	15672	86.16	86.51	85.17
Year	175038	217836	225504	78.06	77.16	76.91

Table 4.13 The energy output in MWh and the performance ratio in % for the Kabd site.

Month	**Energy output** (MWh)			**Performance ratio (PR)** %		
	Fixed	**Single-axis**	**Dual-axis**	**Fixed**	**Single-axis**	**Dual-axis**
January	12994	14564	15889	85.77	86.08	84.88
February	13216	15344	16042	84.18	84.12	83.51
March	16349	20260	20562	81.58	81.43	81.37
April	14676	18488	18638	79.29	78.81	79.04
May	15514	20217	20664	76.16	75.55	75.61
June	15787	20641	21200	72.25	70.18	69.65
July	16351	21664	22144	70.48	68.10	67.62
August	16376	21135	21342	69.92	67.85	67.88
September	16191	20042	20152	72.02	70.84	70.68
October	15490	18536	19079	77.14	77.04	76.38
November	12443	14142	15093	82.57	82.70	81.72
December	12132	13257	14677	85.38	85.69	84.45
Year	177519	218290	225482	77.16	75.91	75.64

Table 4.14 The energy output in MWh and the performance ratio in % for the Sabria site.

Month	**Energy output** (MWh)			**Performance ratio (PR)** %		
	Fixed	**Single-axis**	**Dual-axis**	**Fixed**	**Single-axis**	**Dual-axis**
January	12719	14299	15653	85.77	86.14	84.93
February	12909	15090	15758	83.99	83.88	83.20
March	16116	20109	20446	81.72	81.68	81.62
April	14486	18472	18639	79.77	79.35	79.55
May	15333	20333	20817	76.55	76.04	76.14
June	15622	21329	21986	72.83	71.14	70.69
July	16080	21978	22540	71.40	69.53	69.18
August	16159	21650	21913	70.59	68.93	69.00
September	16099	20424	20578	72.39	71.39	71.23
October	15293	18502	19094	77.39	77.38	76.68
November	12499	14205	15288	82.61	82.83	81.84
December	12061	13380	14843	85.72	86.10	84.87
Year	175376	219771	227555	77.54	76.46	76.21

Table 4.15 The energy output in MWh and the performance ratio in % for the Mutribah site.

Month	**Energy output** (MWh)			**Performance ratio (PR)** %		
	Fixed	**Single-axis**	**Dual-axis**	**Fixed**	**Single-axis**	**Dual-axis**
January	12832	14451	15853	86.41	86.79	85.60
February	13060	15242	15944	84.53	84.44	83.74
March	16414	20569	20962	82.11	82.14	82.08
April	14452	18688	18879	79.63	79.49	79.73
May	15113	19921	20366	75.91	75.23	75.29
June	15455	21281	21951	72.39	70.87	70.45
July	15935	21911	22485	70.70	68.77	68.45
August	15979	21448	21706	69.96	68.20	68.26
September	15922	20227	20380	72.27	71.42	71.23
October	14850	17887	18388	77.63	77.67	76.94
November	12335	13982	15044	83.29	83.52	82.57
December	12001	13252	14748	86.40	86.78	85.59
Year	174348	218859	226706	77.51	76.41	76.18

Table 4.16 The energy output in MWh and the performance ratio in % for the UmGudair site.

Month	**Energy output** (MWh)			**Performance ratio (PR)** %		
	Fixed	**Single-axis**	**Dual-axis**	**Fixed**	**Single-axis**	**Dual-axis**
January	13556	15347	16705	85.63	85.93	84.75
February	13553	15895	16568	83.82	83.70	83.05
March	16513	20616	20934	81.47	81.33	81.27
April	14767	18949	19127	79.01	78.46	78.68
May	15389	20214	20676	76.26	75.57	75.57
June	15464	21148	21822	72.70	71.04	70.51
July	16080	21888	22439	71.21	69.09	68.62
August	16204	21815	22089	70.70	68.95	68.99
September	16179	20507	20651	72.52	71.38	71.28
October	15822	19218	19783	77.26	77.09	76.47
November	12757	14465	15441	82.36	82.37	81.31
December	12560	13872	15328	85.62	85.95	84.73
Year	178844	223934	231563	77.47	76.28	76.00

The literature review established that the efficiency of solar modules is highly influenced by climate conditions, and in particular high temperatures, i.e. one of the most common characteristics of Kuwait. A comparison based on the energy output and performance parameters of different tracking systems can be seen in Figures 4.7 to 4.16, which also include the effect of temperature, based on the average monthly temperature in Kuwait.

Figures 4.7 to 4.16 reveal that the maximum energy output values were obtained in March for the fixed tracking systems, and in July for the single-axis and dual-axis tracking systems, while, for all tracking systems, the minimum energy output values were observed in December. The highest performance ratios were observed in January for all tracking systems, while the minimum values occurred in August for both fixed and single-axis tracking systems, and in July for dual-axis tracking systems.

The energy output of the proposed PV systems was impacted in two ways for all tracking systems: firstly, the increase in temperature (commencing in April and reaching its peak values in July, then subsequently decreasing); and secondly, the increase in hours of sunshine during this period. As a result, the figures reveal that the combined effect of the increase in temperature and the length of sunshine was insignificant. However, an examination of the performance ratio of the proposed systems is the most effective way of understanding the correlation between the temperature and performance of the PV systems. It was observed that the performance ratio of all the proposed systems decreases with an increase in temperature. This is primarily attributable to the heating of the solar modules as the temperature increases during summer, leading to a decrease in the efficiency of the solar modules.

In addition, the fixed tracking systems demonstrated the most effective average performance (78.17 %) and the dual-axis tracking systems the lowest average performance ratio (76.61 %), while the single-axis tracking systems demonstrated an average performance value of (77.32 %), due to the high amount of energy lost. This can be observed in the behaviour of the dual-axis tracking systems, which move in two separate directions to follow the sun with the optimum inclination and orientation of the solar modules, in order to collect the maximum amount of solar irradiation. Although the highest amount of output energy was observed to originate from the dual-axis solar trackers, they also have the highest degree of energy loss, as observed in the performance ratios. The highest performance ratios were achieved by the fixed tracking systems, in which the amount of collected energy was less than the single-axis and dual-axis tracking systems, but less energy was also lost.

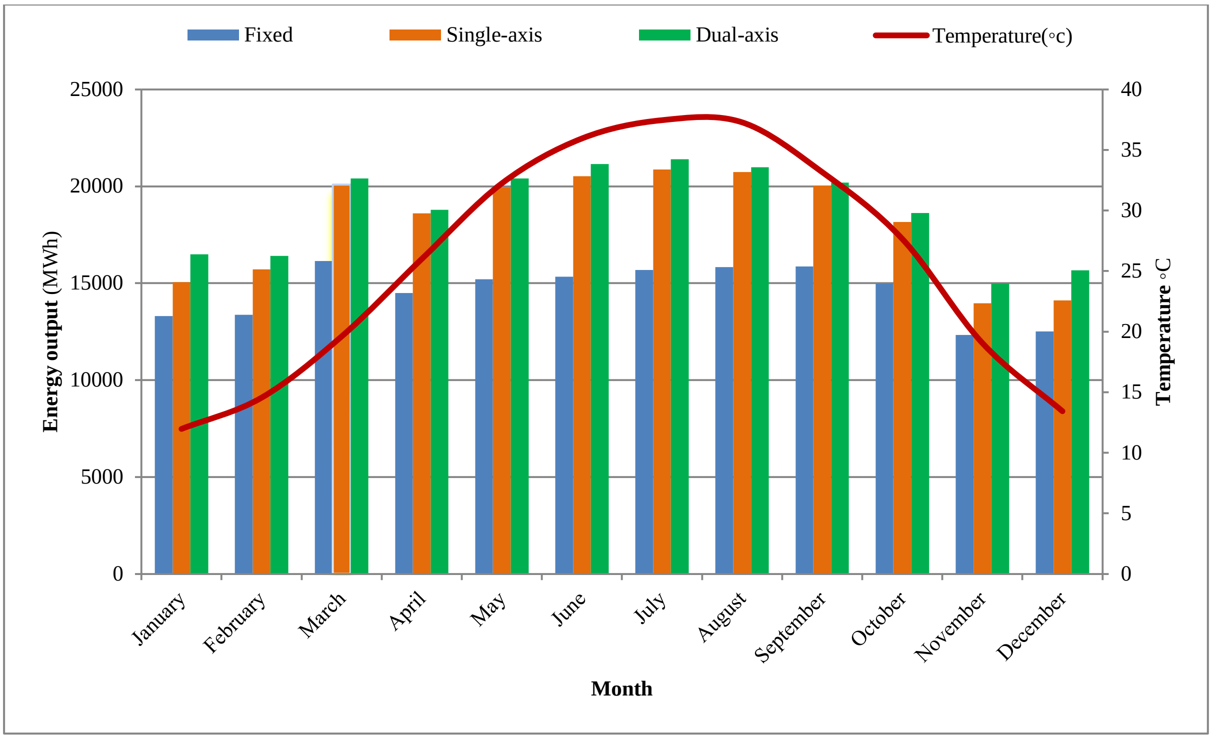


Figure 4.7 The monthly energy output with different tracking systems for the Shagaya site.

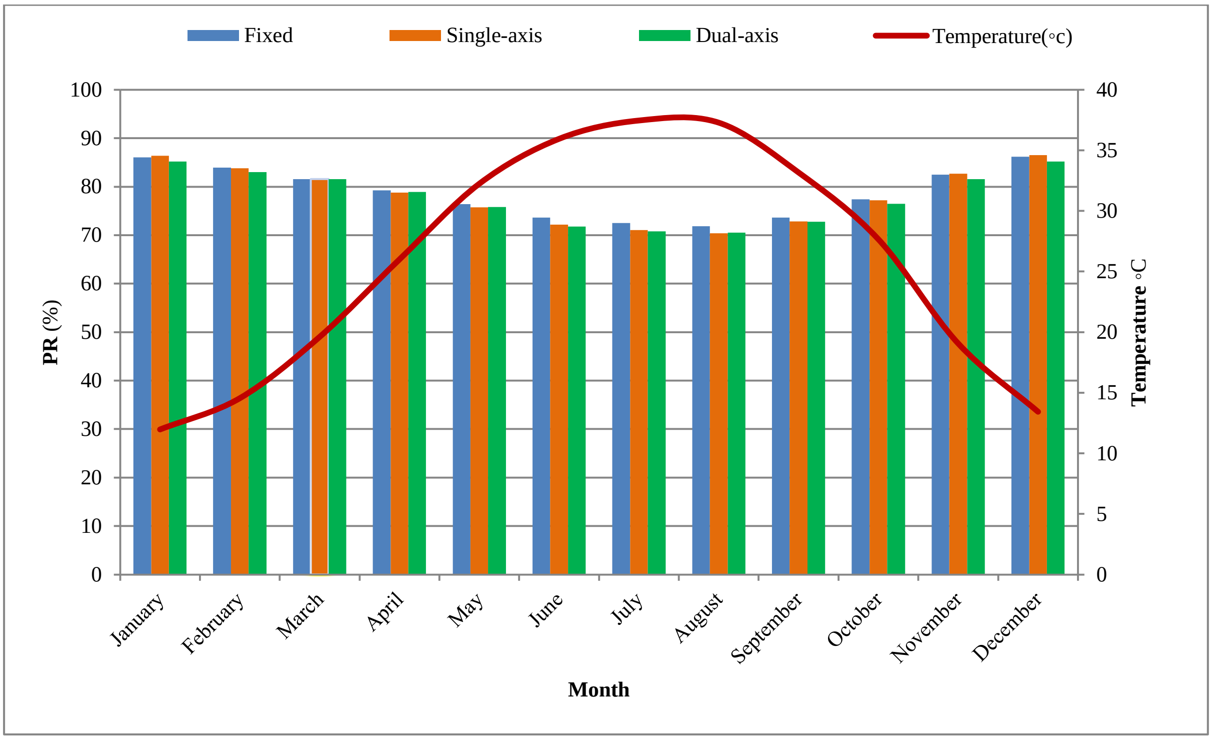


Figure 4.8 The monthly performance ratio with different tracking systems for the Shagaya site.

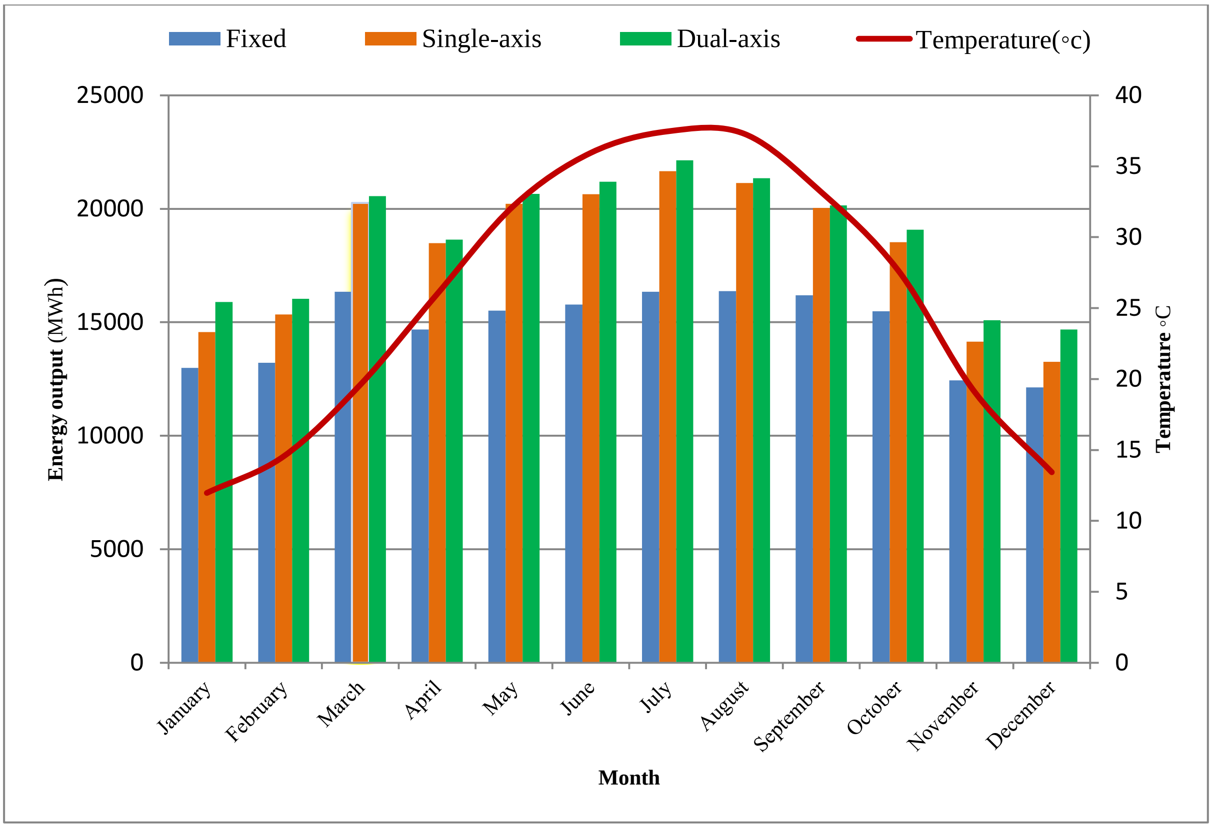


Figure 4.9 The monthly energy output with different tracking systems for the Kabd site.

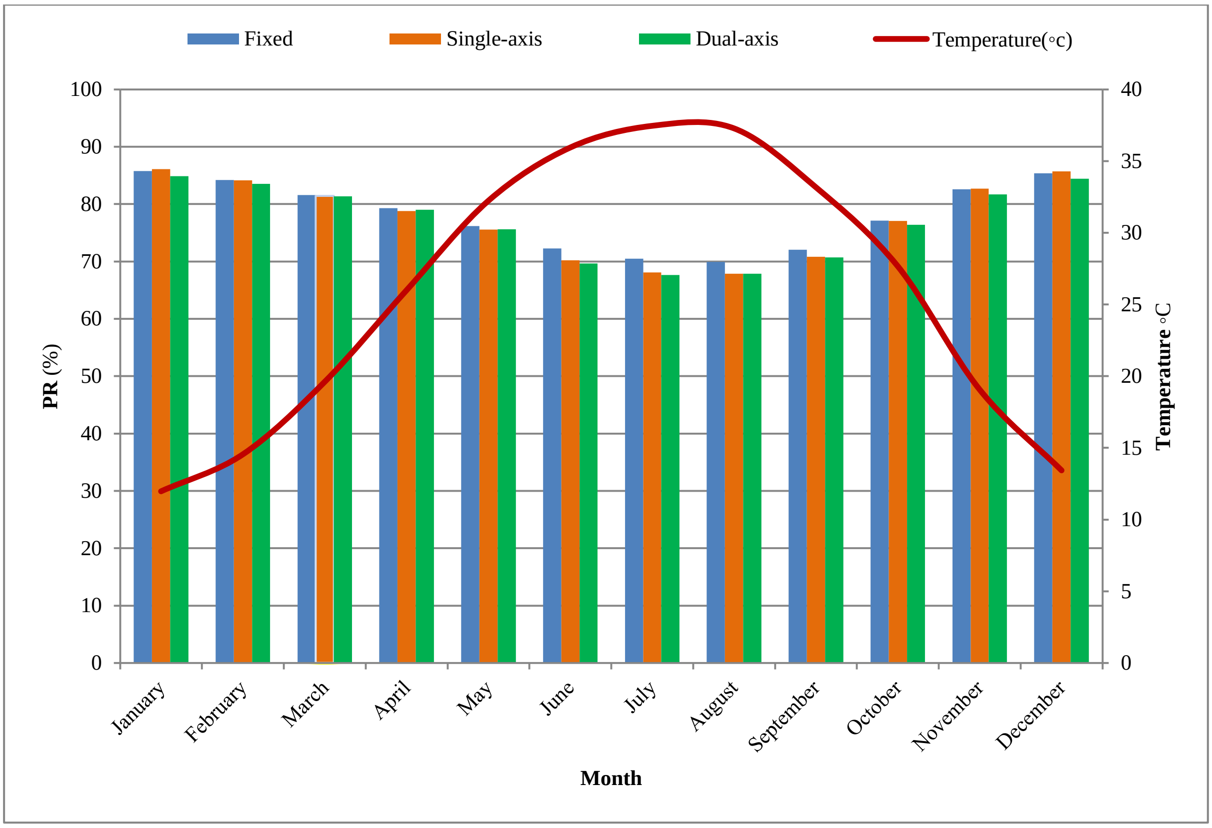


Figure 4.10 The monthly performance ratio with different tracking systems for the Kabd site.

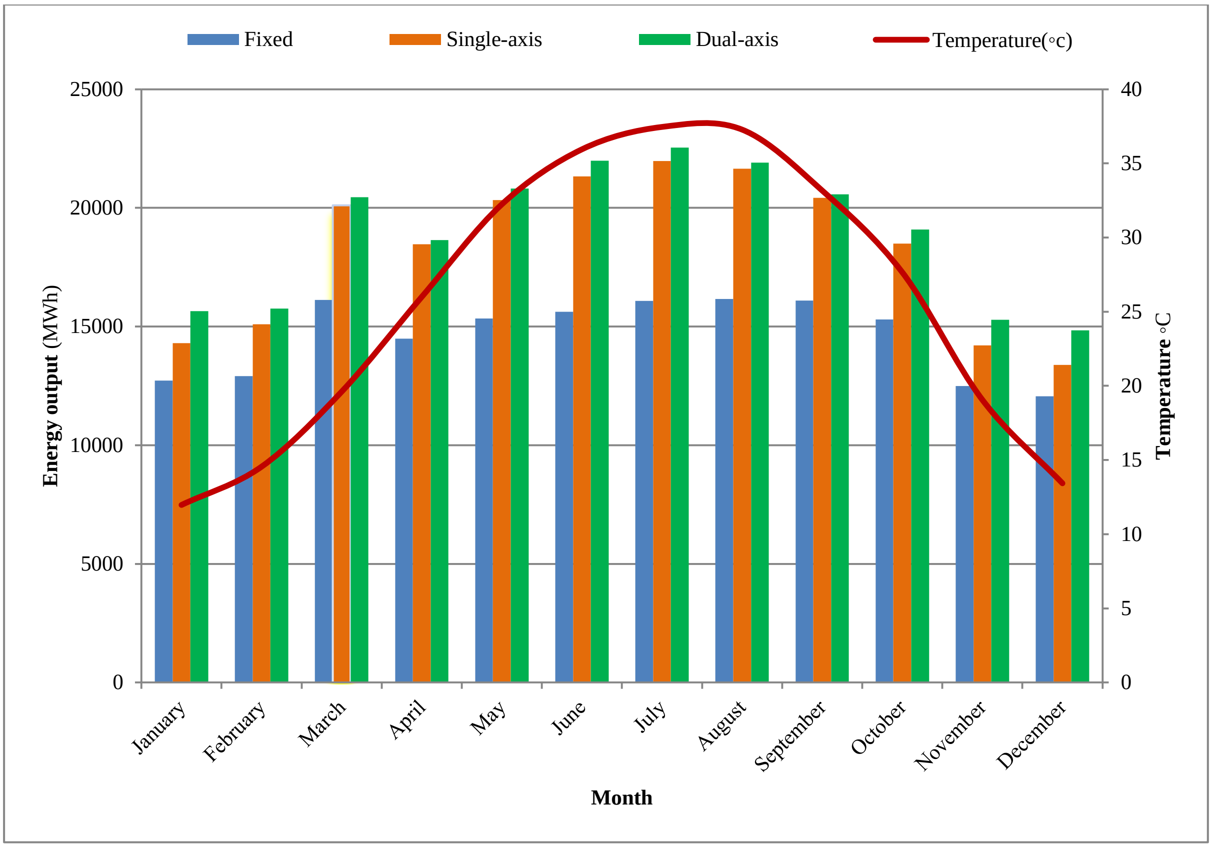


Figure 4.11 The monthly energy output with different tracking systems for the Sabria site.

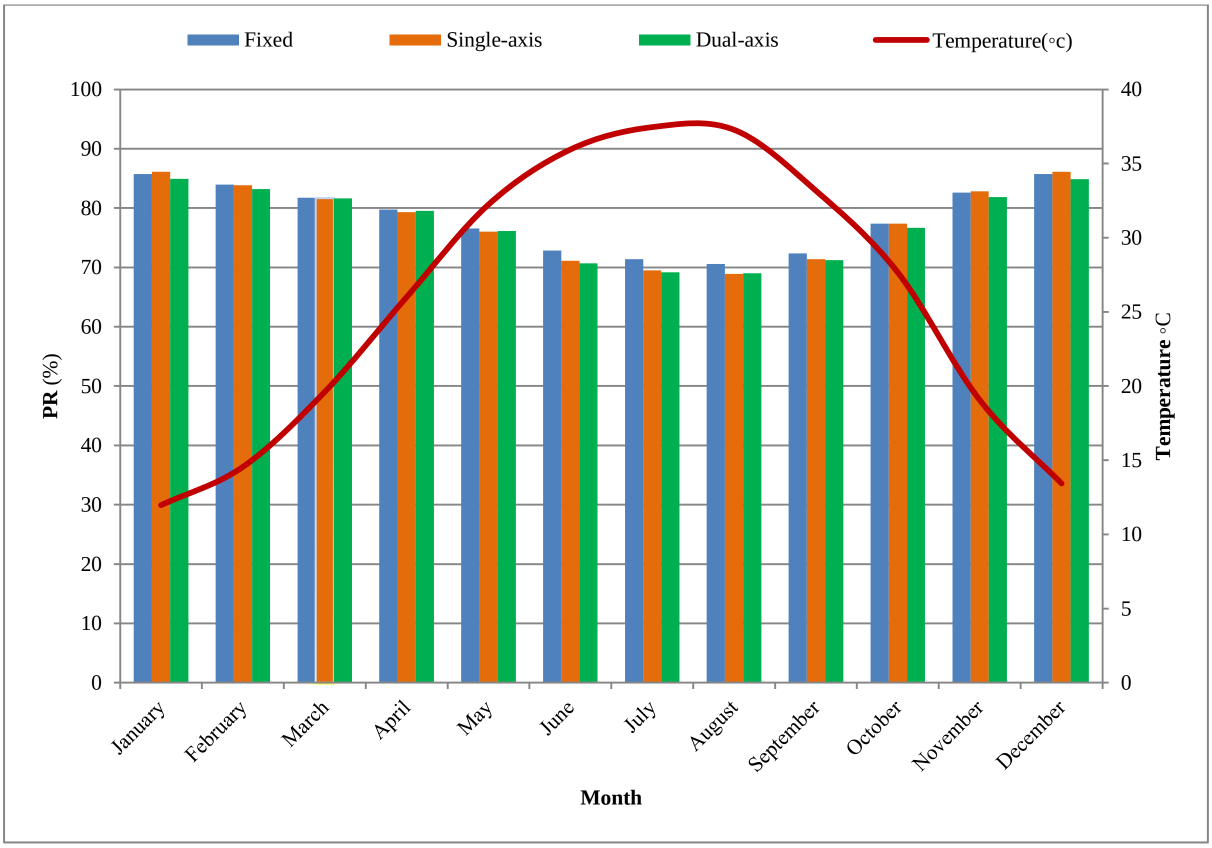


Figure 4.12 The monthly performance ratio with different tracking systems for the Sabria site.

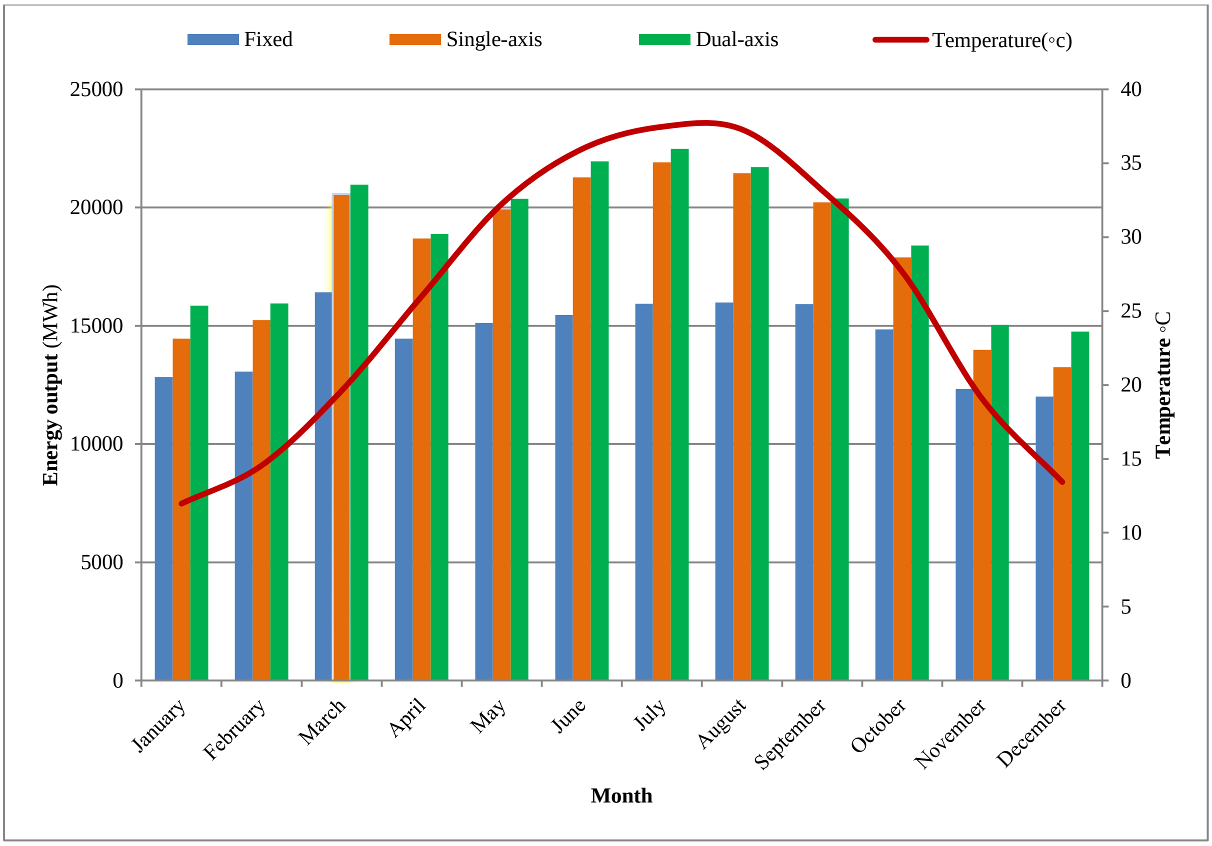


Figure 4.13 The monthly energy output with different tracking systems for the Mutribah site.

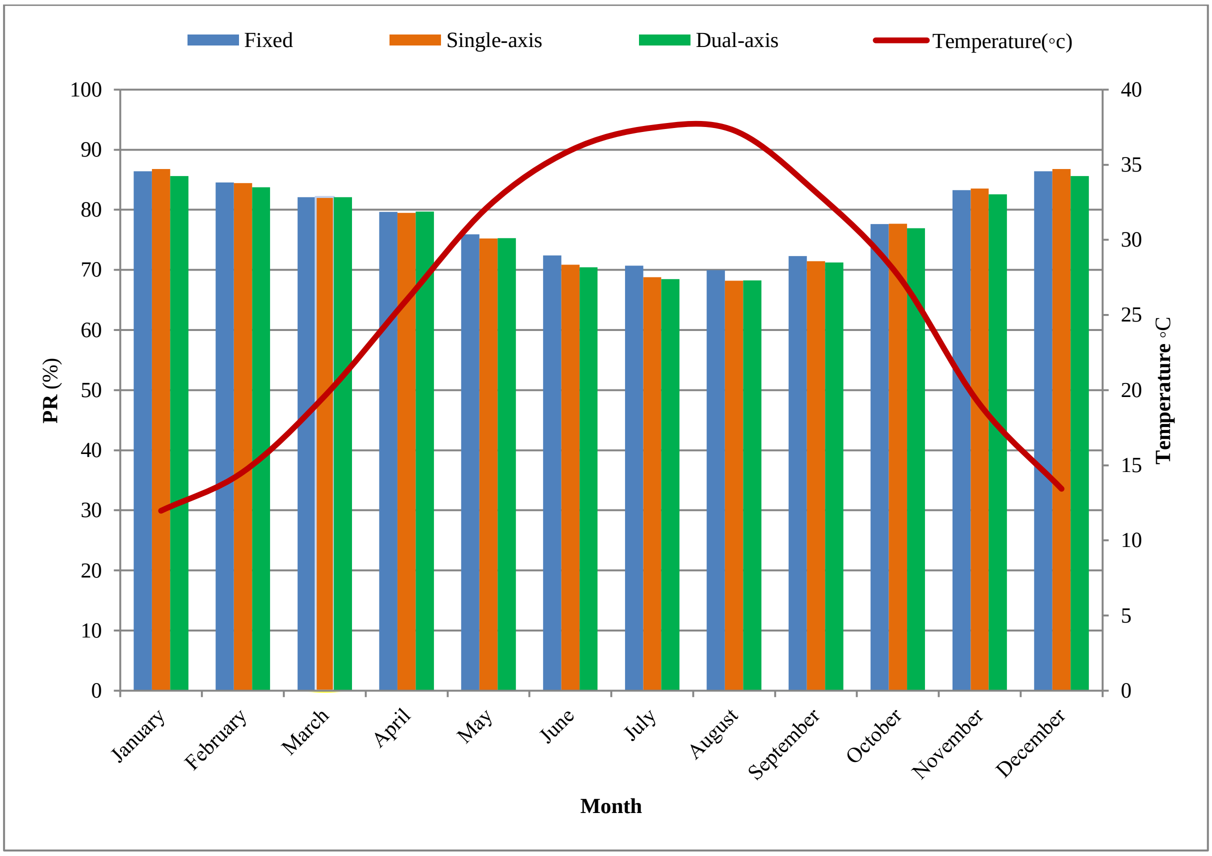


Figure 4.14 The monthly performance ratio with different tracking systems for the Mutribah site.

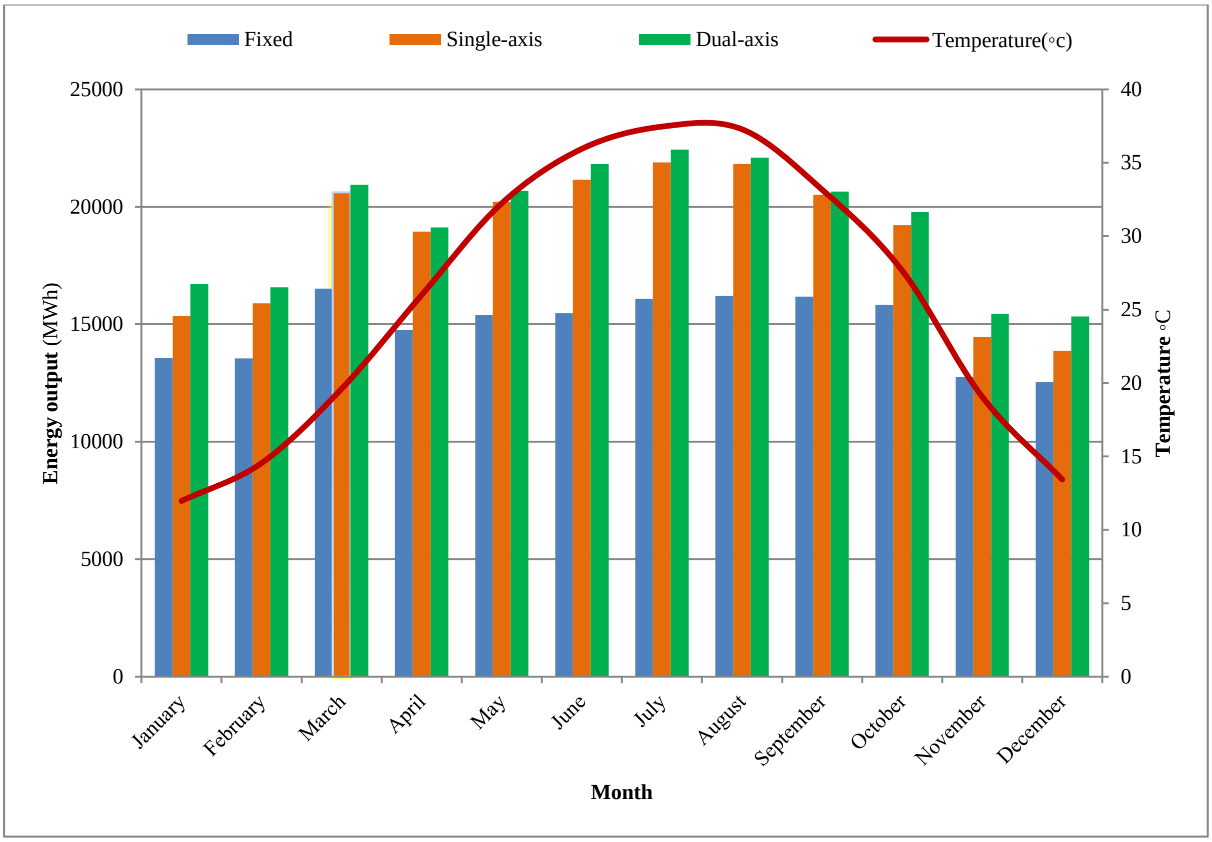


Figure 4.15 The monthly energy output with different tracking systems for the UmGudair site.

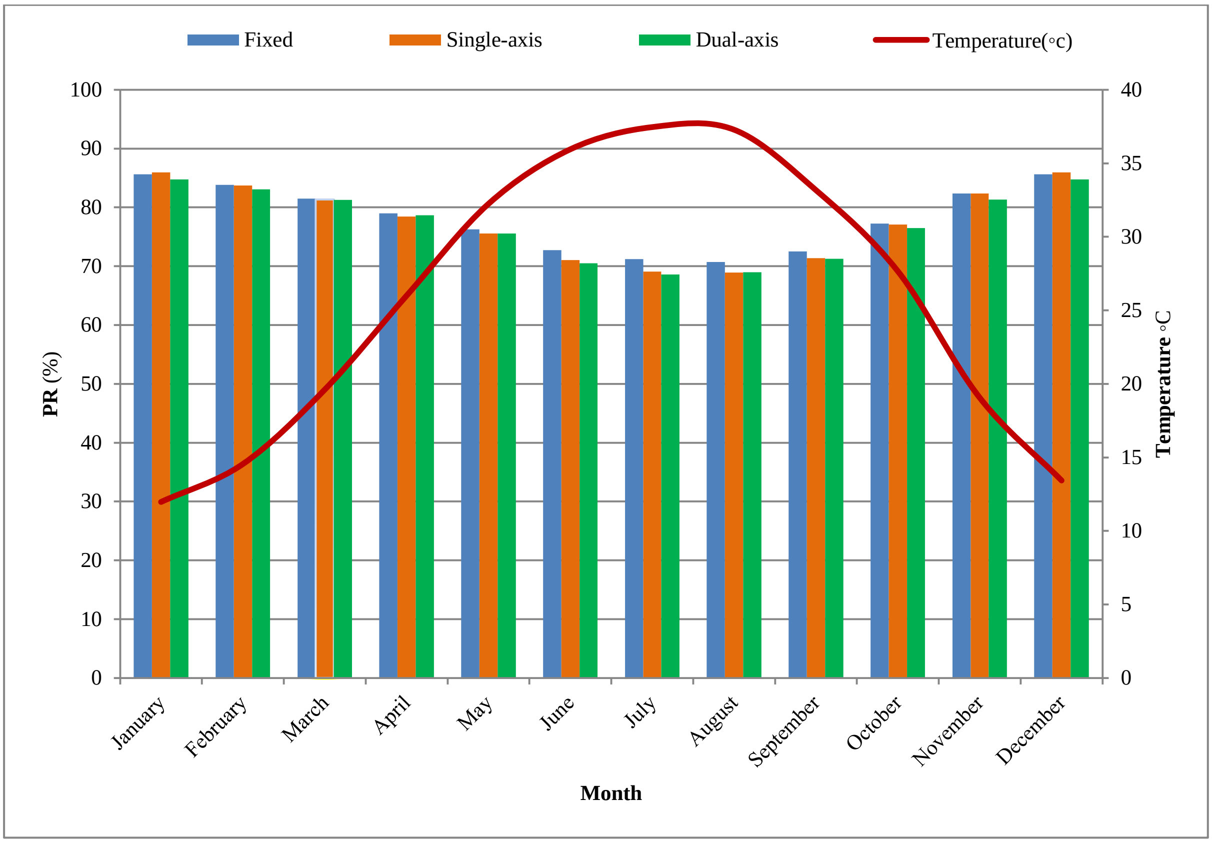


Figure 4.16 The monthly performance ratio with different tracking systems for the UmGudair site.

The yearly basis analyses were considered to obtain a more focused analysis and compare the obtained results of this current research with those found in the literature. The detailed results of the performance parameters study for the proposed sites can be seen in Table 4.17.

Annual energy production varies between 17434 and 178843 MWh, with an average of 176232.4 MWh for fixed tracking systems, and 217835 and 223935 MWh and 225481 and 231563 MWh, with an average of 219738.4 MWh and 227361.6 MWh for the single-axis and dual-axis tracking systems, respectively. The minimum values of annual production were achieved at the Mutribah, Shagaya and Kabd sites, while the highest values for all tracking systems were obtained at the UmGudair site.

The performance ratios varied between 77.1% and 78.1% for the fixed tracking systems, and between 75.6% and 77.2%, and 75.6% and 76.9 %, for the single-axis and dual-axis tracking systems, respectively. The highest performance ratios were recorded at the Shagaya site and the lowest at the Kabd site.

It is generally understood in the field of PV energy that the performance ratio of PV systems range between 75% and 85% (Aste and Del Pero, 2010). Moreover, a number of performance ratio values for a number of selected countries have been collected from the literature are listed in Table 4.18.

The average annual production gained from using fixed tracking system was 176232.4 MWh while 219738.4 MWh and 227361.6 MWh were obtained through the use of single-axis and dual-axis tracking systems, respectively. This increase in annual production (i.e. approximately 24.7% and 29%) forms a key element, and therefore needs to be taken in consideration.

Table 4.17 reveals that the capacity factor (CF) for all sites for the fixed tracking system varied between 19.9% and 20.42%, while single-axis and dual-axis systems varied between 24.87 % and 25.56 %, and between 25.74 % and 26.43 %, respectively. These values are within the typical capacity factor range for PV systems (15-40%) (Hajiah et al., 2012).

Table 4.17 Performance parameters for the selected sites (Al-Rashidi and El-Hamalawi, 2016)

Site	Annual production (MWh/year)	Yield factor (kWh/kW/year)	Yield reference	Performance ratio (%)	Capacity factor (%)
Shagaya					
Fixed	175075	1750.75	2242.3	78.1	19.99
Single-axis Tracking System	217835	2178.35	2822.9	77.2	24.87
Dual-axis Tracking System	225503	2255.03	2932.1	76.9	25.74
Kabd					
Fixed	177519	1775.19	2301	77.1	20.26
Single-axis Tracking System	218291	2182.91	2875.5	75.9	24.92
Dual-axis Tracking System	225481	2254.81	2980.6	75.6	25.74
Sabriya					
Fixed	175378	1753.78	2261.7	77.5	20.02
Single-axis Tracking System	219772	2197.72	2874.6	76.5	25.09
Dual-axis Tracking System	227556	2275.56	2985.9	76.2	25.98
Mutribah					
Fixed	174347	1743.47	2249.3	77.5	19.90
Single-axis Tracking System	218859	2188.59	2864.4	76.4	24.98
Dual-axis Tracking System	226705	2267.05	2976	76.2	25.88
UmmGudair					
Fixed	178843	1788.43	2308.7	77.5	20.42
Single-axis Tracking System	223935	2239.35	2935.3	76.3	25.56
Dual-axis Tracking System	231563	2315.63	3046.7	76.0	26.43

Table 4.18 Selected different performance values for multi-Si PV from literature.

Location	Mounting type	Performance ratio (%)	Reference
Western Europe	Ground mounted	75	(Alsema, 2000)
North Africa	Rooftop	85	(Pehnt et al., 2003)
Japan	Rooftop	77	(Hondo, 2005)
Southern Europe	Ground mounted	87	(Frankl et al., 2005)
Europe	Rooftop	75	(Fthenakis and Alsema, 2006)
Turkey	Ground mounted	83	(Stoppato, 2008)
Gobi desert	Rooftop	75	(Ito et al., 2010)
Southern Europe	Rooftop	75	(De Wild-Scholten, 2013)
China	LS-PV	75	(Hou et al., 2016)

CF is a main element to be considered when assessing the usage of a power source, with its maximum value being theoretically equal to 100%. In practice, this value cannot be achieved, due to this requiring an operational rate of twenty-four hours per day, and it is impossible to obtain such an availability of sunlight. Thus, if sunlight is assumed to be available for twelve hours a day, the ideal CF value is 50%. However, in reality, the maximum CF is slightly lower than 50%, as a result of the energy conversion losses, while the typical CF for PV systems varies between15% and 40%.

YF values range between 1743.47 and 1813.27 kWh/kW/year for fixed tracking systems. These results are excellent when compared with the leading countries using PV systems (Table 4.19).

A significant increase was achieved in CF and YF values, these being approximately 24% and 28.8% in relation to the use of single-axis and dual-axis tracking systems, respectively. The average values of PR for fixed, single-axis and dual-axis systems were 77.5 %, 76.4 % and 76.2 %, respectively. These values are important indicators in establishing the causes of the large amounts of energy lost due to the solar energy conversion processes and the hot climate during the summer months in Kuwait.

Figures 4.17 to 4.20 compare the selected sites, based on: (1) the annual energy production; (2) yield factor; (3) yield reference; and (4) the performance ratio. This reveals that the most effective results were from UmmGudair. This was anticipated, due to the site having the highest annual solar irradiance (2176.8 kWh/m^2/year).

Moreover, although the Mutribah site had the lowest solar irradiance value (2075.8 kWh/m^2/year), its results were identical (or slightly improved) in comparison to the Shagaya and Kabd sites, which had improved solar irradiance values. From this, it can be observed that it is important to analyse processes for all available metrological data to obtain realistic results, in particular when selecting sites stage in solar projects.

Table 4.19 YF (kWh/kW/year) of different countries (data taken from Hajiah et al., 2012)

Country	**Yield factor (YF)** (kWh/kW/year)
Germany	400-1300
Japan	470-1230
Netherlands	400-900
Italy	450-1250
Switzerland	450-1400

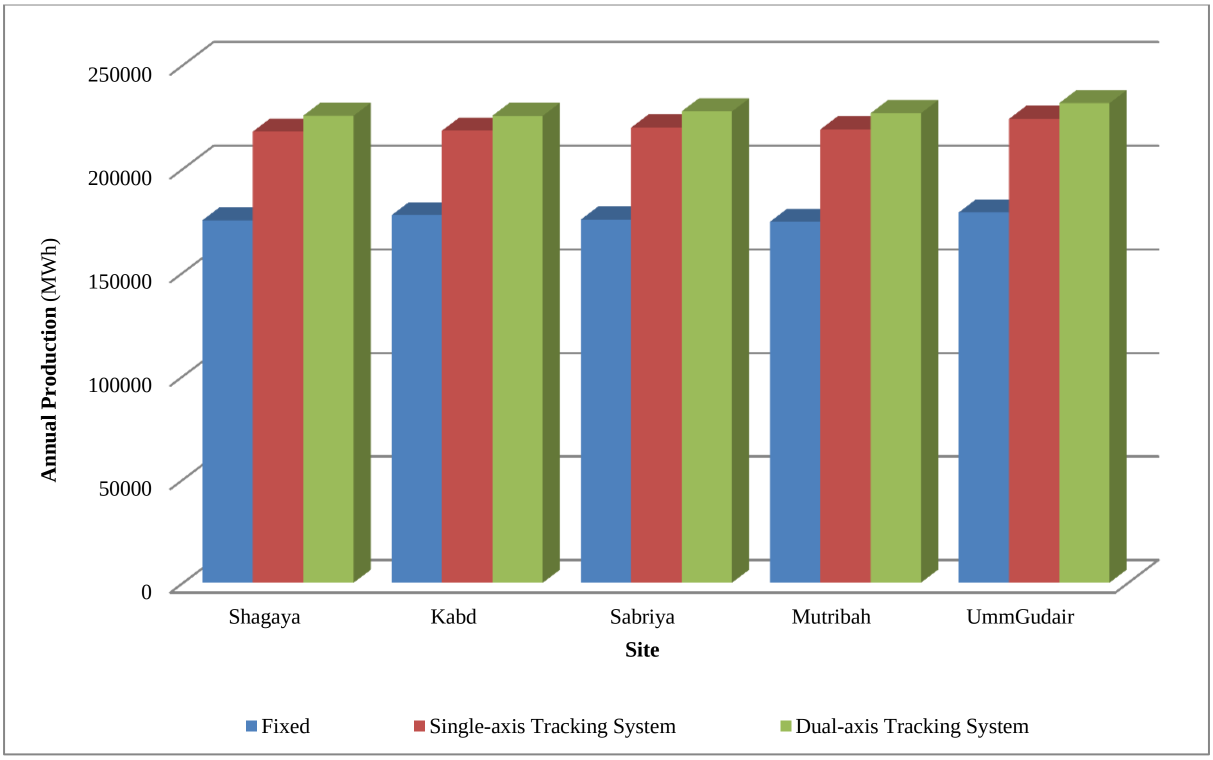


Figure 4.17 Annual production of the selected sites (Al-Rashidi and El-Hamalawi, 2016)

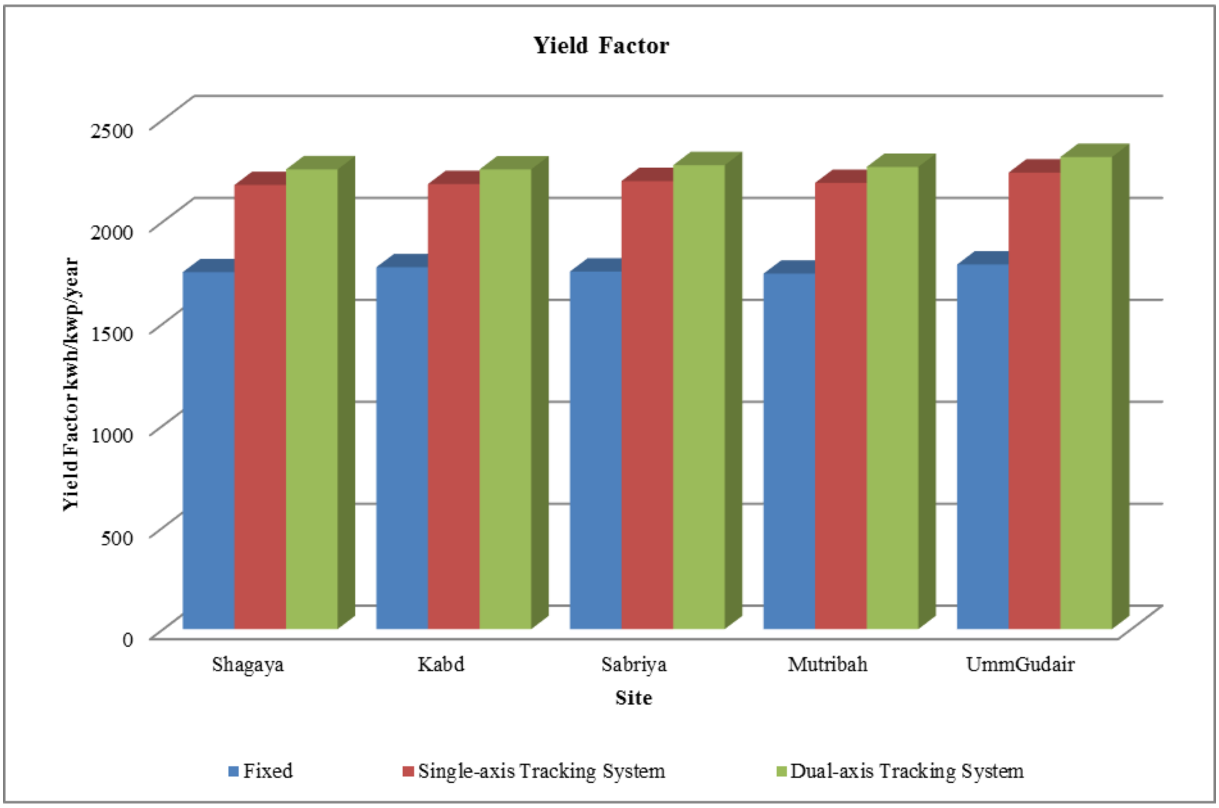


Figure 4.18 Yield factor of the selected sites (Al-Rashidi and El-Hamalawi, 2016)

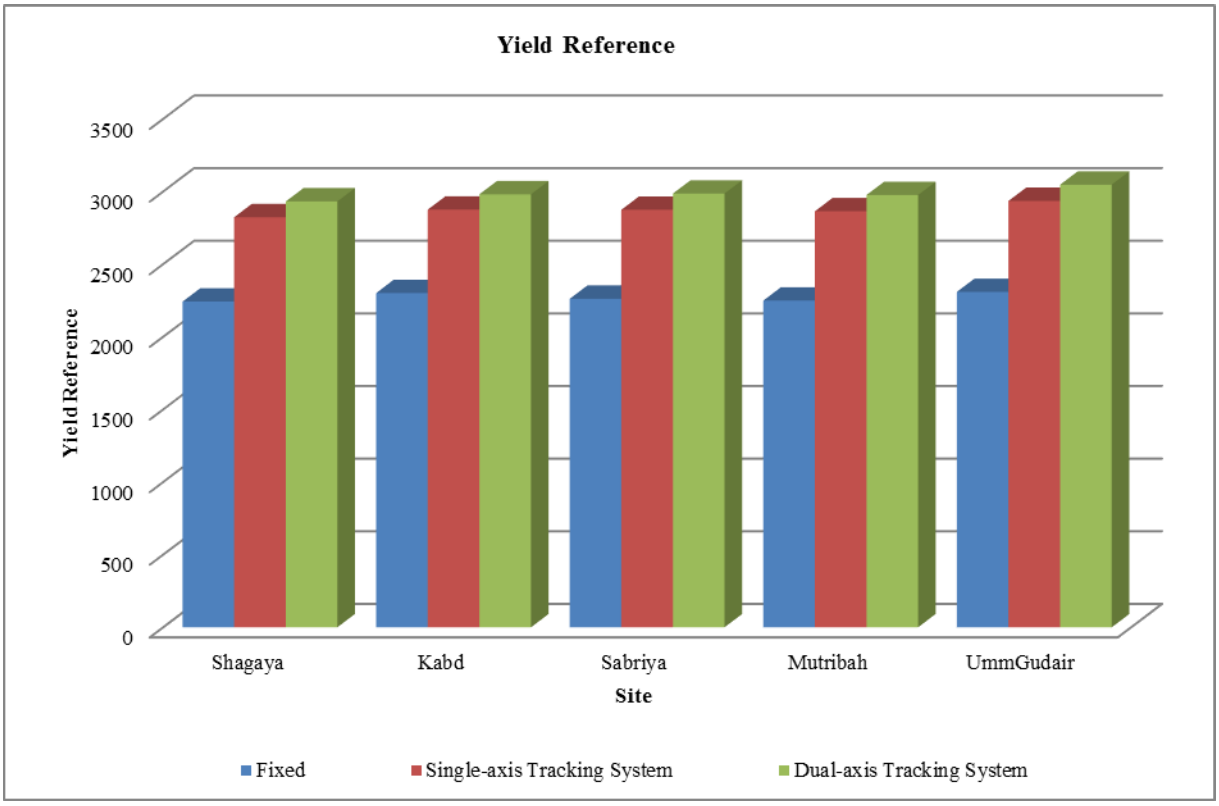


Figure 4.19 Yield Reference of the selected sites (Al-Rashidi and El-Hamalawi, 2016)

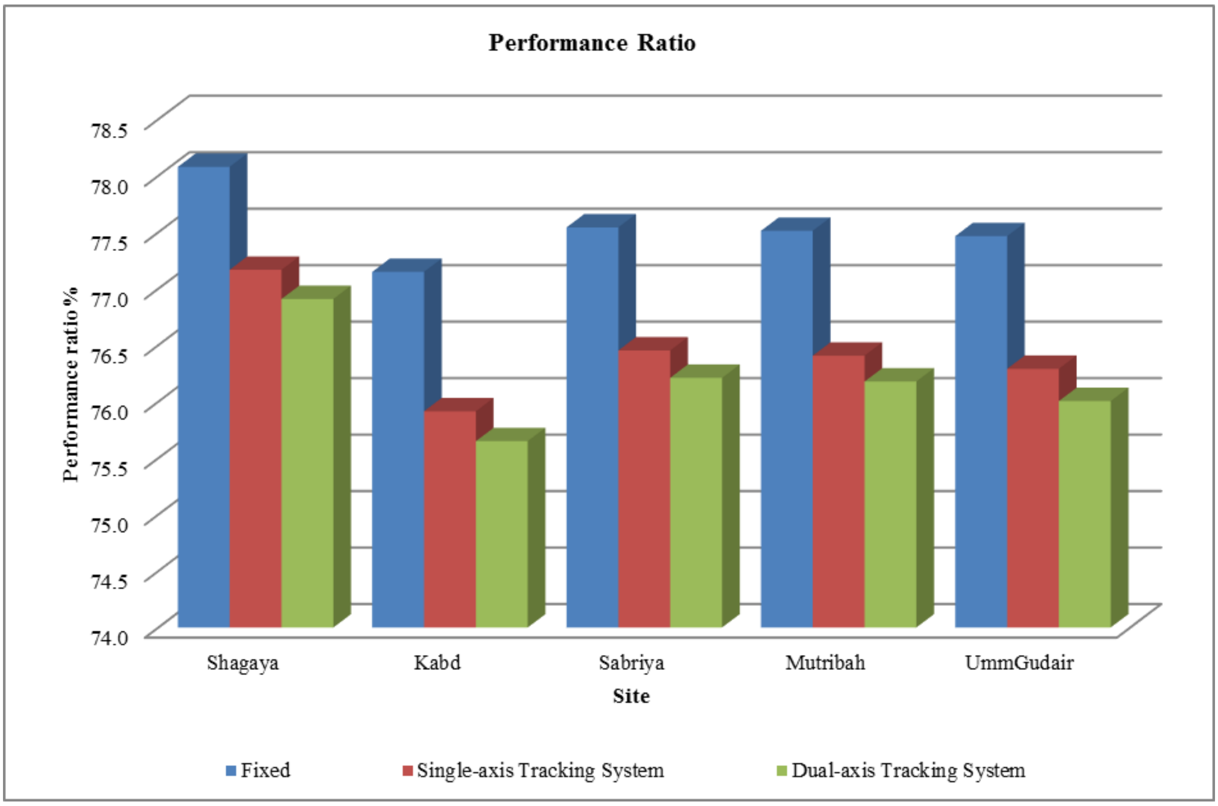


Figure 4.20 Performance Ratio of the selected sites (Al-Rashidi and El-Hamalawi, 2016)

4.6 Conclusions

In this current study, a technical evaluation was undertaken of the use of PV systems at five different sites in Kuwait, in order to determine the performance parameters, along with an examination of the effect of using fixed, single-axis and dual-axis tracking systems.

The amount of produced energy ranged between 174347 and 178843 MWh for the fixed tracking systems, and from 217835 and 223935 MWh and 225481 and 231563 MWh for the single-axis and dual-axis tracking systems, respectively. It was established that the variance in the annual production energy between the proposed sites was 2.58 % for the fixed tracking systems, and 2.80 and 2.70 % for the single-axis and dual-axis tracking systems, respectively. This indicates that the effect of location is insignificant for the state of Kuwait, as the country is relatively small in area. This conclusion is also found in the literature for relevant research conducted in Kuwait, due to the majority of the studies considering the whole country as one site. However, these small degrees of variation in the results have a significant influence when it comes to accuracy and research undertaken in a professional manner, in particular for large-scale projects.

The implementation of solar tracking systems led to this increasing by 24.7% and 29%. In addition, there was a significant increase in CF and YF values of approximately 24% and 28.8%, related to the use of single-axis and dual-axis systems, respectively. However, despite the encouraging results gained by the use of single-axis and dual-axis PV systems, lower performance values were obtained for tracking systems, due to the high energy loss resulting from overheating of PV modules as a result of high summer temperatures. This current study established that the performance parameters values obtained by using tracking systems are highly beneficial to electricity generation in Kuwait, as an alternative source to conventional power plants.

Chapter 5 – Environmental Evaluation

5.1 Introduction

An environmental evaluation study is one of the most important elements of feasibility studies of renewable energy projects. It is also considered that renewable energy sources, such as photovoltaic technology, will play a vital role, whether directly or indirectly, in minimising the serious effects of global warming.

From another perspective, the final decision with regard to accepting or rejecting renewable energy projects is strongly affected by the results of the environmental evaluation study. For example, the need to meet the requirements of pressure from the international community, represented by the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto protocol, could be prioritised over other issues, such as financial concerns.

It is important to carefully include all of the stages that PV systems have passed through, from the acquisition of the raw materials to the final stage, when used materials are recycled instead of becoming waste materials. Moreover, it is also important to look at the amounts of greenhouse gas (GHG) emissions that would be avoided by implementing PV systems. In this chapter, the environmental impacts of utilising PV systems, with different tracking systems, in Kuwait will be assessed by conducting two different studies, as follow:

- Life cycle assessment
- Environmental benefits

In other words, this chapter will investigate the negative impact of GHG emissions on the environment resulting from conventional power plants, and will then show how this is avoidable through the use of PV systems. The amount of GHG emissions that can be avoided at selected sites will be investigated, as well as the effect of using different types of tracking system. To this end, the effects of using fixed, single-axis, and dual-axis tracking systems will be evaluated. Section 5.2 will present a brief overview of the life cycle assessment (LCA). The specific aspects of LCAs related to PV systems will be described in in Section 5.3, and the life cycle assessment of the proposed PV sites will be presented in Section 5.4. The environmental benefits evaluation will be introduced in Section 5.5, and the conclusions presented in Section 5.6.

5.2 Life Cycle Assessment (LCA) - Overview

PV systems technology is often called an environmentally friendly technology, as it generates electricity by converting solar irradiation into electricity without producing emissions throughout its operation over time. In the operation stage, this is almost true, ignoring the very small amount of energy that is used for maintenance purposes.

The fact that PV technology is a source of free and clean energy does not mean that such technology makes no contribution to environmental issues such as global warming. It seems likely that there has been a misunderstanding in the use of the term ‘environmentally friendly technology’. It is essential to include the total life cycle of each component of any proposed system in order to properly evaluate its impact on the environment.

LCA is a widely-used measure in environmental evaluations of PV systems. The assessment includes all of the life stages of the product, from the acquisition of the materials (through multiple stages of manufacture and use) to the recycling stage (see Figure 5.1). It is generally considered a ‘cradle to grave’ approach, as it includes all of the emissions from the different life cycle phases of a product, from manufacturing to recycling.

LCA studies of PV systems are carried out according to ISO standards (ISO 14040, 2006; ISO 14044, 2006) and any change or addition to the basic terms should be clearly stated (Fthenakis et al., 2011). It is generally agreed that it is important to carry out a LCA, as emissions into the environment may occur at different life cycle stages (Fthenakis and Kim, 2011).

It has been found that most GHG emissions (approximately 85%) occur in the production stage of solar modules (Dones and Frischknecht, 1998). This is due to the high use of electrical energy by the tools and machines used for this purpose. Moreover, this is one of the important advantages of using life cycle assessments (LCA), in which the production processes of all PV system components are taken into account. This approach, which will be applied in this study, is most appropriate and most commonly used in the renewable energy field, particularly in relation to photovoltaic energy, and will facilitate a detailed understanding of the effects that PV systems have on the environment.

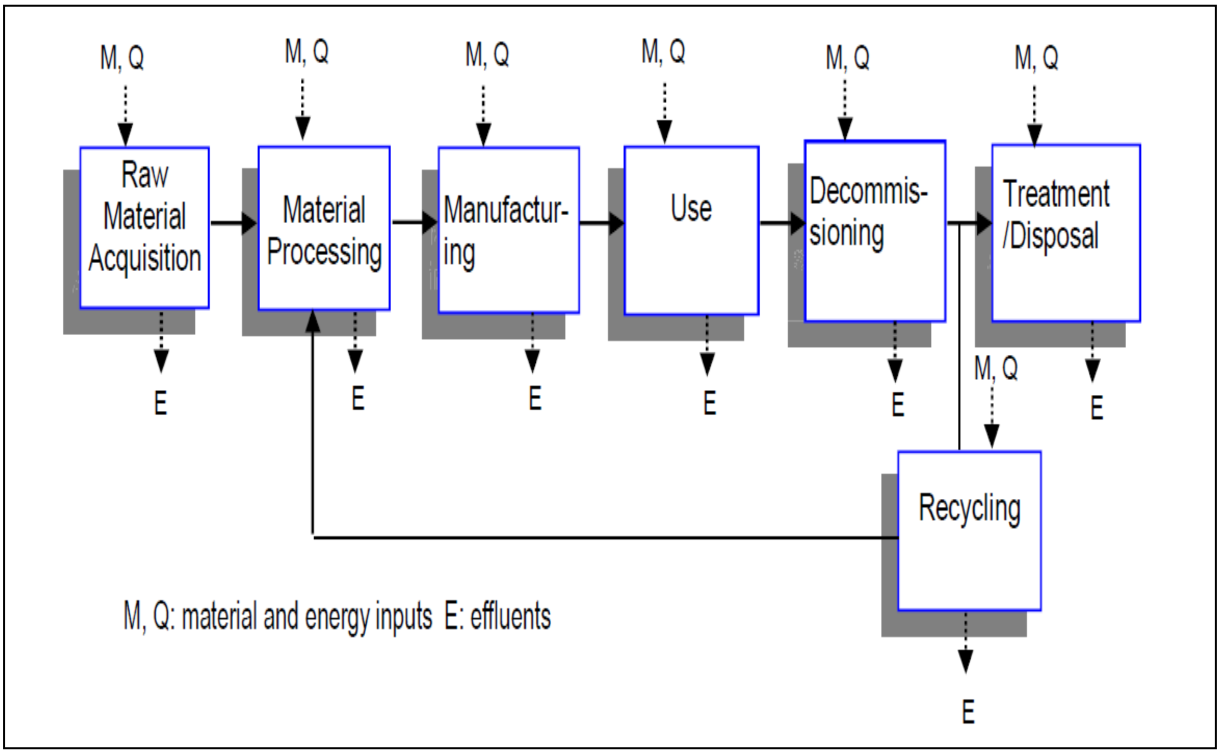


Figure 5.1 Flow of the lifecycle stages, energy, materials, and waste from PV systems (Fthenakis and Kim, 2011)

The amount of GHG emissions will be estimated for each individual stage, and then a sum total given. The process of manufacturing solar modules, from the initial acquisition of the material, is a very long one, as the primary material, silicon, is not available in a pure form. Even though silicon is the second most abundant element (making up 28% of the Earth's crust), a large amount of energy is needed to access it in its pure form. High energy, in the form of heating, is applied to the raw materials quartz and sand, in order to produce metallurgical grade silicon (MG-Si), which is characterised by a high level of purity. Further purification processes are conducted using different methods, such as Czochralski and Siemens processes (Sonnenenergie, 2008), to produce solar grade silicon (SoG-Si). Finally, the silicon ingots are sawed into columns. Figure 5.2 shows the manufacturing process of silicon photovoltaic (Si-PV) modules, from raw acquisition to manufacturing stages.

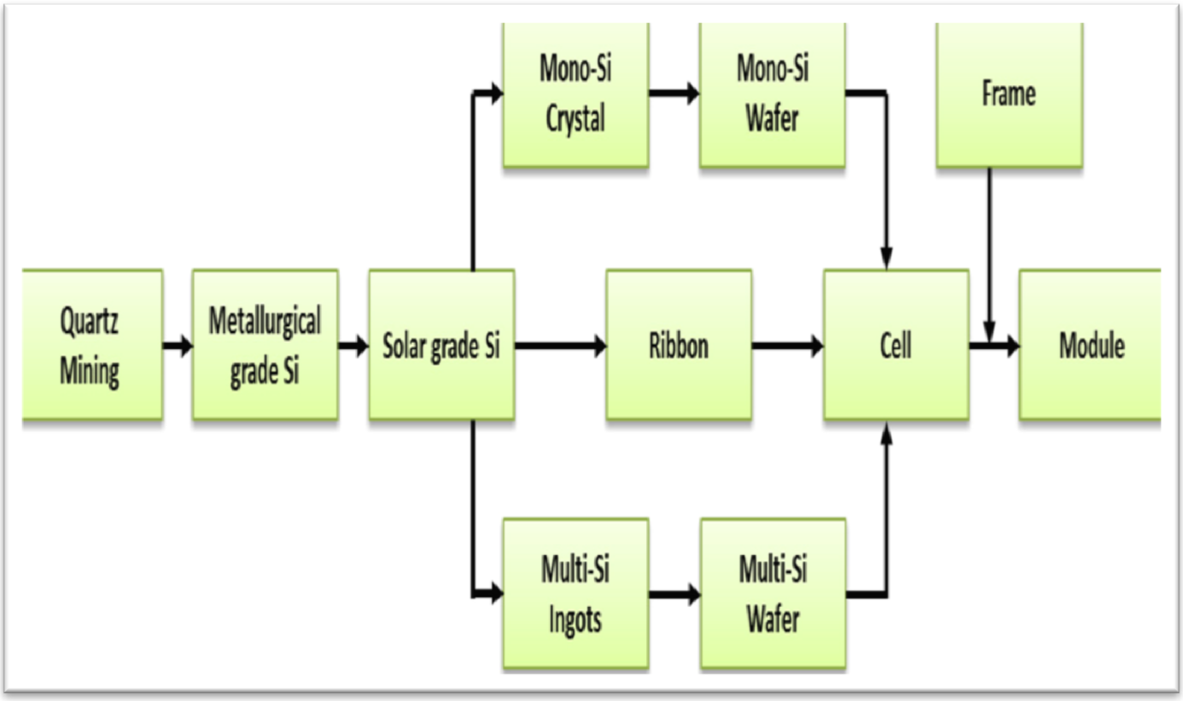


Figure 5.2 Flow diagram from raw acquisition to manufacturing stages of Si-PV modules (Yue et al., 2014).

The manufacturing technology used is another important factor, which is evident in Figure 5.3, which shows that different amounts of energy are needed, even when using the same technology, for example, in China and in Europe. Furthermore, the variance in the results obtained by the same technology is arguably significant, and can be attributed to many factors, such as applying different boundary conditions.

In addition, the amount of energy used to produce solar modules is not a fixed quantity. It is dependent on a number of factors, such as the type of solar module and the efficiency level of the proposed modules. For instance, the energy needed to produce ribbon-Si, polycrystalline-Si, and mono-Si modules is 2300, 3700 and 4200 MJ/m^2, respectively (Fthenakis and Kim, 2011). Figure 5.4 presents the different energy requirements during the lifecycles of different PV systems.

Moreover, the variance in CO_2 emissions rates between the different LCA studies that have been conducted, is an important issue. For instance, when comparing Polycrystalline-Si and mono-Si, modules, which are the most dominant in the PV system market, it can be seen that although the mono-Si modules have higher efficiency than polycrystalline-Si modules, a higher amount of energy is consumed in their production, and more GHGs are emitted (Peng et al., 2013).

However, the complexity of LCA studies mainly results from uncertainties in the input data, and the method and scope of the study. These complexities are to be expected, as photovoltaic technology is not yet a mature technology. Therefore, with the greater experience that will be gained with time, more accurate results will be achieved.

As previously mentioned, the majority of GHG emissions from PV systems result from manufacturing processes, and typically due to the use of energy in refining and purifying metallurgical grade silicon (MG-Si) to be used for the production of crystalline silicon solar cells. Based on several studies carried out in the United States, Europe, and Japan, it has been concluded that GHG emissions produced in this process range from 40 to 180 g-CO_2,eq./kWh (Wong et al., 2016).

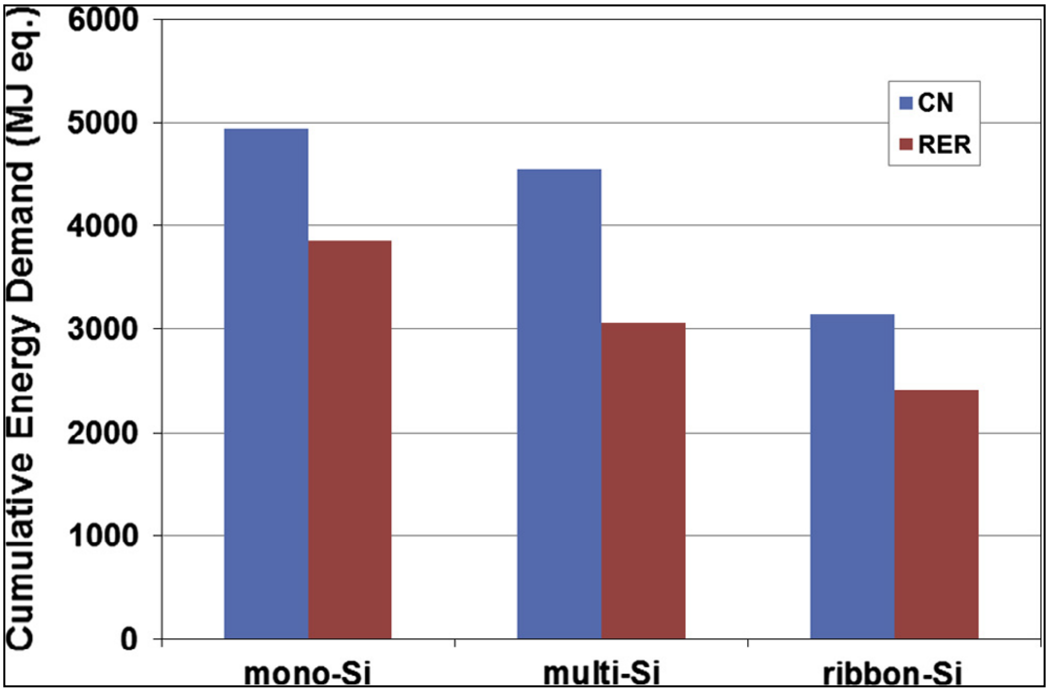


Figure 5.3 Cumulative energy demand (CED) results (CN: China, RER: Europe) (Yue et al., 2014)

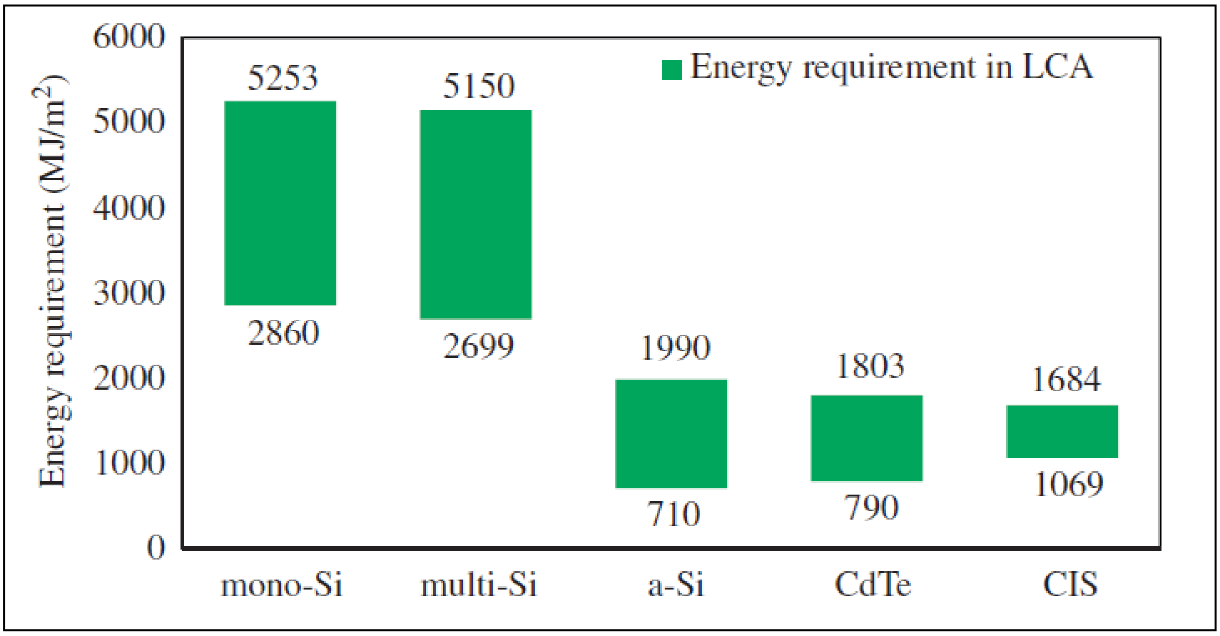


Figure 5.4 Review of energy requirements during the lifecycle of various PV systems (Peng et al., 2013)

5.3 LCA Specific Aspects of PV Systems

As mentioned previously, the LCA is known to be a comprehensive approach, in which all the lifecycle stages of any proposed product are covered, from manufacturing to recycling. However, depending on the purposes of the study, or perhaps a lack of information, one or more stages could be excluded from an assessment. Therefore, the goal and the boundaries of any proposed LCA study should be clearly stated, in order to avoid or minimise variance in LCA studies' results, as was discussed in Section 5.2. In this study, all of the LCA stages mentioned will be considered, and the amount of energy used in each, or assumed values, will be clarified.

It is vital to have robust and basic reference data for use when there is a lack of input data, in order to carry out an effective LCA study. Currently, reference data is not fully available for PV technology, as it takes a long time to properly evaluate each component with adequate testing. Photovoltaic energy, which is considered a highly promising technology, is not yet fully mature in comparison to other technologies. However, the International Energy Agency Photovoltaic Power System Programme (IEA-PVPS) provides very useful guidelines (Fthenakis et al., 2011), which can serve as an important reference point to all stakeholders in PV systems technology. According to these guidelines, lifetime expectancy, solar irradiation data, performance ratio, and degradation rate are all important parameters in an LCA assessment. Solar irradiation data and performance ratio were discussed in Chapter 2;

however, lifetime expectancy and degradation rate will be briefly discussed in the following subsections.

5.3.1 Lifetime Expectancy of PV Components

Lifetime, or lifespan, is an important parameter of different energy technologies, such as PV systems technologies, and is essential to economic and environmental evaluations. The evaluation indices, such as the energy payback time (EPBT), which will be used in this research, are functionally and directly dependent on the used lifetime of the PV system. The sole or most important reference of PV systems components is the specifications and warranties that are provided with the products. However, the IEA-PVPS provides good recommendations that can be used as a reference when lifetime data for different PV systems components is required. Table 5.1 lists the lifetimes of different PV systems.

Table 5.1 Lifetime of different PV systems (data taken from Basu, 2011)

Modules	30 years for mature module technologies, assuming module warranties (25 years - 80% degradation or less after 25 years).
Inverters	15 years for small plants (residential PV); 30 years with 10% part replacement every 10 years; 15 years for small plants (residential PV); 30 years with 10% part replacement for large size plants utility PV.
Transformers	30 years.
Structure	30 years for roof-top, and between 30 to 60 years for ground-mount installations on metal supports.
Cabling	30 years.

5.3.2 Degradation Rate

Even though solar modules play a substantial role in converting solar irradiation into electricity, the other PV components, such as inverters, also play a vital role in ensuring that the whole process of converting solar irradiation into electricity is achieved successfully. Hence, any performance failure of any PV system component will systematically affect the performance of the whole PV system. Furthermore, because photovoltaic energy is known as a long-term technology, in that it is implemented over long periods, the time parameter should also be taken into account. The term ‘degradation’ is used here to represent the effect of different parameters, such as climate, on the performance of the PV system components. In order to accurately predict the amount of power that will be generated by PV systems, an accurate estimation of the degradation rate of PV system components is first required (Jordan and Kurtz, 2013).

The power production capacities of PV systems throughout their lifetimes are highly dependent on their degradation rate. An inappropriate degradation rate value will lead to incorrect financial evaluation results, as well as failure of the system (Jordan and Kurtz, 2013). The recommended degradation rate of PV systems is 0.5% per year for crystalline silicon PV modules, and it is assumed that mature module technologies will operate at approximately 80% of their initial efficiency at the end of their 30-year lifetime (Basu, 2011; Fthenakis and Kim, 2011).

5.3.3 Evaluation Indices for PV Systems

The LCA approach essentially computes the amount of energy used for and throughout each individual stage of the whole lifecycle of any product, as well as the amount of emissions produced. It is primarily concerned with the amount of energy that has been used, and is expected to be used. A LCA study provides a wide range of information and data in the form of input and output data, whereby the proposed PV system is analysed and the environmental evaluation then conducted. The literature review identified that evaluating PV systems using an LCA study involves the following measures:

- Energy Payback Time (EPBT)
- Energy yield ratio (EYR)
- CO_2 emission rate

The above measures are widely used in the photovoltaic field, and are the ways in which PV systems and conventional power plants can be most effectively and clearly evaluated and compared. In addition, a comparison of the feasibility studies relating to renewable energy could also be investigated using these measures.

Energy Payback Time (EPBT), which is the point at which PV systems begin to produce the same amount of energy as is used in production throughout their lifecycle, as well as the GHG emission rate, are the most common indices used in LCAs (Fthenakis et al., 2011).

EPBT is calculated using the following equation (Basu, 2011):

EPBT [year] = total energy throughout the life cycle / annual power generation (5.1)

The EPBT value depends on the type of PV system used. The efficiency and expected lifetime of solar modules are the main inputs for the EPBT equation. In addition, location is another important parameter, as irradiation data varies from one site to another. Figure 5.5 shows the EPBT values of different types of solar technologies, in other words the point in the lifecycle at which the PV systems recover the used energy, which ranges from 2 to 3 years.

The energy yield ratio (EYR) is another measure that is commonly used in environmental evaluations of renewable technologies, such as solar power technologies. This is the ratio between the total energy output in operation throughout the lifecycle and the total energy used over the complete lifecycle of the system. This ratio can be calculated using the following equation (Hou et al., 2016):

EYR = lifecycle output energy / total consumed energy (5.2)

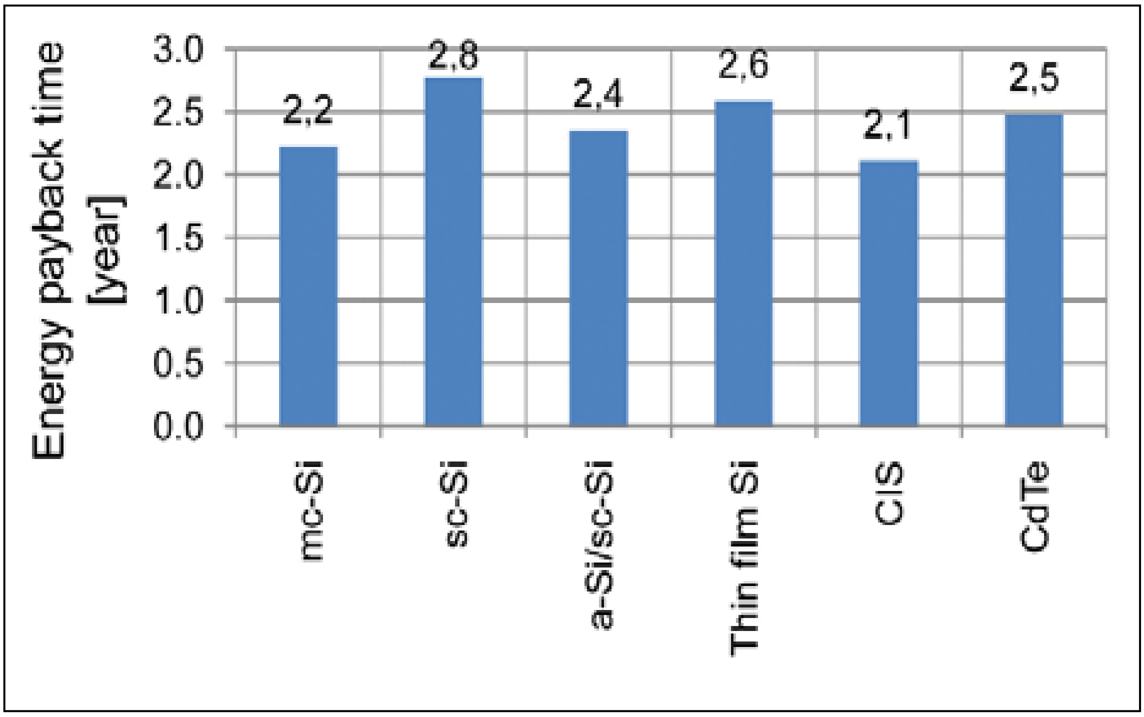


Figure 5.5 Energy Payback Time (EPBT) of VLS-PV systems (Komoto et al., 2009)

The EYR provides a clear overview, as it includes the total lifecycle of the proposed system. It compares the amount of energy produced throughout the expected lifecycle of the proposed system to the amount of energy used over the same period. It is a useful measure to use when comparing different technologies.

In addition to the EPBT and EYR, the CO_2 emission rate is another important indicator in LCA studies, especially when investigating the impact of PV systems on the environment, in terms of global warming.

The vital role of GHGs in global warming is mainly due to the absorbing energy and decreasing rate of energy to be expelled (EPA, 2016b). The different GHGs have different effects; these can be identified using the Global Warming Potential (GWP) indicator.

Table 5.2 lists the global warming potentials of greenhouse gases. In general, the CO_2 emission rate for different PV systems ranges from 51.5 to 71 g-CO_2,eq/kWh (Figure 5.6). It is calculated as an equivalent of CO_2, using the following equation (Basu, 2011):

CO_2 emission rate [g-CO_2,eq/kWh] =

Total CO_2 emission during lifecycle [g CO_2] / annual power generation [kWh/year] x lifetime [year] (5.3)

This study seeks to determine the amount of GHG emissions that could be avoided by implementing PV systems at the proposed sites. In addition, the effects of using single-axis and dual-axis solar trackers will be examined.

Table 5.2 Global warming potentials of greenhouse gases (data taken from EPA, 2016b)

Greenhouse Gas	**GWP**
Carbon Dioxide (CO_2)	1
Methane (CH4)	28-36
Nitrous Oxide (N2O)	265-298
Chlorofluorocarbons (CFCs)	Thousands, or tens of thousands

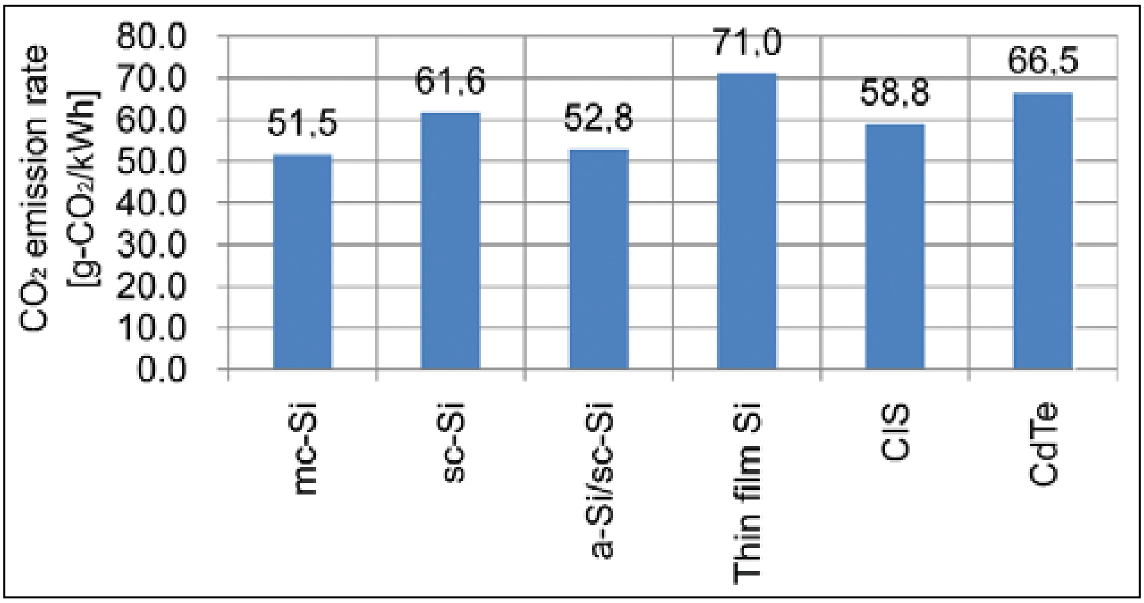


Figure 5.6 CO_2 emission rates of VLS-PV systems (Komoto et al., 2009)

5.4 LCA for the Proposed PV Systems

A LCA study was conducted for all of the proposed sites (Shagaya, Kabd, Sabria, Mutribah, and Umm Gudair); the effect of using a tracker system, specifically fixed, single-axis and dual-axis tracking systems, was also examined. As stated in Section 5.3.3, the most commonly used indices (EPBT, EYR, and CO_2 emission rate) in the photovoltaic energy field were the main criteria of the LCA studies carried out for this research.

The technical data, which includes all of the input data for the proposed PV systems, is shown in Table 5.3. It should be emphasized here again the importance of the inputs used in order to give stakeholders and decision-makers in the renewable energy field a complete understanding of these types of studies. For example, the efficiency of the solar modules is a key point that researchers and stakeholders in photovoltaic technology have been focusing on in order to increase the amount of power that is generated by PV systems. Its importance can also be observed in the different PV module technologies available, where many companies are competing in the production and manufacturing of photovoltaic components.

Currently, monocrystalline PV modules are more efficient than polycrystalline modules, and both are more efficient than thin films. The point here is that different amounts of energy are used by each of the aforementioned technologies. It is generally estimated that the amount of energy used to produce silicon crystalline-based PV modules ranges between 2,400 and

16,500 MJ/m^2, whereas a relatively small amount of energy, between 710 and 1980 MJ/m^2, is needed for the production of thin film modules (Alsema, 2000).

The literature review identified that the energy consumed in the production of multi-Si modules varies between 2699 and 5150 MJ/m^2; however, for this study, the amount of energy used in the production stage was taken as 2876 MJ/m^2 (799 kWh/m^2), which is the five-year average from 2009 to 2014 (Wong et al., 2016). This energy is consumed over a long period of time, from the point at which the raw material is collected, through manufacturing and fabricating the solar modules, and ending finally with the energy used in the recycling stage.

In addition, as determining the effect of using single-axis and dual-axis tracking systems in Kuwait is one of the aims of this study, as previously stated, the amount of energy used in the production of these tracking systems was also included. This amount was estimated at 4 and 12 kWh/kW for the single-axis and dual-axis tracking systems, respectively (Perpinan et al., 2008). This technical data is also included in Table 5.3. The total annual energy produced for each site was identified in Chapter 4.

Equations 5.1 and 5.2 were used to calculate the EPBT and EYR, respectively; Table 5.4 lists the EPBTs and EYRs for the proposed PV systems at the selected sites, for fixed, single-axis, and dual-axis tracking systems. It can be seen that the EPBT results vary between 1.74 to 1.79 year, 1.40 to 1.43 year, and 1.35 to 1.39 year for the fixed tracking system, single-axis tracking system, and dual-axis tracking system, respectively. These variations in the obtained results between the selected sites were expected, and can be attributed to the different amounts of energy produced, as discussed above. It can also be observed from Table 5.4 that the EYR values varied between 13.97 and 14.33 year, with an average of 14.15 year for the fixed tracking systems, whereas the EYR values for the single-axis and dual-axis tracking systems ranged between 17.43 and 17.92, and between 18.00 and 18.48 year, with an average of 17.675 year and 18.24 year, respectively.

Table 5.3 Technical input data for the proposed PV systems

Energy	Value	Reference
Total energy for production (MJ/m^2)	2876	(Wong et al., 2016)
Multi-Si module efficiency (%)	15.5	
Module lifetime (year)	25	
Single-axis tracker (kWh/kW)	4	(Perpinan et al., 2008)
Dual-axis tracker (kWh/kW)	12	
Total energy (kWh/kW)		
For fixed tracking system	3.120	
For single-axis tracking system	3.124	
For dual-axis tracking system	3.132	

The EPBT and EYR values listed above show that the effect of using tracking with the proposed PV systems at all of the selected sites in Kuwait was tremendous. Utilising the single-axis and dual-axis tracking systems, the EPBT values decreased by 19.66% and 22.145% respectively, and the EYR increased by 24.53% and 28.53% respectively. The effectiveness of using tracking systems can clearly be seen from Figures 5.7 and 5.8, in which a comparison between the EPBT and EYR values for the proposed sites is given.

In general, the Umm Gudair site was shown to have the lowest EPBT values: 1.74 year for the fixed tracking system, and 1.4 and 1.39 year for the single-axis and dual-axis tracking systems respectively. This site also had the highest solar irradiation and the highest produced energy for all of the different tracking systems, compared with the other proposed sites. On the other hand, the Mutribah site had the highest EPBT value for the fixed tracking system, and the Kabd site had the highest EPBT value for the dual-axis tracking system.

In terms of the EYR measure, the Umm Gudair site was again the best of the proposed sites. It had the highest values, at 14.33 for the fixed tracking system, and 17.92 and 18.48 for the single-axis and dual-axis tracking systems, respectively. The Mutribah site had the lowest EYR value for the fixed tracking system, and the Shagaya site had the lowest EYR values for the single-axis and dual–axis tracking systems, respectively.

The effect of different locations, as determined by meteorological data, is clear from the obtained results by the EPBT and EYR indices. Though the obtained results varied between the selected sites, the results of this study provide stakeholders and decision-makers with more alternatives when selecting the most appropriate locations for future proposed projects.

It is important to again highlight that the feasibility of large-scale PV systems, from an environmental perspective, is strongly influenced by EPBT and EYR indices. These measures are typically compared with those of other renewable technologies, such as wind energy. Thus, the importance of the EPBT and EYR indices is at least equal to that of the third index (CO_2 emissions rate), which will be discussed in more detail later in this section.

Table 5.4 EPBT and EYR values for the proposed PV systems at the selected sites

Site	Annual energy (kWh/W)	Total energy (kWh/W)	Energy consumption (kWh/W)	EPBT (Year)	EYR (Year)
Shagaya					
Fixed tracking system	1.75	43.77	3.120	1.78	14.03
Single-axis tracking system	2.18	54.46	3.124	1.43	17.43
Dual-axis tracking system	2.26	56.38	3.132	1.39	18.00
Kabd					
Fixed tracking system	1.78	44.38	3.120	1.76	14.22
Single-axis tracking system	2.18	54.57	3.124	1.43	17.47
Dual-axis tracking system	2.25	56.37	3.132	1.39	18.00
Sabriya					
Fixed tracking system	1.75	43.84	3.120	1.78	14.05
Single-axis tracking system	2.20	54.94	3.124	1.42	17.59
Dual-axis tracking system	2.28	56.89	3.132	1.38	18.16
Mutribah					
Fixed tracking system	1.74	43.59	3.120	1.79	13.97
Single-axis tracking system	2.19	54.71	3.124	1.43	17.51
Dual-axis tracking system	2.27	56.68	3.132	1.38	18.10
UmmGudair					
Fixed tracking system	1.79	44.71	3.120	1.74	14.33
Single-axis tracking system	2.24	55.98	3.124	1.40	17.92
Dual-axis tracking system	2.32	57.89	3.132	1.35	18.48

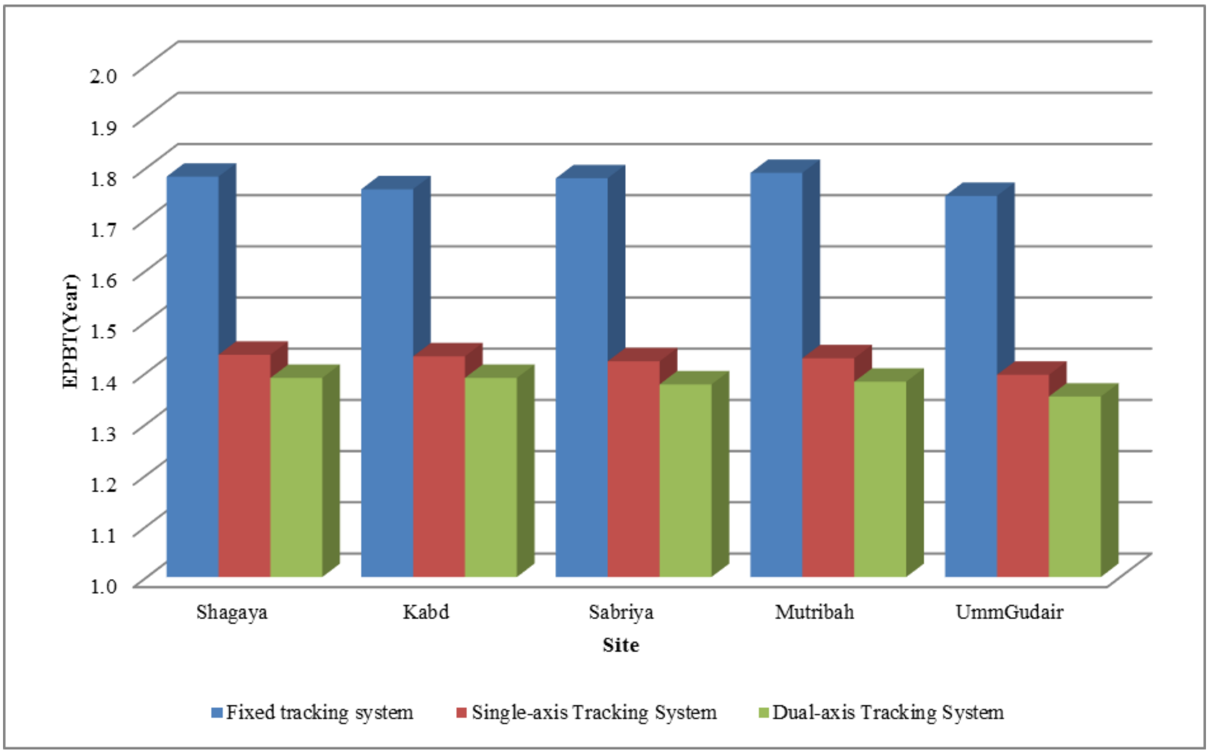


Figure 5.7 EPBTs for the selected sites

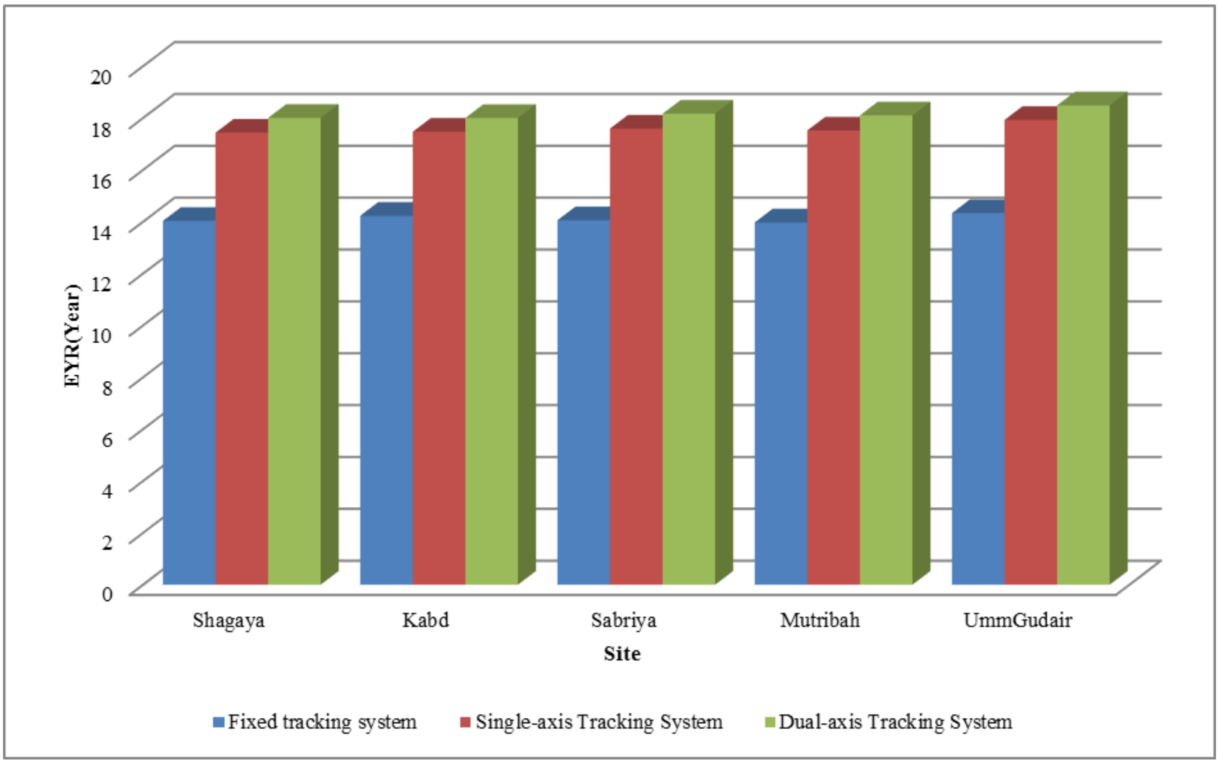


Figure 5.8 EYRs for the selected sites

As mentioned in Section 5.1, the CO_2 emission rate was used in this study as another LCA assessment index. This is an important measure that can be used to determine the effectiveness of the proposed systems, in terms of global warming.

It is important to recall that the scope of the LCA study includes the transportation stage; as such, the amounts of GHGs that will be emitted as a result of transporting the PV components from Germany (the proposed supplier) to Kuwait were included in this study.

According to Sea-Distances (2016), the distance from Germany (Hamburg port) to Kuwait (AL-Shwaikh port) is approximately 6,833 nautical miles (12,655km) via the Suez Canal. It is assumed that the shipping route is by sea with 10 g CO_2/tonne-km and by road 62 g CO_2 (Eickmann and Halder, 2003).

The weight of the solar modules was the most important parameter in reference to which the calculations of CO_2 emissions rates in the transportation stage were computed. The solar modules consist of four components: one acrylic glass top, two ethylene vinyl acetate layers, solar cells in the middle, and Tedlar-Aluminium sheets at the base and the frames. Figure 5.9 shows an exploded view of a solar module.

A Si-poly model (S255P60 Professional) PV module type was selected to be used in this study, and the weight of equivalent 1 kW modules was estimated as 80kg (Centro Solar, 2014). The transportation emissions were calculated using the following equation (Eickmann and Halder, 2003):

$$\text{Emission [g]} = \text{emission factor [g / (tons. km)]} \times \text{mass [tons]} \times \text{distance [km]} \qquad (5.4)$$

The results for the total emissions produced in the transportation stage are shown in Table 5.5. These values will be included in the total lifecycle. It can be seen that, in terms of LCA, the transportation of PV system has an insignificant effect on the total CO_2 emissions rate; this is also evident in much past LCA research, where many authors have not included the transportation stage in their studies. However, for this research, the transportation stage was investigated in order to provide a better understanding in terms of the complete lifecycle stages.

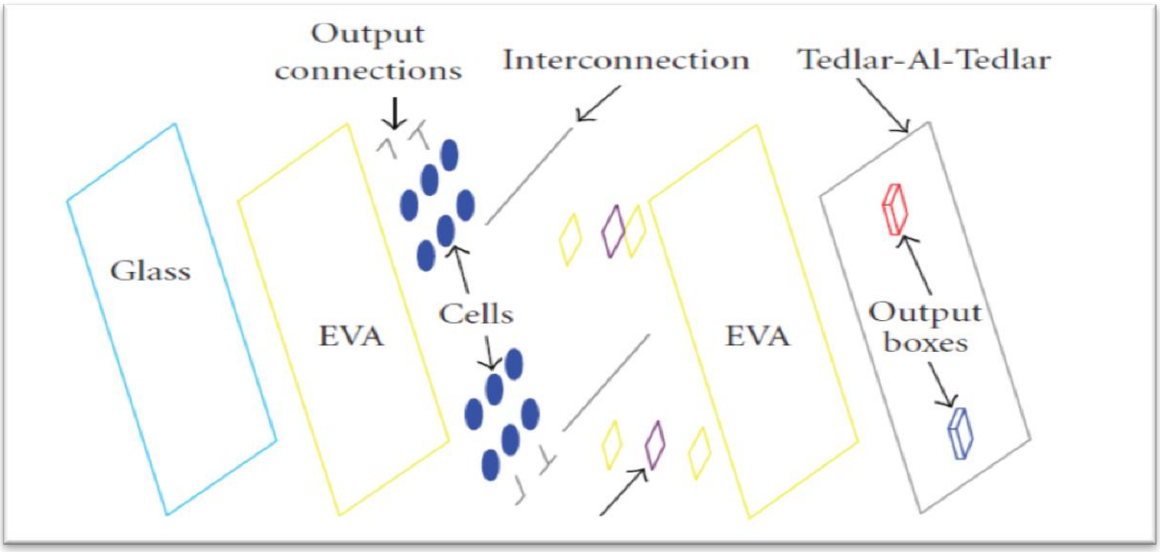


Figure 5.9 An exploded view of a solar module (El Amrani et al., 2007)

In Germany, the amount of CO_2 emitted as a result of using electricity in the production of silicon based solar cells is estimated at approximately 672 g-CO2,eq/kWh (Brander et al., 2011). This value was used to calculate the total amount of CO_2 during the lifecycle. In addition, the amount of CO_2 resulting from the PV station operation, PV electricity transmission, and PV station recycling were set as 8.97 g-CO_2,eq/kWh (Hou et al., 2016). The total CO_2 emission rates were calculated using Equation 5.1. Table 5.6 shows the total CO_2 emissions rate for all of the proposed sites. The effect of using single-axis and dual-axis tracking systems on the total CO_2 emissions at the selected sites can be seen in Figure 5.10.

It can be seen from the results presented in Table 5.6 that the total CO_2 emission rate varied between 56.17 and 57.48 g-CO_2,eq/kWh, with an average of 56.94 g-CO_2,eq/kWh for the fixed tracking systems, and from 46.47 to 47.87 g-CO_2,eq/kWh, and 45.63 to 46.66 g-CO_2,eq/kWh with an average of 47.56 g-CO_2,eq/kWh and 46.38 CO_2,eq /kWh for single-axis and dual-axis tracking systems, respectively.

It is also very important to highlight here the effect of using tracking systems. These tracking systems play an important role in minimizing total CO_2 emissions rates. The total CO_2 emissions rate decreased by 19.72% and 22.78% respectively when using single-axis and dual-axis tracking systems.

The total CO_2 emission rate of the Umm Gudair site was the lowest of the selected sites, for all proposed solar tracking system types. The low CO_2 rates for this site were due to the relatively large amount of energy production at this site compared with the other sites. On the other hand, the opposite was true for the Mutribah site, which had the highest total CO_2 emission rate for the fixed tracking system. The Shagaya site had the highest total CO_2 emission rate for both the single-axis and dual-axis tracking systems.

In general, the influence of the total amount of energy generated by the PV systems was significant. This is explained simply by the fact that CO_2 is a function of the generated energy of the proposed PV system.

From an environmental viewpoint, it is very useful to compare the results of the present study with other relevant studies, in order to provide a realistic reference point to be used for evaluation or validation purposes. Thus, in order to have a better understanding of the environmental impact of using PV systems in Kuwait, the results of this study will be compared with those of other relevant studies of photovoltaic energy.

Table 5.5 CO_2 emissions (g-CO_2,eq/kWh) produced in the transportation stage for the proposed sites

Site	**Distance**		
Shagaya	**from Alsuwake port to the site (km)**	**from the factory to Kuwait (km)**	**CO_2 (g-CO_2,eq /kWh)**
Fixed tracking system	70	12655	0.355
Single-axis tracking system	70	12655	0.354
Dual-axis tracking system	70	12655	0.353
Kabd			
Fixed tracking system	40	12655	0.203
Single-axis tracking system	40	12655	0.202
Dual-axis tracking system	40	12655	0.202
Sabriya			
Fixed tracking system	120	12655	0.609
Single- axis tracking system	120	12655	0.606
Dual-axis tracking system	120	12655	0.606
Mutribah			
Fixed tracking system	80	12655	0.406
Single-axis tracking system	80	12655	0.404
Dual-axis tracking system	80	12655	0.404
Umm Gudair			
Fixed tracking system	60	12655	0.304
Single-axis tracking system	60	12655	0.303
Dual-axis tracking system	60	12655	0.303

Table 5.6 Total CO_2 emissions (g-CO_2,eq/kWh) for the proposed sites

Site	CO_2 emissions **(g-CO_2 g, eq /kWh)**
Shagaya	
Fixed tracking system	57.23
Single-axis tracking system	47.87
Dual-axis tracking system	46.66
Kabd	
Fixed tracking system	56.42
Single-axis tracking system	47.64
Dual-axis tracking system	46.51
Sabriya	
Fixed tracking system	57.40
Single-axis tracking system	47.79
Dual-axis tracking system	46.57
Mutribah	
Fixed tracking system	57.48
Single-axis tracking system	47.74
Dual-axis tracking system	46.51
Umm Gudair	
Fixed tracking system	56.17
Single-axis tracking system	46.77
Dual-axis tracking system	45.63

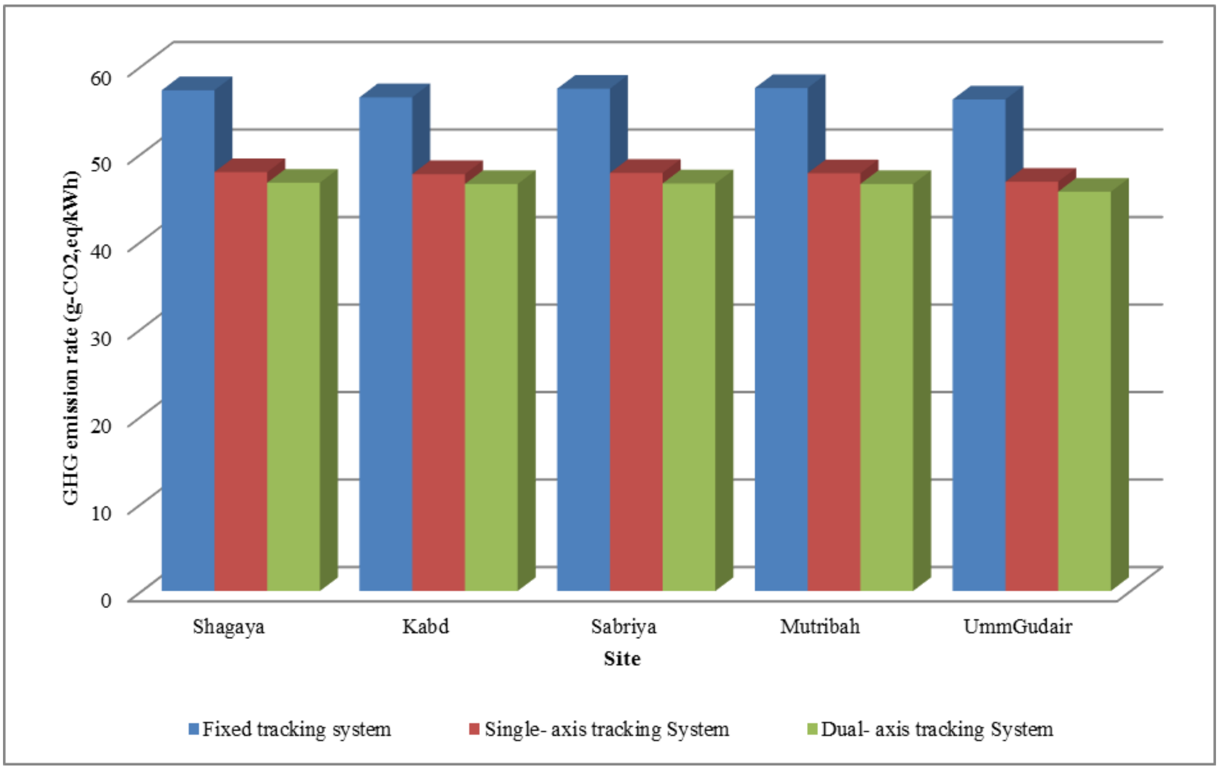


Figure 5.10 The total CO_2 emissions at the selected sites

Table 5.7 shows the CO_2 emissions associated with the implementation of the PV systems proposed in previous literature. It should be emphasised here that a large number of studies were reviewed for this purpose; however, differences in the specified boundary conditions and the type of technology used are important parameters that should be taken into account when comparing previous studies.

In addition, the accelerated rate of development in the photovoltaic field is another important factor. The fast development in this field is evidenced by higher efficiency manufacturing and more durable solar modules. Figure 5.11 shows a comparison between the present study and previous studies in terms of GHG emissions.

It can be seen from Table 5.7 that the CO_2 emissions rate measured in the selected studies varied between 44 and 62 g-CO_2,eq/kWh, where the CO_2 emissions rate obtained in the present study ranged from 46.38 to 56.94 g-CO_2,eq/kWh. The results obtained in the present study were thus within the range of those achieved in previous studies. In addition, the effect of using tracking systems, both single-axis and dual-axis, was significant.

It is also important to compare the obtained results with different results achieved using different technologies, such as wind energy, in order to provide a better understanding of the impact of PV systems on the environment compared with other available technology. Table 5.8 presents the average emissions of different technologies. From Figure 5.12, it is clear that the emissions produced by fossil fuel based technologies, such as coal, are the highest, with a relatively high percentage among the other listed technologies. Nuclear, hydroelectric, and wind energies have the lowest emissions.

The emissions produced by photovoltaic solar energy production are relatively low compared with fossil fuel based technologies, such as coal and oil, but high in comparison with other renewable technologies, such as wind energy. As previously stated in this chapter, this can be attributed to the large amounts of energy used in the manufacturing and fabrication of solar modules.

Table 5.7 CO_2 emissions measured in previous selected studies

Location	**Mounting type**	**CO_2 emission** (g-CO_2,eq/kWh)	**Reference**
Western Europe	Ground mounted	60	(Alsema, 2000)
North Africa	Rooftop	57	(Pehnt et al., 2003)
Japan	Rooftop	53	(Hondo, 2005)
Southern Europe	Ground mounted	44	(Frankl et al., 2005)
Gobi Desert	Rooftop	62	(Ito et al., 2010)
China	LS-PV	60.1	(Hou et al., 2016)

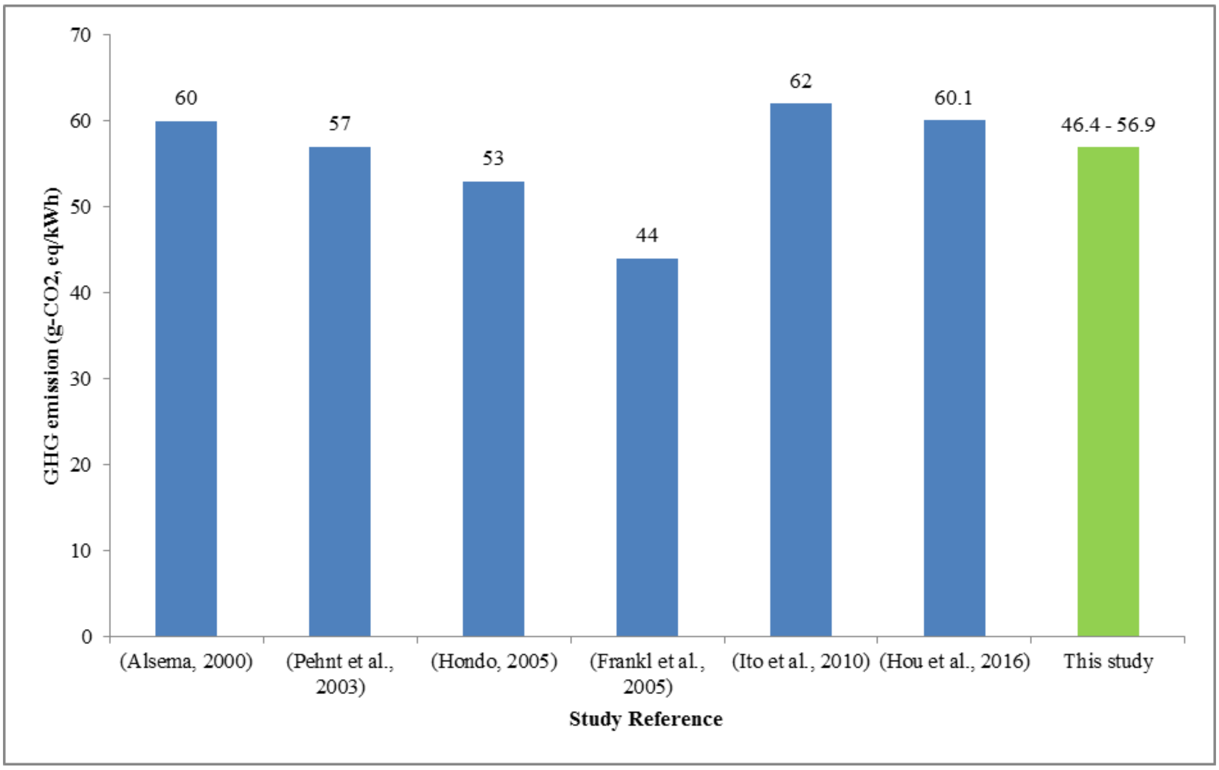


Figure 5.11 The CO_2 emissions measured in selected studies

Table 5.8 The average emissions of different technologies (World Nuclear Association, 2011)

Technology	**Average Emissions** (g-CO_2,eq/kWh)
Coal	888
Oil	733
Natural Gas	499
Solar PV	85
Biomass	45
Nuclear	29
Hydroelectric	26
Wind	26

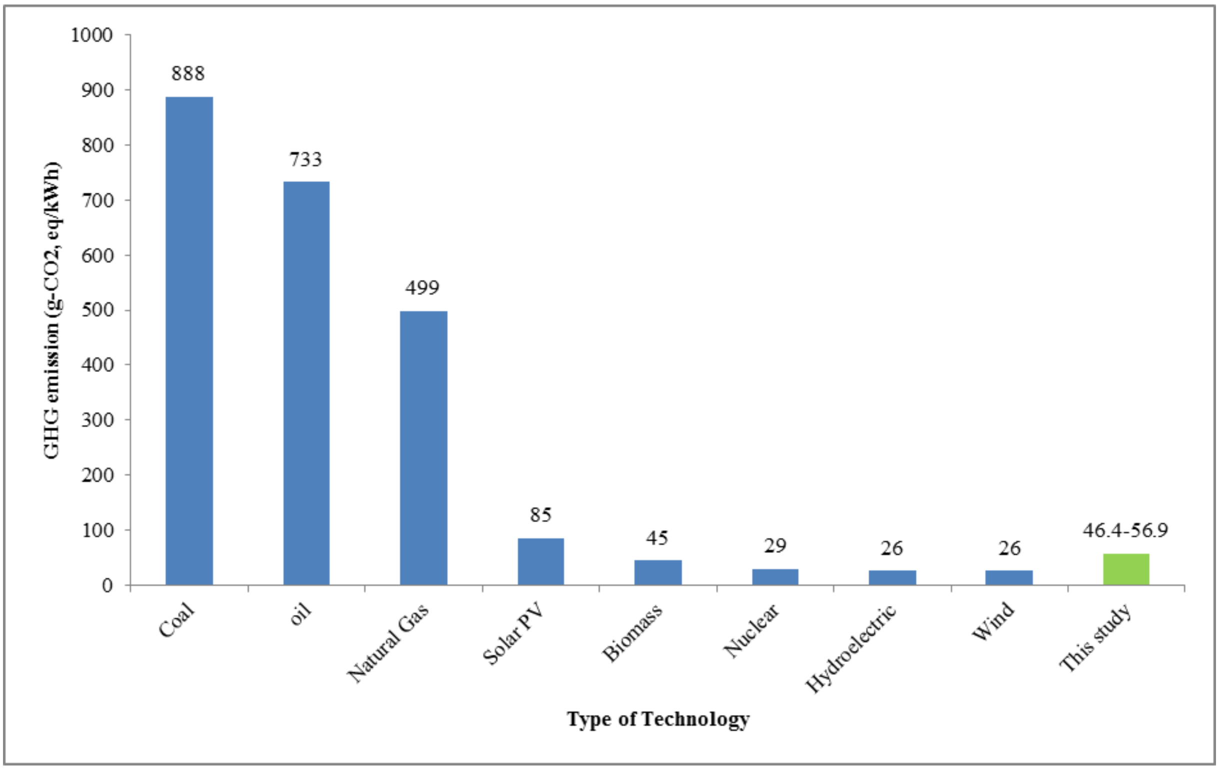


Figure 5.12 The total CO_2 emissions of different renewable energy

5.5 Environmental Benefit Evaluation

‘Global warming’ or ‘climate change’ are the best descriptive terms for what most researchers in the environmental field are focusing on currently. As stated in the literature review, the increasing rate of the industrial revolutions in many different fields, such as manufacturing, in addition to the increasing population, is causing an increase in the demands of everyday life.

In this context, the reliance on natural fossil fuels to produce energy is driving an increase in GHG emissions. It is generally accepted that the conversion of forests to agricultural land, and the GHG emissions produced by industrial factories, are the main causes of air pollution (Gevorkian, 2014).

In this section, the role of implementing PV systems in minimising GHG emissions caused by conventional power plants will be investigated. Specifically, the amount of GHG emissions that would be avoided by utilising PV systems in Kuwait to generate electricity will be evaluated, and the effect of using tracking systems will also be investigated.

The importance of this study is clear, and the State of Kuwait, which is almost entirely dependent on conventional power plants for electricity generation, is a good example due to environmental evaluation criteria being comparatively more important than economic evaluation criteria. Conventional power plants consume fossil fuels, and Kuwait is one of the largest oil exporting countries, with the country's annual budget almost completely determined by oil export revenues.

In addition to the LCA study, it is very useful to estimate the environmental benefits of reducing or avoiding GHG emissions, which have a direct harmful effect on the environment, in terms of both global warming and human life.

The implementation of the proposed PV systems at the selected sites will generate electricity with zero emissions. In this study, the amount of GHG emissions that would be avoided was calculated based on the expected amount of energy that would be introduced by the proposed PV systems, and the equivalent amount of emissions produced by conventional power plants in Kuwait.

Notably, most previous studies have not investigated the amount of SO_2 and NO_x saved. In other words, these studies focused solely on determining the equivalent CO_2, rather than all GHGs (SO_2, NO_x, and CO_2); this is reasonable, as the percentage of CO_2 emissions is very high in comparison to other GHGs.

However, in this study, the effects of all GHGs were investigated, as the capacities of the proposed PV stations were relatively large. Therefore, the total emissions rates for Kuwait power plants were taken into consideration in this study (see Table 5.9).

In order to gain a better understanding of the potential benefit of utilising PV systems in Kuwait, an environmental benefits study was conducted on the selected sites. The amounts of GHG emissions were determined based on the expected annual production for each site (annual energy production data was given in Chapter 4). Table 5.10 shows the CO_2, SO_2, and NO_x emissions (in tons) for the selected sites. The results were obtained using fixed, single-axis and dual-axis tracking systems.

The avoided emissions, for all of the proposed sites, ranged from 104,608 to 107,306 tons, with an average of 105,739.4 tons, of CO_2; from 174.35 to 178.84 tons, with an average of 176.23 tons, of SO_2; and from 26.15 to 26.83 tons, with an average of 26.43 tons, of $NO_{x,}$ for the fixed tracking systems.

The avoided emissions when using single-axis and dual-axis tracking systems ranged between 130,701 and 134,361 tons of $CO_{2,}$ with an average of 131,843 tons; and between 135,289 and 138,938 tons of $CO_{2,}$ with an average of 136,417.2 tons, respectively. The avoided SO_2 emissions when using the single-axis and dual-axis tracking systems varied between 217.84 and 223.94 tons, with an average of 219.74 tons, and between 225.48 and 231.56 tons, with an average of 227.362 tons, respectively. The avoided NO_x emissions ranged from between 326.75 and 335.9 tons, with an average of 329.61 tons, and between 338.22 and 347.34 tons, with an average of 341.04 tons, respectively.

The effects of using single-axis and dual-axis tracker systems are clearly apparent from Figures 6.13 to 6.15. The amount of avoided CO_2, SO_2 and NO_x emissions increased, on average, by 24.4% and 28.8% with the use of single-axis and dual-axis tracker systems, respectively. Figures 5.13 to 5.15 present a comparison between the selected sites based on the amounts of avoided CO_2, SO_2 and NO_x emissions, and also the type of tracking system used.

The findings of the environmental benefits analysis has shown that large amounts of GHG emissions could be avoided by implementing PV systems to generate electricity in Kuwait. This would constitute a positive contribution to helping minimize certain environmental issues, such as global warming.

Table 5.9 Total emissions rates for power plants in Kuwait (Alhaddad et al., 2011)

Parameter	**Value**	**Units**
SO_2	1	kg/MWh
NO_X	0.15	kg/MWh
CO_2	600	kg/MWh

Table 5.10 Total amounts of CO_2, SO_2 and NO_x emissions avoided for the selected sites

Site	Annual Production (MWh/year)	CO_2 (tons)	SO_2 (tons)	NO_x (tons)
Shagaya				
Fixed tracking system	175075	105045	175.08	26.26
Single-axis tracking system	217835	130701	217.84	32.68
Dual-axis tracking system	225503	135302	225.50	33.83
Kabd				
Fixed tracking system	177519	106511	177.52	26.63
Single-axis tracking system	218291	130975	218.29	32.74
Dual-axis tracking system	225481	135289	225.48	33.82
Sabriya				
Fixed tracking system	175378	105227	175.38	26.31
Single-axis tracking system	219772	131863	219.77	32.97
Dual-axis tracking system	227556	136534	227.56	34.13
Mutribah				
Fixed tracking system	174347	104608	174.35	26.15
Single-axis tracking system	218859	131315	218.86	32.83
Dual-axis tracking system	226705	136023	226.71	34.01
Umm Gudair				
Fixed tracking system	178843	107306	178.84	26.83
Single-axis tracking system	223935	134361	223.94	33.59
Dual-axis tracking system	231563	138938	231.56	34.73

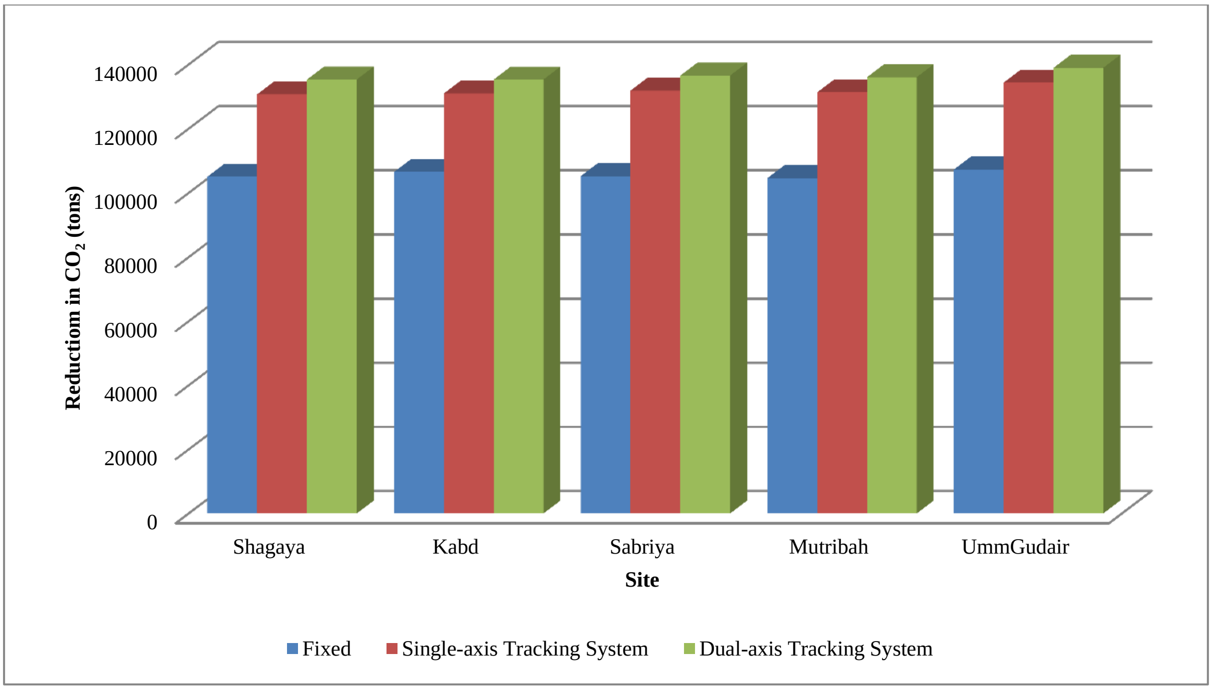


Figure 5.13 Reduction in CO_2 for the selected sites

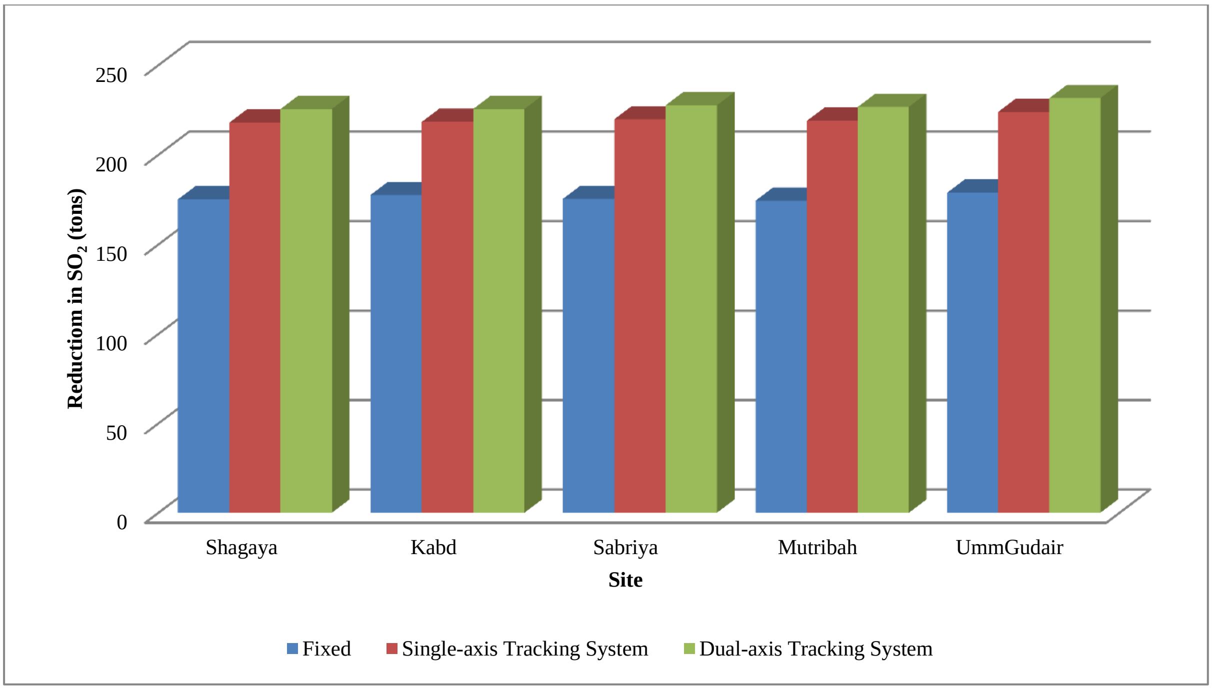


Figure 5.14 Reduction in SO_2 for the selected sites

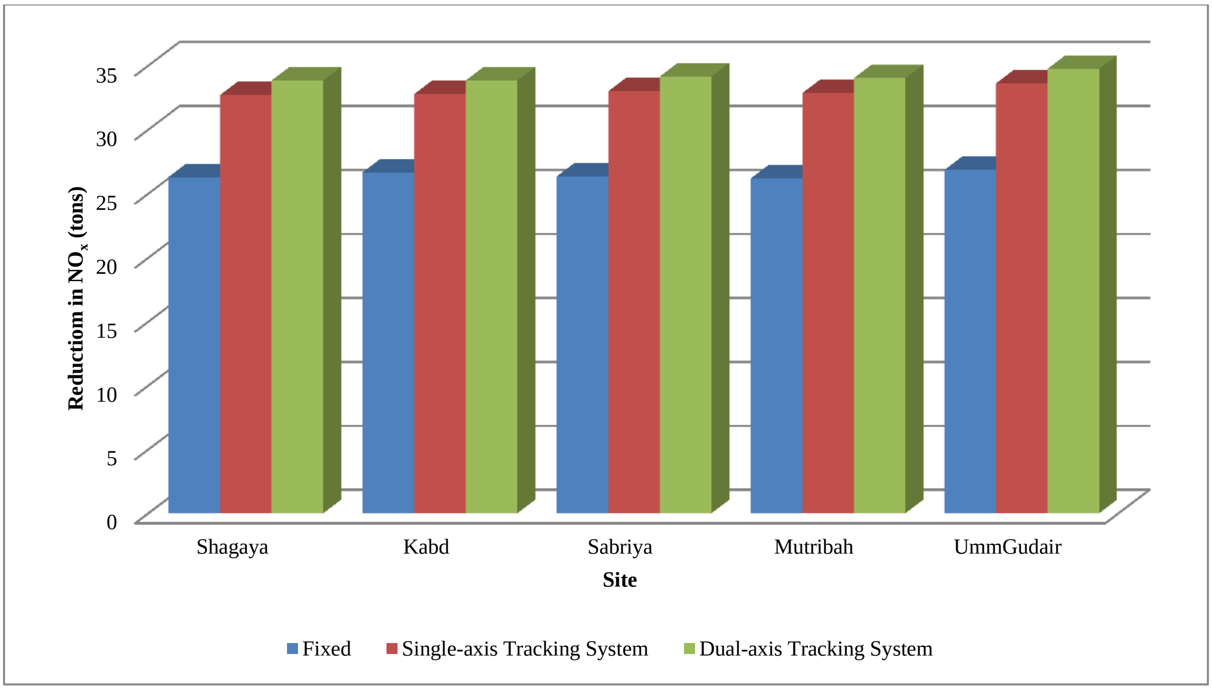


Figure 5.15 Reduction in NO_x for the selected sites

5.6 Conclusions

The manufacturing stage of PV system components is a critical stage in this regard, as a high volume of emissions are produced due to the large amounts of energy consumed in manufacturing and fabricating PV systems components.

The average EPBTs obtained in the present study were 1.765 year, 1.415 year and 1.37 year for the fixed tracking system, single-axis tracking system and dual-axis tracking system, respectively. These EPBT results are encouraging, and show that shorter periods can be achieved by using single-axis and dual-axis tracking systems. The average EYR values obtained in this study were 14.15 year for the fixed tracking system, and 17.675 year and 18.24 year for the single-axis and dual-axis tracking systems, respectively. The EYRs obtained are also propitious, and show that better values can be achieved using single-axis and dual-axis tracking systems.

It was found that the transportation stage, which has been included as a boundary condition in this study, had an insignificant effect on the total CO_2 emission rate of the proposed PV systems at the selected sites, compared with other stages. However, including the emissions produced in the transportation stage in the LCA provided more realistic results.

It was found that the CO_2 emission rates obtained in this study, which ranged between 46.38 and 56.94 g-CO_2,eq/kWh, were within the range of the results obtained in previous studies. Comparing the obtained results with other relevant studies conducted in the photovoltaic fields is important, in order to get more trusted values for both the input data and the obtained results. In addition, the results obtained in this study were compared with the data for other energy technologies, such as renewable energy. It was found that the emissions from fossil fuel based technologies, such as coal, were the highest, with a relatively high percentage compared to other listed technologies, where nuclear, hydroelectric and wind energy had the lowest emissions. It was also found that the emissions resulting from photovoltaic solar energy are relatively low compared with fossil fuel based technologies such as coal and oil, but are relatively high when compared with other renewable technologies, such as wind energy. This was attributed to the large amounts of energy consumed in the manufacturing and fabrication of the solar modules.

Based on the environmental benefits analysis, a large amount of GHG emissions, as stated above, would be avoided by implementing PV systems to generate electricity in Kuwait. This would constitute a positive contribution to helping minimise certain environmental issues, such as global warming.

Chapter 6 - Economic Evaluation

6.1 Introduction

One important criterion when evaluating the feasibility of PV systems is the financial assessment. An economic evaluation of the proposed PV system is an essential part of this thesis, as it will help determine the feasibility of using solar PV technology in Kuwait.

There is no doubt that most renewable energy have the shared advantage of the continuing decrease in the cost of implementing different renewable technologies, such as wind energy. This could be attributed to many possible causes, such the extensive interest in this field of both specialists and investors seeking to benefit from clean and fuel-free technologies.

For solar photovoltaic technology, in particular, as shown in the literature review, there are many factors that make it distinct from other renewable energy technologies. One of its advantages is the rapidly decreasing cost of PV system components, particularly the solar modules, which represent approximately 60% of the total cost (Feldman et al., 2012). It is extremely important to emphasise again the rapid development in photovoltaic technology that has occurred in the past decade. The development and improvement in this field has led to a significant reduction in the installation cost of photovoltaic systems.

As such, solar photovoltaic energy is becoming relatively more attractive than other renewable energy technologies. One likely explanation for this is simply the basic principle of the technology, the key point of which is converting solar irradiation into electricity using solar modules. Moreover, the importance of solar modules can also be deduced from the highly competitive solar market across the world. This can be seen in different ways, such as the increased focus on improving the efficiency and durability of solar modules, whereby warranties are provided with high standards specifications, as well as more competitive prices.

Photovoltaic technology is a silicon-based technology; this is a key point, which will be discussed further. Photovoltaic energy is substantially influenced by the performance of the solar modules, more so than any other factor. It is generally agreed that solar photovoltaic module efficiency and solar irradiation at the installation site are the two most important factors in PV technology (Smestad, 2008).

Solar photovoltaic technology is different to other renewable energy in terms of their conventional working systems. For example, other renewable energy technologies are created based on complete systems in which many materials, such as steel and concrete, are needed. Moreover, safety and security systems are an important and necessary element of the whole system, throughout both the installation and operation stages, and require a team of specialists and labourers as well as equipment. Any change in the cost of the materials, equipment, or workers' wages will directly affect the total cost of using the technologies.

Conversely, PV system technology is primarily dependent on solar modules, which have benefitted from an accelerated rate of development. The remarkable decrease in the installation cost of PV systems technology has resulted mainly from the significant evolution and improvement of the solar module properties over a short period of time.

The installation cost of any proposed PV system is a primary input for any economic assessment study, as it will be used to calculate the levelized cost of electricity (LCOE); this will be explained in detail in the next section.

In this chapter, an economic evaluation will be conducted for the selected sites, using the LCOE approach. The LCOE values will be computed for the proposed PV systems, and the effects of using single-axis and dual-axis solar PV solar trackers will also be investigated. Moreover, the effects of the fluctuation of oil prices, as an important variable, will be considered.

Section 6.2 will present an economic assessment of implementing PV systems in Kuwait. A sensitivty analysis will be conducted in Section 6.3. In Section 6.4, a cost-benefit analysis of using the proposed PV systems will be carried out, and the cost of CO_2 that would be saved by implementing the proposed PV systems will be calculated in Section 6.5. Finally, the study conclusions will be presented in Section 6.6.

6.2 Economic Assessment of Implementing PV Systems in Kuwait

The results obtained from the performance parameters evaluation of the proposed systems at the selected sites, presented in Chapter 4, are encouraging; hence, the economic evaluation is a crucial step in order to build a complete picture of the potential for implementing PV systems in Kuwait, which is the primary aim of this research. An economic evaluation will be conducted for all of the proposed sites (Shagaya, Kabd, Sabria, Mutribah and Umm Gudair), and three different tracking systems (fixed, single-axis and dual-axis tracking systems) will be examined at each individual site.

As stated in the methodology chapter (Chapter 3), the levelized cost of electricity (LCOE) approach will be used in the economic assessments of the proposed PV systems. It is generally agreed that the levelized cost of electricity is the most appropriate method for comparing the feasibility of different electricity generation technologies, such as PV systems and conventional power plants (Hernández-Moro and Martínez-Duart, 2013; IRENA, 2012). The LCOE is an important measure that can be used to evaluate the economic viability of many energy generation technologies.

A lot of solar technology projects have been economically evaluated using the LCOE approach, which calculates the lifetime of generated energy and the total cost of the installed system (Branker et al., 2011). Moreover, the LCOE method is widely used to measure the cost effectiveness of PV systems, which is defined as the levelized cost per unit of energy produced (Kang and Rohatgi, 2016). The main inputs of LCOE are the installation cost and operation and maintenance costs (OM).

The levelized cost of electricity can be calculated using the following equation (Smestad, 2008):

$$\text{LCOE} = (\text{Annual cost} + \text{OM})/\text{Annual Output} \tag{6.1}$$

$$\text{Annual Cost} = (\text{Installation Cost} \times \text{CRF}) + \text{OM} \tag{6.2}$$

CRF is the capital recovery factor, and is given as the following equation:

$$\text{CRF} = i \times (1+i)^{n} / (1+i)^{n}-1 \tag{6.3}$$

Where i and n are the interest rate and the project life, respectively.

$$\text{Installation Cost} = \text{Capital Cost} \times \text{Station Capacity} \tag{6.4}$$

As shown in the above equations, the installation cost is an important input, as it is used to estimate the annual cost of the proposed system. Calculating an accurate installation cost is important in order to determine the LCOE values; however, due to some uncertainty in the data, such as the price of solar modules (normally represented in $/W), which is dependent on the global market price, it is not easy to determine a specific value for the installation cost of a PV system. This is clear from the literature review of past research, in which different values were used in different countries across the world. In addition, a few studies have taken account of the effect of tracking systems in the installation cost.

It is extremely important to note here that the installation cost of the proposed PV systems in Kuwait was one of the main challenges encountered in this study. This was due to a lack of information and relevant data regarding the implementation of photovoltaic technology in Kuwait. For example, although some research has been carried out on photovoltaic energy in Middle East, and in Kuwait in particular, no study has investigated the single-axis and dual-axis tracking systems in this context. Furthermore, most of the recently published research on the state of Kuwait references relied on older studies when calculating the installation cost. Unfortunately, this will definitely lead to inaccurate results. However, a sensitivty analysis will be conducted in Section 6.4 in order to deal with such a situation with a high level of caution.

The installation cost of a PV system has decreased from approximately $5 (£3.83)/kW in 2005, and is expected to be approximately $1 (£0.77)/kW in 2020. This significant reduction in the installation cost, along with the rapid development of photovoltaic technology itself, meaning that this technology is one of the most interesting and competitive alternatives for producing electricity across the world. Moreover, it is generally agreed that the significant decline in prices of the PV systems will play a vital role in implementation of this technology (Nemet et al., 2017).

In this study, the installation cost is set as $1.77 (£1.36)/kW for a fixed tracking system, and $1.91 (£1.46)/kW and $2.05 (£1.57)/kW for single-axis and dual-axis tracking systems, respectively (Chung et al., 2015; Kang and Rohatgi, 2016; NREL, 2016). The operation and maintenance (OM) cost is assumed to be 3% of the investment cost per year (Ramadhan and Naseeb, 2011; Zweibel, 1999). Table 6.1 lists the input data used for the LCOE calculation. The annual energy production of the proposed PV systems was calculated in detail in Chapter 4.

Table 6.1 Input data used for the LCOE calculations

Input Parameter	**Value**	**Unit**
Station Capacity	100	MW
Installation Cost		$/W (£/W)
Fixed tracking	1.77 (1.36)	
Single-axis tracking	1.91 (1.46)	
Dual-axis tracking	2.05 (1.57)	
OM	3% of installation cost per year	$ (£)
Interest Rate	5	%
Project Life	25	year

Based on the input parameters listed in Table 6.1 above, the LCOE values were obtained for the proposed PV systems at each single site, and the effect of using single-axis and dual-axis tracking systems was also investigated (detailed results are presented in Table 6.2.)

The obtained LCOE values varied from 0.071 to 0.073 $/kWh (0.054 to 0.056 £/kWh) for the fixed tracking systems, and from 0.062 to 0.063 $/kWh (0.0475 to 0.0483 £/kWh), and 0.064 to 0.066 $/kWh (0.0491 to 0.0506 £/kWh) for the single-axis and dual axis-tracking systems, respectively.

From Table 6.2, it is apparent that the Umm Gudair site had the best values, as it showed the lowest LCOE for all of the proposed tracking systems – an LCOE of 0.071 $/kWh (0.054 £/kWh) for a fixed tracking system, and 0.062 $/kWh (0.048 £/kWh) and 0.064 $/kWh (0.049 £/kWh) for single-axis and dual-axis systems, respectively. As the Umm Gudair site showed the highest amount of energy generated by the PV system, and in light of the fact that LCOE is directly inversely to the amount of generated energy, these values were expected in advance.

The achieved LCOEs for the other sites were almost identical, at 0.073 $/kWh (0.056 £/kWh) for a fixed tracking system, and 0.063 $/kWh (0.048 £/kWh) and 0.066 $/kWh (0.051 £/kWh) for single-axis and dual-axis systems, respectively.

It can be seen also that the average LCOE was \$0.072 (£0.055)/kWh for fixed tracking systems. This value decreased by 13.10% and 9.72% as a result of using single-axis and dual-axis tracking systems, respectively.

On the other hand, although using a dual-axis tracking system increased the amount of produced energy by 28.8% and 4.8% over the fixed and single-axis tracking systems, respectively, the single-axis tracking system had better LCOE values. This is due to dual-axis solar tracking systems being more expensive in terms of installation and maintenance costs.

Since the LCOE for the conventional power plants in Kuwait is the key comparison measure used in this study, the obtained LCOE values will be compared with its value, which is estimated at \$0.12 (£0.092)/ kWh (Ramadhan and Naseeb, 2011). Accordingly, the proposed PV systems achieved lower LCOE values at all selected sites, and with all different tracking systems.

In addition, the significant impact of utilising tracking systems can be clearly observed from Figure 6.1, in which the LCOE values decreased significantly through the use of the single-axis and dual-axis tracking systems. Moreover, the single-axis tracking system appears to be the best choice for all of the selected sites in the State of Kuwait.

It can be seen also that all sites produced very close values for all the different tracking system types, which is due to the fact that the country is relatively small in terms of geographical area and the distances between the sites are thus not far. In addition, the variation in solar irradiation and climate data between the different sites is insignificant. This can be easily deduced from most studies in the solar energy field in the State of Kuwait, which have been conducted under the assumption that data for one location can be used for the whole country.

This assumption is helpful to a certain extent, for instance, for the purpose of preliminary analysis, in which only a brief understanding of PV systems is required. However, this research aims to determine the feasibility of using PV systems in Kuwait according to a more holistic view, and therefore a comprehensive analysis is required.

Table 6.2 Detailed results for the proposed systems at the selected sites

	Annual production (MWh/year)	**Installation cost** ($/W)	**Installation cost** (million $)	**Total annual cost** (million $)	**LCOE** ($/kWh)
Shagaya					
Fixed	175075	1.77	177	12.77	0.073
Single-axis Tracking System	217835	1.91	191	13.78	0.063
Dual-axis Tracking System	225503	2.05	205	14.79	0.066
Kabd					
Fixed	177519	1.77	177	12.77	0.072
Single-axis Tracking System	218291	1.91	191	13.78	0.063
Dual-axis Tracking System	225481	2.05	205	14.79	0.066
Sabriya					
Fixed	175378	1.77	177	12.77	0.073
Single-axis Tracking System	219772	1.91	191	13.78	0.063
Dual-axis Tracking System	227556	2.05	205	14.79	0.065
Mutribah					
Fixed	174347	1.77	177	12.77	0.073
Single-axis Tracking System	218859	1.91	191	13.78	0.063
Dual-axis Tracking System	226705	2.05	205	14.79	0.065
Umm Gudair					
Fixed	178843	1.77	177	12.77	0.071
Single-axis Tracking System	223935	1.91	191	13.78	0.062
Dual-axis Tracking System	231563	2.05	205	14.79	0.064

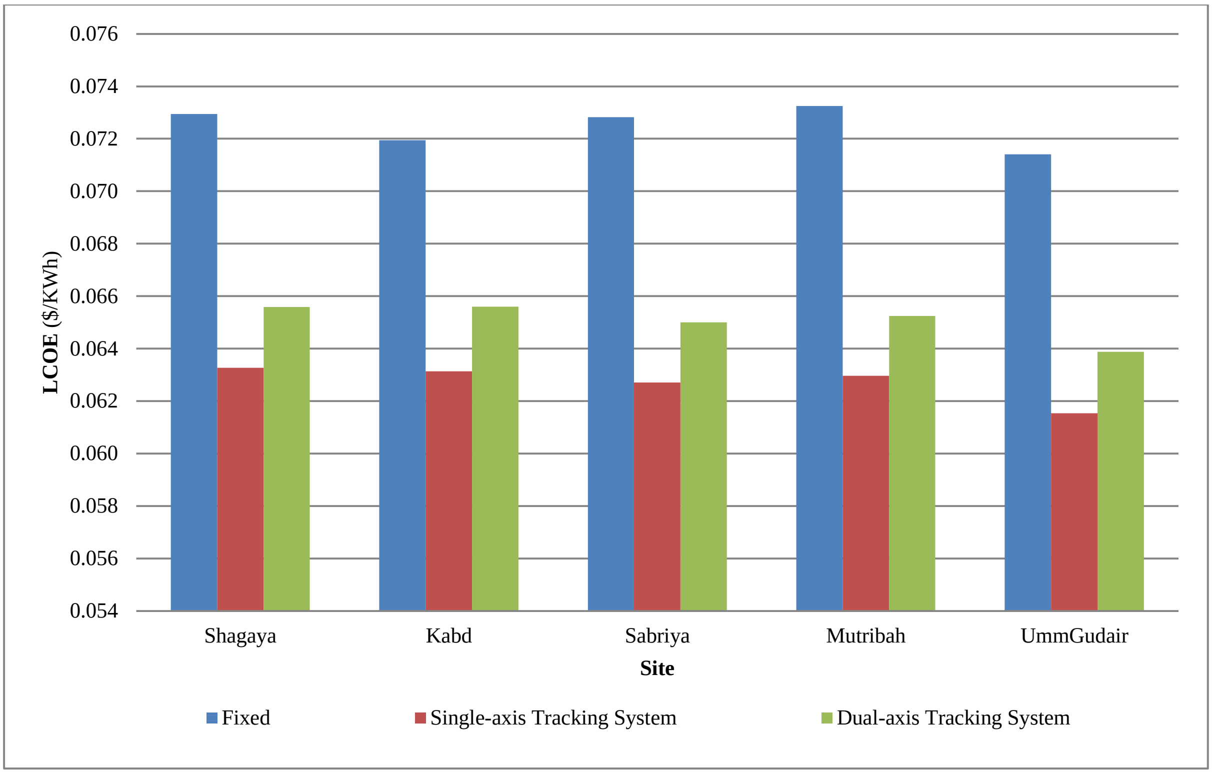


Figure 6.1 LCOE for the selected sites with different tracking systems

6.3 Sensitivity Analysis

In order to effectively account for the possible effects of the most changeable parameters in the LCOE approach, such as the installation cost of the PV systems, and to best understand the effects of these parameters, an LCOE sensitivity analysis with the following input parameters was conducted:

- Installation cost
- Interest rate
- Lifetime

As mentioned above, the prices of PV system components have decreased significantly over the last decade. This can clearly be seen, from an economic perspective, in the decrease in installation costs of PV systems from approximately $5.0 (£3.83)/kW in 2008 to approximately $2.0 (£1.53)/kW in 2016, moreover, this decrease is expected to continue, and reach $1.0 (£0.77)/kW in 2020 (Chung et al., 2015; GTM Research, 2016).

The significant development of PV technology in terms of efficiency and the lifetime of PV modules is another important parameter that should be taken into account when conducting an economic assessment of such a technology. Based on the above, and on the uncertainty of the input data for the LCOE method, the main LCOE inputs suggest high installation cost, interest rates, over their lifetime.

A LCOE sensitivity analysis is useful for covering all possibilities related to a change in certain input parameters, as described above, and can also be extended for use over a longer time and a large area. In the following section, installation costs, interest rates and lifetime will be considered in detail in regard to conducting a sensitivity analysis of LCOE with a view to implementing PV systems in Kuwait.

6.3.1 Installation Cost

As mentioned in the literature review, one of the disadvantages of photovoltaic technology, and the primary barrier facing all investors, is the high initial cost, whereby all of the PV system components must be sourced in order to start running the proposed system. From an economic viewpoint, this will require high financial liquidity, which is typically provided by investors.

In this study, five different cost scenarios, ranging from 1$/kW to 3 $/kW in increments of 0.5 $/kW, were used to determine the LCOE for the selected sites, and the effect of implementing single-axis and dual-axis tracking systems was considered. Table 6.3 lists the assumed installation rates used in this study. In this analysis, the fixed tracking system will be considered in order to make the analysis more clear, and also to compare the results with different LCOEs from relevant literature.

Table 6.3 Assumed installation rates

Scenario (No.)	**Fixed** ($/W)	**Single-axis** ($/W)	**Dual-axis** ($/W)
1	1	1.08	1.16
2	1.5	1.62	1.74
3	2	2.16	2.32
4	2.5	2.70	2.90
5	3	3.24	3.47

Scenario No.1 represents the best case scenario, and scenario No. 5 represents the worst. As stated above, and in the literature, scenario No.1 is likely to become the reality in the coming five years, due to the on-going and significant development and evolution in solar technology. In addition, solar energy, and particularly PV systems, are becoming more mature with time. Undoubtedly, this will lead to a significant decline in the cost of PV system components over time. However, the selected scenarios above were used to provide a complete and solid base of data taking all future probabilities into account. Table 6.4 shows the computed LCOEs for the selected sites with different assumed scenarios.

Table 6.4 LCOEs for different installation cost values

Site	**Scenario No.**				
	1	**2**	**3**	**4**	**5**
Shagaya					
Fixed	0.041	0.062	0.082	0.103	0.124
Single-axis Tracking System	0.036	0.054	0.072	0.089	0.107
Dual-axis Tracking System	0.037	0.056	0.074	0.093	0.111
Kabd					
Fixed	0.041	0.061	0.081	0.102	0.122
Single-axis Tracking System	0.036	0.054	0.071	0.089	0.107
Dual-axis Tracking System	0.037	0.056	0.074	0.093	0.111
Sabriya					
Fixed	0.041	0.062	0.082	0.103	0.123
Single-axis Tracking System	0.035	0.053	0.071	0.089	0.106
Dual-axis Tracking System	0.037	0.055	0.074	0.092	0.11
Mutribah					
Fixed	0.041	0.062	0.083	0.103	0.124
Single-axis Tracking System	0.036	0.053	0.071	0.089	0.107
Dual-axis Tracking System	0.037	0.055	0.074	0.092	0.11
Umm Gudair					
Fixed	0.04	0.061	0.081	0.101	0.121
Single-axis Tracking System	0.035	0.052	0.07	0.087	0.104
Dual-axis Tracking System	0.036	0.054	0.072	0.09	0.108

It can be seen that the LCOE varied between 0.0408 and 0.1228 $/kWh (0.031 and 0.094 £/kWh) for the fixed tracking systems. The LCOE varied between 0.036 and 0.106 $/kWh (0.027 and 0.081 £/kWh) for the single-axis tracking systems and varied between 0.037 and 0.110 $/kWh (0.028 and 0.084 £/kWh) for the dual-axis tracking systems. Therefore, the proposed PV systems with single-axis and dual-axis PV systems in all assumed scenarios showed LCOEs of less than 0.12 $/kWh (0.092 £/kWh), where the fixed tracking systems showed LCOEs of less than 0.12 $/kWh for all scenarios, except scenario No. 5.

Figure 6.2 shows a comparison between the selected sites with different tracking systems based on the LCOE. From Figure 6.2, it is apparent that the LCOE increased alongside an increase in installation costs for all types of tracking system, and for all assumed scenarios. Notably, the single-axis tracking system had the lowest LCOEs, whereas the highest LCOEs were found in the fixed tracking systems. Table 6.5 presents the computed average LCOEs for the fixed, single-axis and dual-axis tracking systems.

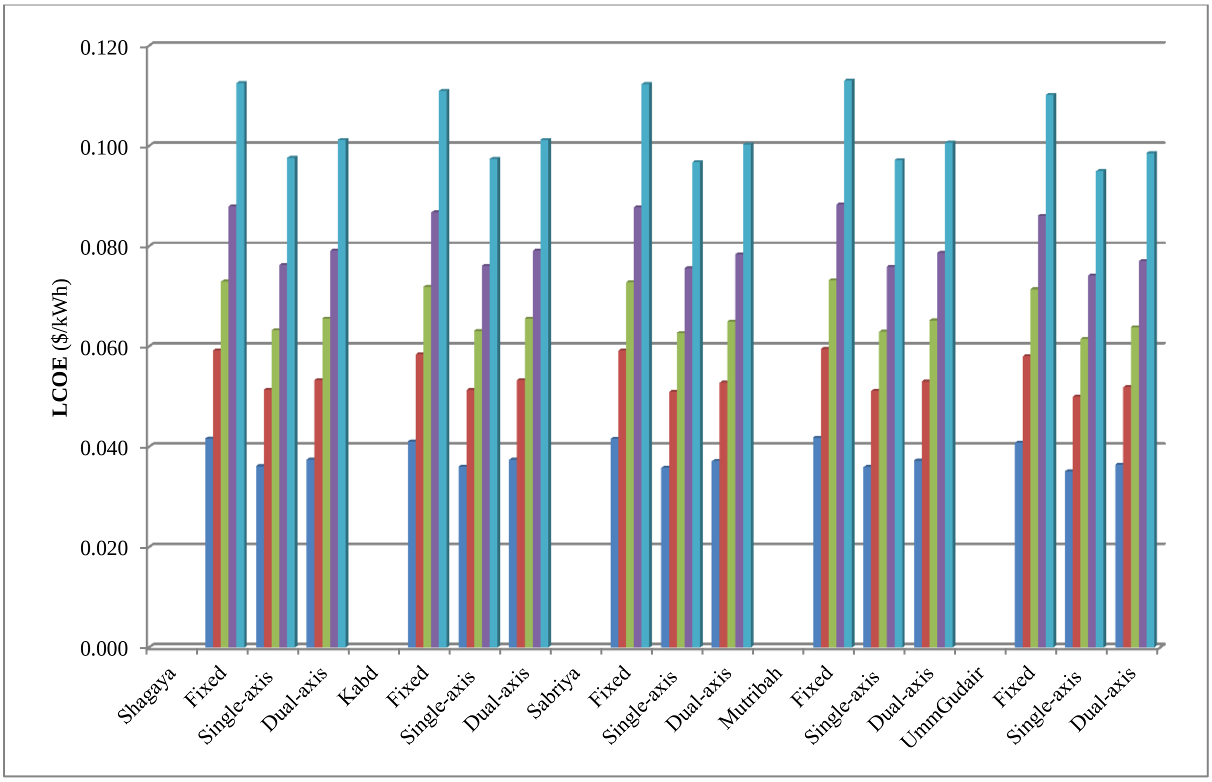


Figure 6.2 The LCOE for the selected sites with different tracking systems for different scenarios.

Table 6.5 Average LCOEs for different tracking systems indifferent scenarios

Installation cost ($/W)	**Scenario No.**				
	1	**2**	**3**	**4**	**5**
Fixed Tracking System	1	1.5	2	2.5	3
Single-axis Tracking System	1.08	1.62	2.16	2.7	3.24
Dual-axis Tracking System	1.16	1.74	2.32	2.9	3.47
LCOE for Fixed Tracking System ($/kWh)	0.041	0.061	0.082	0.102	0.123
LCOE for Single-axis Tracking System ($/kWh)	0.035	0.053	0.071	0.089	0.106
LCOE for Dual-axis Tracking System ($/kWh)	0.037	0.055	0.074	0.092	0.110

Figure 6.3 shows a comparison between the different tracking systems used based on their average LCOEs in different scenarios. The comparison shows that the single-axis tracker is the best choice for implementing PV systems in Kuwait. It had an LCOE range from $0.035 (£0.027)/kWh for the best case scenario, and $0.106 (£0.081)/kWh for the worst case scenario. Thus, if the average scenario is considered (Scenario 3), the LCOE value will be $0.071 (£0.054)/kWh for single-axis tracking systems. When generating electricity through PV systems, this value would be considered feasible when compared with the cost of producing electricity via conventional power plants in Kuwait, which is 0.12 $/kWh (Ramadhan and Naseeb, 2011).

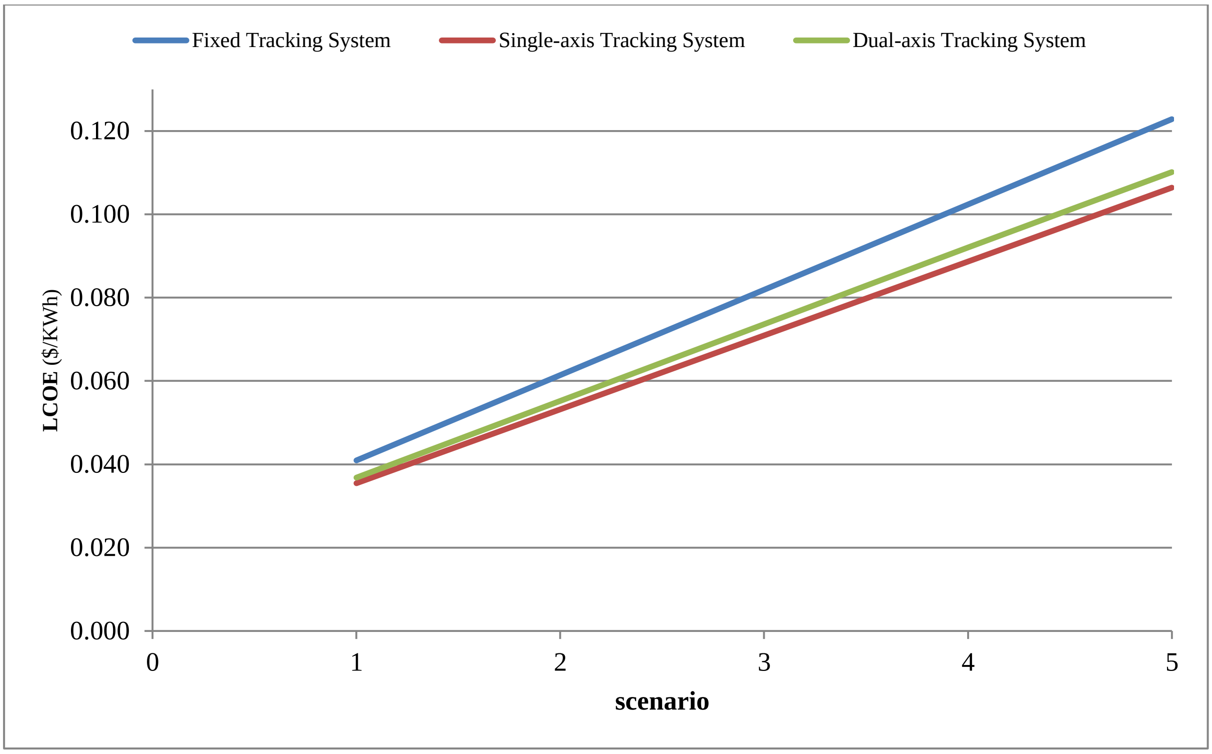


Figure 6.3 Average LCOEs for different tracking systems in different scenarios

6.3.2 Interest Rate

There is no doubt that the interest rate plays a vital role in terms of the feasibility of any project, from an economic perspective. Although there is increased motivation to support investment in renewable energy projects, as governments typically provide financial incentives to do so, the effect of different interest rate values requires investigation in order to understand the range of authentic data.

PV system projects should be approached in the same way as any other type of industrial project, as they will succeed or fail depending on several factors. The risk of investing in solar technology should not be ignored; therefore, estimation of the main input parameters should be estimated within an acceptable range, in order to gain a full picture of the relevant financial factors, such as interest rates. This will help investors and/or decision-makers to effectively evaluate any proposed projects in reference to a good range of alternatives.

As the LCOE method is directly influenced by the mount of selected interest rates, a proper estimation of these values are important in order to have a realistic results for any kind of feasibility' studies. It is generally accepted in the public investments in the power sector in Kuwait that a 5% interest rate, which has been estimated based on the governmental development plan and the assets of the sovereign wealth funds of Kuwait, is the commonly used value in the feasibility studies (Ramadhan et al., 2013).

In order to have a better understanding of the impacts of the interest rate on the LCOE, a wide range of interest rate values (from 0 to 10%) were selected. Table 6.6 presents the computed LCOE values for the selected sites with different interest rate cost values. A comparison between the selected sites based on different interest rates is shown in Figure 6.4.

Table 6.6 LCOEs for different interest rate cost values

Site	Interest rate (%)				
	0	**3**	**5**	**7**	**10**
Shagaya					
Fixed	0.042	0.059	0.073	0.088	0.113
Single-axis Tracking System	0.036	0.051	0.063	0.076	0.098
Dual-axis Tracking System	0.037	0.053	0.066	0.079	0.101
Kabd					
Fixed	0.041	0.058	0.072	0.087	0.111
Single-axis Tracking System	0.036	0.051	0.063	0.076	0.097
Dual-axis Tracking System	0.037	0.053	0.066	0.079	0.101
Sabriya					
Fixed	0.042	0.059	0.073	0.088	0.112
Single-axis Tracking System	0.036	0.051	0.063	0.076	0.097
Dual-axis Tracking System	0.037	0.053	0.065	0.078	0.1
Mutribah					
Fixed	0.042	0.06	0.073	0.088	0.113
Single-axis Tracking System	0.036	0.051	0.063	0.076	0.097
Dual-axis Tracking System	0.037	0.053	0.065	0.079	0.101
Umm Gudair					
Fixed	0.041	0.058	0.071	0.086	0.11
Single-axis Tracking System	0.035	0.05	0.062	0.074	0.095
Dual-axis Tracking System	0.037	0.052	0.064	0.077	0.099

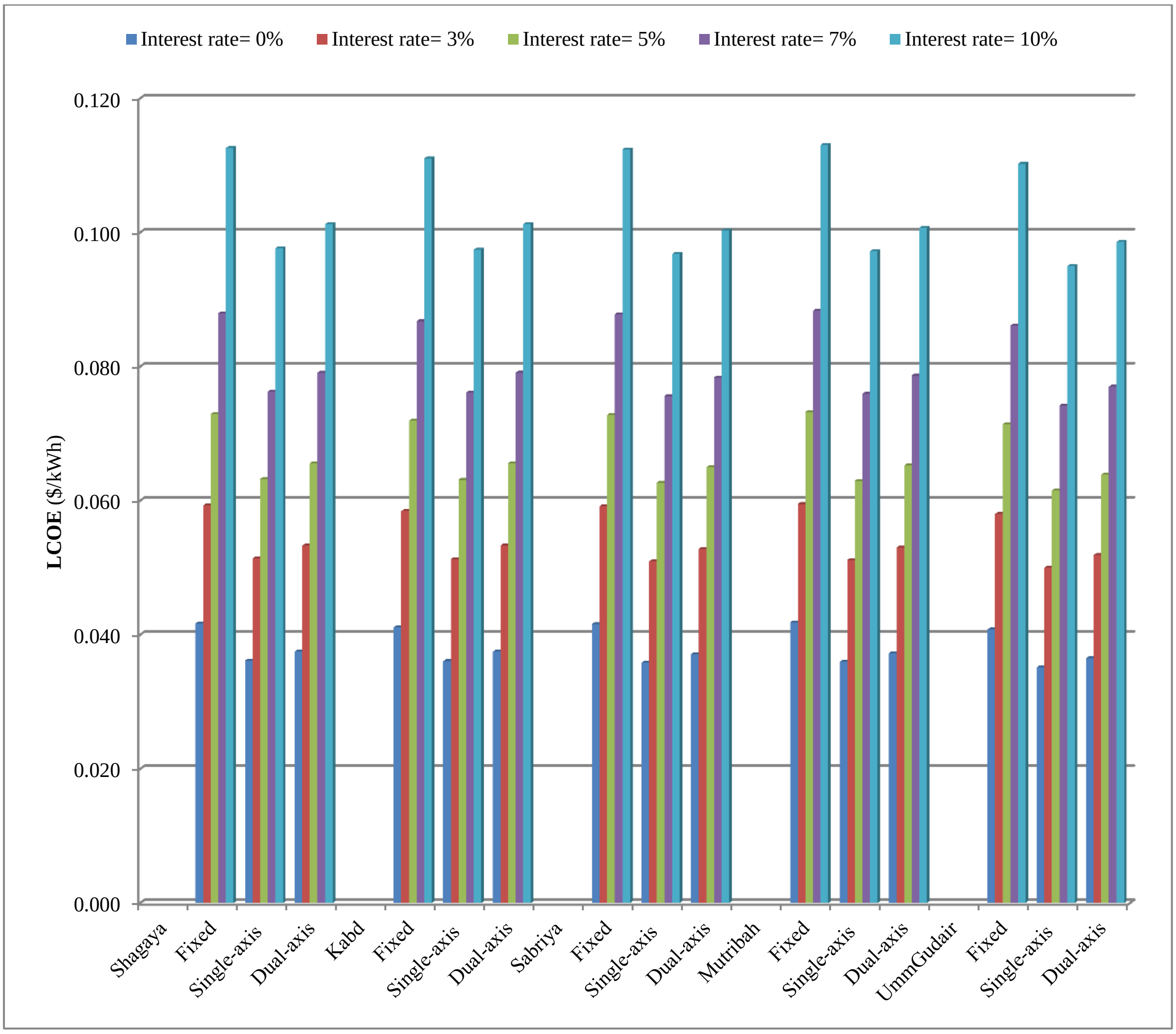


Figure 6.4 LCOEs for the selected sites with different interest rates

Table 6.7 presents the average LCOEs for the different tracking systems with different interest rates. Figure 6.5 shows a comparison between the applied tracking systems with different interest rates based on the LCOEs.

It can be seen that the LCOE values varied between 0.041 and 0.122 \$/kWh (0.031 and 0.094 £/kWh) for the fixed tracking systems, and between 0.036 and 0.097 \$/kWh (0.028 and 0.072 £/kWh), and 0.037 to 0.100 \$/kWh (0.028 and 0.077 £/kWh) for the single-axis and dual-axis tracking systems, respectively.

The results obtained are considered feasible compared with the LCOEs of the conventional power plants in Kuwait (0.120 \$/kWh), except for the scenario where the interest rate is 10%. The LCOE values varied between 0.036 and 0.097 \$/kWh (0.028 and 0.074 £/kWh) for the single-axis tracking systems, and between 0.037 and 0.100 \$/kWh (0.028 and 0.077 £/kWh) for the dual-axis tracking systems. These values are considered feasible for both systems at all of the selected sites.

The effect of a high interest rate is clear, and more than double when comparing interest rates of 5% and 10%, for instance. However, all of the obtained results were economically feasible (less than 0.12 \$/kWh). Based on the results, it can be concluded that the single-axis tracking systems are still the best choice for implementing PV systems in Kuwait.

Table 6.7 Average LCOEs for the different tracking systems with different interest rates

Interest rate	**0 %**	**3 %**	**5 %**	**7 %**	**10 %**
LCOE for Fixed Tracking System (\$/kWh)	0.041	0.059	0.072	0.087	0.112
LCOE for Single-axis Tracking System (\$/kWh**)**	0.036	0.051	0.063	0.076	0.097
LCOE for Dual-axis Tracking System (\$/kWh**)**	0.037	0.053	0.065	0.078	0.100

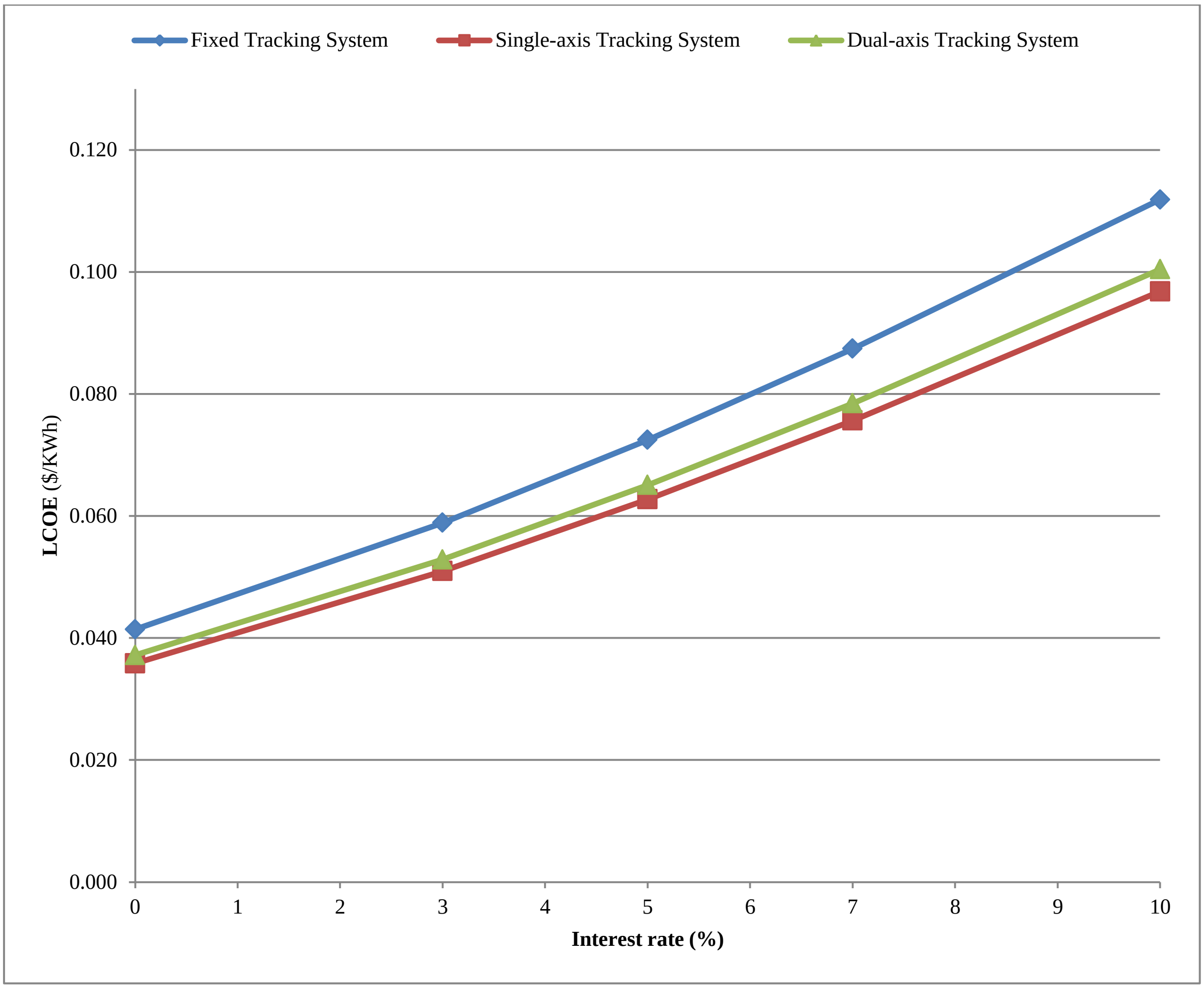


Figure 6.5 Average LCOEs for different tracking systems with different interest rates

6.3.3 Lifetime

A common way of determining the lifetime of PV components is to consult the warranty sheets included with products, and data produced by specialised organizations (see Section 5.3.1). However, these recommendations do not represent the real values, which will have a significant impact on the results of a feasibility study (Hernández-Moro and Martínez-Duart, 2013).

For instance, the same products have different lifetime values in different regions. Kuwait is a good example of this, as most of the studies conducted in the country assume a twenty year lifetime for the PV systems due to the harsh weather, specifically the dusty and hot weather in the summer months. On the other hand, the rapid development in PV technology should not be ignored; a number of researchers have suggested frequent cleaning of systems and more technical ways of reducing or preventing the accumulation of dust. This can be observed from relatively high values of lifetimes in different countries, for example, 30 years in Switzerland (Peng et al., 2013).

In this study, five different lifetime values (between 20 and 40 years) were tested. These selected values were chosen to gain a better understanding of the effect of this parameter in both the worst and the best case scenarios.

The obtained LCOEs results of the selected sites with different lifetime periods are shown in Table 6.8 and the effect of using different lifetime periods can be seen in Figure 6.6. It is clear that the LCOE decreases as the lifetime increases. This result was expected, as the LCOE is a function of the lifetime value, and an increase in lifetime thus means that more power will be produced. In addition, the average LCOE for fixed tracking varied between 0.082 and 0.060 $/kWh (0.063 and 0.047 £/kWh), and the LCOE for single-axis and dual-axis varied between 0.071 and 0.054 $/kWh (0.054 and 0.041 £/kWh) (Table 6.9). The obtained average LCOEs for different tracking systems with different lifetime periods are shown in Figure 6.7. Based on the results of the analysis, the lifetime parameter will not affect the feasibility of the proposed systems, even in the worst case scenario. However, increasing the lifetime value through using high quality materials and greater caution will conserve the materials and PV components, and thus will contribute to achieving excellent results. The results found in this study are encouraging, and the single-axis tracking system still clearly is the best option for utilising PV systems in Kuwait.

Table 6.8 Computed LCOEs for the selected sites with different lifetime periods

Site	Lifetime (year)				
	20	**25**	**30**	**35**	**40**
Shagaya					
Fixed	0.042	0.059	0.073	0.088	0.113
Single-axis Tracking System	0.036	0.051	0.063	0.076	0.098
Dual-axis Tracking System	0.037	0.053	0.066	0.079	0.101
Kabd					
Fixed	0.041	0.058	0.072	0.087	0.111
Single-axis Tracking System	0.036	0.051	0.063	0.076	0.097
Dual-axis Tracking System	0.037	0.053	0.066	0.079	0.101
Sabriya					
Fixed	0.042	0.059	0.073	0.088	0.112
Single-axis Tracking System	0.036	0.051	0.063	0.076	0.097
Dual-axis Tracking System	0.037	0.053	0.065	0.078	0.1
Mutribah					
Fixed	0.042	0.06	0.073	0.088	0.113
Single-axis Tracking System	0.036	0.051	0.063	0.076	0.097
Dual-axis Tracking System	0.037	0.053	0.065	0.079	0.101
Umm Gudair					
Fixed	0.041	0.058	0.071	0.086	0.11
Single-axis Tracking System	0.035	0.05	0.062	0.074	0.095
Dual-axis Tracking System	0.037	0.052	0.064	0.077	0.099

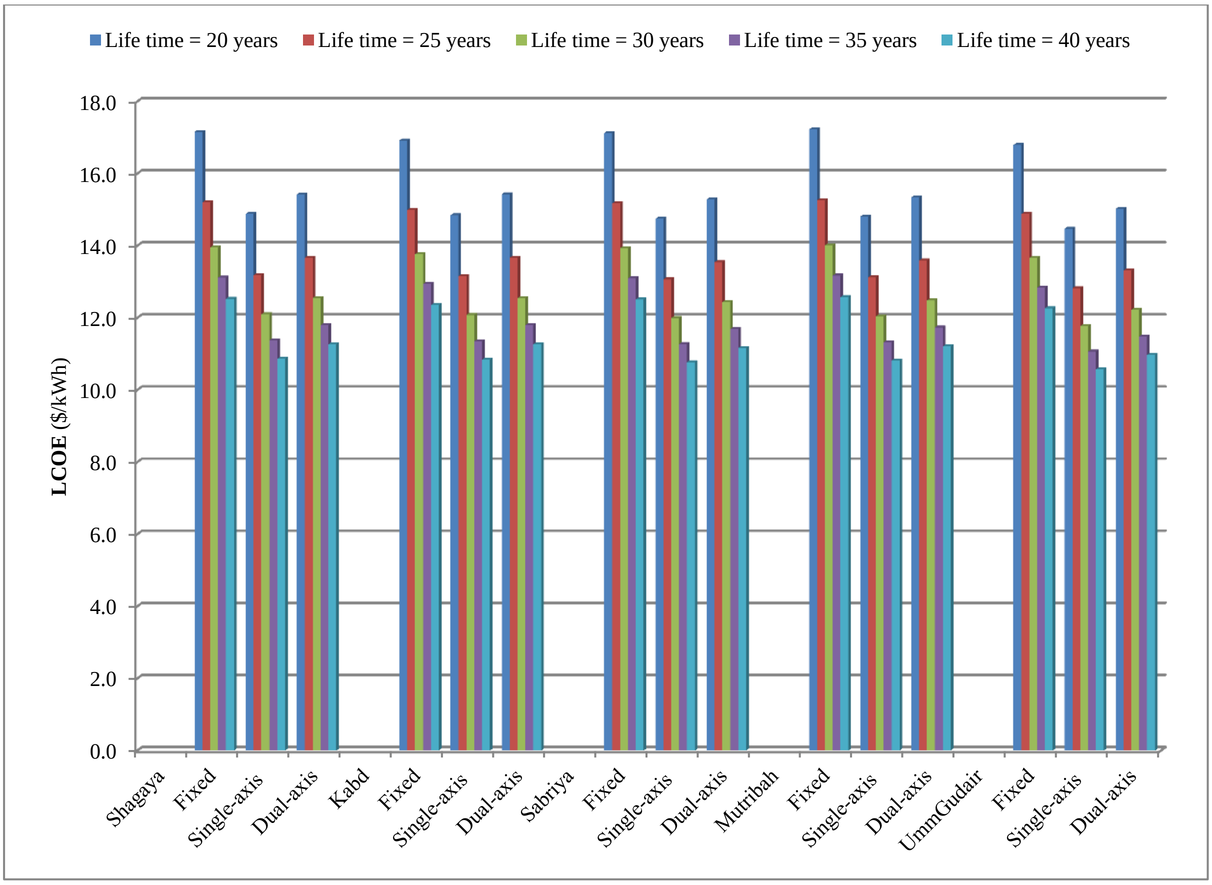


Figure 6.6 LCOEs for the selected sites with different lifetime periods

Table 6.9 Average computed LCOEs for different tracking systems

Lifetime (year)	**20**	**25**	**30**	**35**	**40**
LCOE for Fixed Tracking System ($/kWh)	0.082	0.072	0.067	0.063	0.060
LCOE for Single-axis Tracking System ($/kWh)	0.071	0.063	0.058	0.054	0.052
LCOE for Dual-axis Tracking System ($/kWh)	0.073	0.065	0.060	0.056	0.054

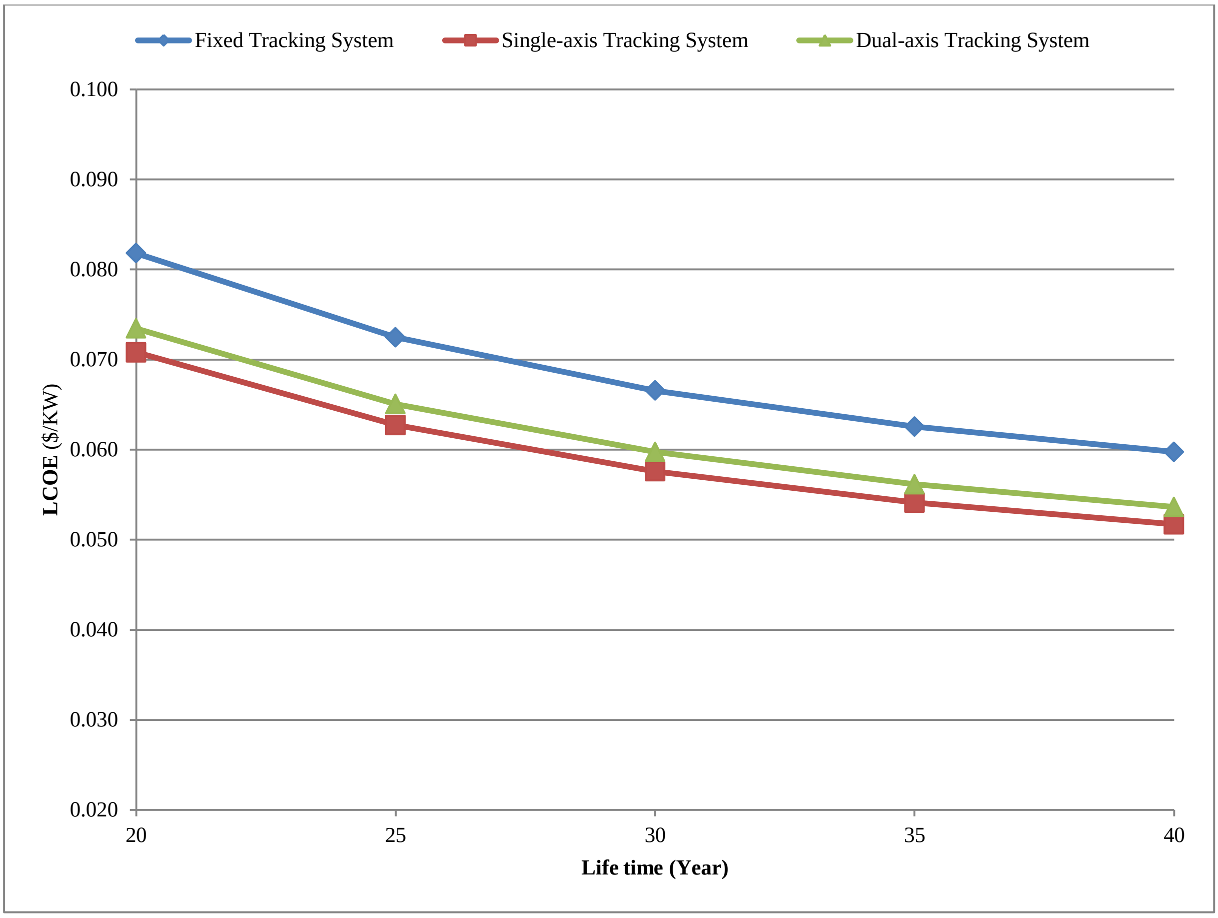


Figure 6.7 Average LCOEs for different tracking systems with different lifetime periods

6.4 Cost-benefit Analysis of Using PV Systems at the Proposed Sites

The cost-benefit analysis of proposed renewable energy projects, such as solar energy, is a crucial step that should not be ignored. In order to compare the economic feasibility of PV systems and conventional power plants, which are fossil fuel consumers, it is important to include the effect of oil prices on LCOE values.

Over the last decade, the fluctuation in oil prices – from $30 (£23)/ barrel in 2001 to $110 (£84.35)/ barrel in 2011 (see Figure 6.8) – has been significant, and must be taken into account. Although this change in oil prices occurred over a relatively small period, the percentage increase is considered high. It has more than doubled, for instance, from $40 (£30.67)/ barrel in 2000 to $80 (£61.34)/ barrel in 2007 (EIA, 2017). The opposite is also true, whereby the change in oil prices could go up or down, as can be clearly seen in the graph as well.

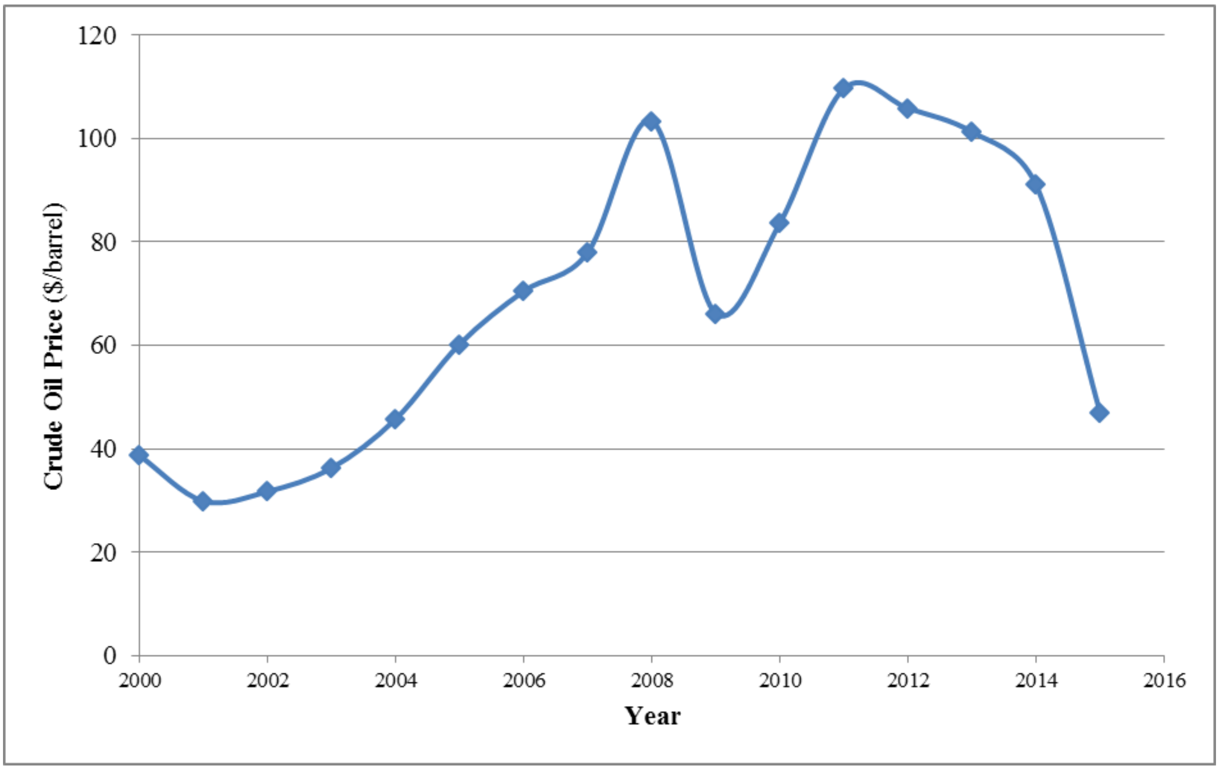


Figure 6.8 Oil prices from 2000 to 2016 (data taken from EIA, 2017)

In this study, the amount of money saved as a result of using PV systems at the selected sites instead of using conventional power plants was calculated based on the assumption that the cost of electricity generated in Kuwait by conventional power plants is \$0.12 (£0.092)/ kWh, based on an estimated cost of \$50 (£38.34) per barrel of oil (Ramadhan and Naseeb, 2011). Moreover, the effect of using single-axis and dual-axis tracking systems at the selected sites was also evaluated.

In this analysis, a wide range of oil prices, from \$20 (£15.34) to \$100 (£76.68) per barrel, were used to investigate the effects of using PV systems in Kuwait to generate electricity, in terms of the amount of money saved. The analysis was simplified by calculating the saved \$/kWh.

It can be observed from Table 6.10 that the oil price of \$30 (£23)/barrel is the critical parameter. In other words, when the oil price is higher than \$30/barrel, then it can be concluded, based on the analysis carried out in Section 6.2, that the proposed PV systems at all selected sites are economically feasible. Moreover, as the electricity generation from conventional power plants cost \$30/kWh, this means any less than this price (less than \$30/barrel) when selling a barrel of oil means PV systems is more expansive and any higher prices (more than \$30/barrel) means that the net will be a profit when using PV systems for energy. It can also be concluded that when oil prices are higher than \$30/barrel, the feasibility level increases dramatically.

On the other hand, when oil prices fall below 30 \$/barrel, negative savings values will be obtained (see Figure 6.9). From an economic perspective, this means that the proposed PV systems are not feasible, and therefore more serious procedures should be applied to resolve the problem, or the project should be stopped. The results obtained for the saved \$/kWh increased by 18.75% and 14.6% as a result of using single-axis and dual-axis tracking systems. It can also be deduced from the results that the single-axis tracking system is again the most appropriate choice for implementing PV systems in Kuwait.

Table 6.10 Savings ($/kWh) made with different oil prices

Oil price ($)	**Saving** ($/kWh)		
	Fixed tracking system	**Single-axis tracking system**	**Dual-axis tracking system**
100	0.168	0.177	0.175
90	0.144	0.153	0.151
80	0.120	0.129	0.127
70	0.096	0.105	0.103
60	0.072	0.081	0.079
50	0.048	0.057	0.055
40	0.024	0.033	0.031
30	0.000	0.009	0.007
20	-0.024	-0.015	-0.017

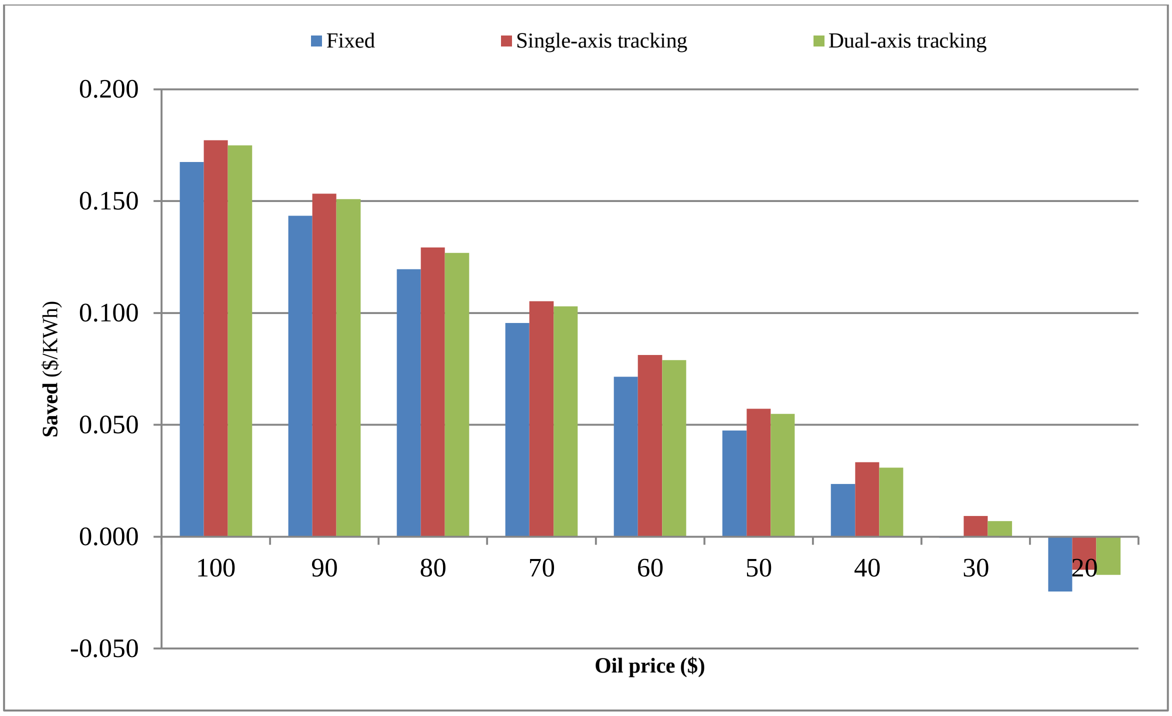


Figure 6.9 Total saved $/kWh for different oil prices

In this analysis, the amount of energy cost ($/kWh) saved correlates to the number of oil barrels saved in the generation of electricity by the proposed PV systems. It is generally accepted that the production of one kWh requires approximately 0.00061 of a barrel of oil. In other words each barrel of oil is equivalent to 1628 kWh (Al-rashed et al., 2016; Juggler, 2016). Table 6.11 shows the average number of oil barrels that would be saved by implementing PV systems at the selected sites. It can also be observed that the number of oil barrels saved would increase by 24% and 29% when utilising single-axis and dual-axis tracking systems, respectively. In order to determine the amount of money that would be saved as a result of implementing the proposed PV systems, oil price must be considered. Therefore, different oil prices were tested. Table 6.12 presents the amount of money saved in the case of several different oil prices for each individual site. A comparison between the selected sites based on the average amount of money saved is presented in Figure 6.10.

Table 6.11 Average number of oil barrels saved using different tracking systems

Type of tracking system	**Number of oil barrels saved**
Fixed tracking system	108251
Single-axis tracking system	134974
Dual-axis tracking system	139657

Table 6.12 Amount of money saved with different oil prices

	Number of oil barrels saved	**Oil price** (million $)								
Shagaya		**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Fixed	107540	2.15	3.23	4.30	5.38	6.45	7.53	8.60	9.68	10.75
Single-axis Tracking System	133805	2.68	4.01	5.35	6.69	8.03	9.37	10.70	12.04	13.38
Dual-axis Tracking System	138515	2.77	4.16	5.54	6.93	8.31	9.70	11.08	12.47	13.85
Kabd										
Fixed	109041	2.18	3.27	4.36	5.45	6.54	7.63	8.72	9.81	10.90
Single-axis Tracking System	134085	2.68	4.02	5.36	6.70	8.05	9.39	10.73	12.07	13.41
Dual-axis Tracking System	138502	2.77	4.16	5.54	6.93	8.31	9.70	11.08	12.47	13.85
Sabriya										
Fixed	107726	2.15	3.23	4.31	5.39	6.46	7.54	8.62	9.70	10.77
Single-axis Tracking System	134995	2.70	4.05	5.40	6.75	8.10	9.45	10.80	12.15	13.50
Dual-axis Tracking System	139776	2.80	4.19	5.59	6.99	8.39	9.78	11.18	12.58	13.98
Mutribah										
Fixed	107093	2.14	3.21	4.28	5.35	6.43	7.50	8.57	9.64	10.71
Single-axis Tracking System	134434	2.69	4.03	5.38	6.72	8.07	9.41	10.75	12.10	13.44
Dual-axis Tracking System	139254	2.79	4.18	5.57	6.96	8.36	9.75	11.14	12.53	13.93
Umm Gudair										
Fixed	109854	2.20	3.30	4.39	5.49	6.59	7.69	8.79	9.89	10.99
Single-axis Tracking System	137552	2.75	4.13	5.50	6.88	8.25	9.63	11.00	12.38	13.76
Dual-axis Tracking System	142238	2.84	4.27	5.69	7.11	8.53	9.96	11.38	12.80	14.22

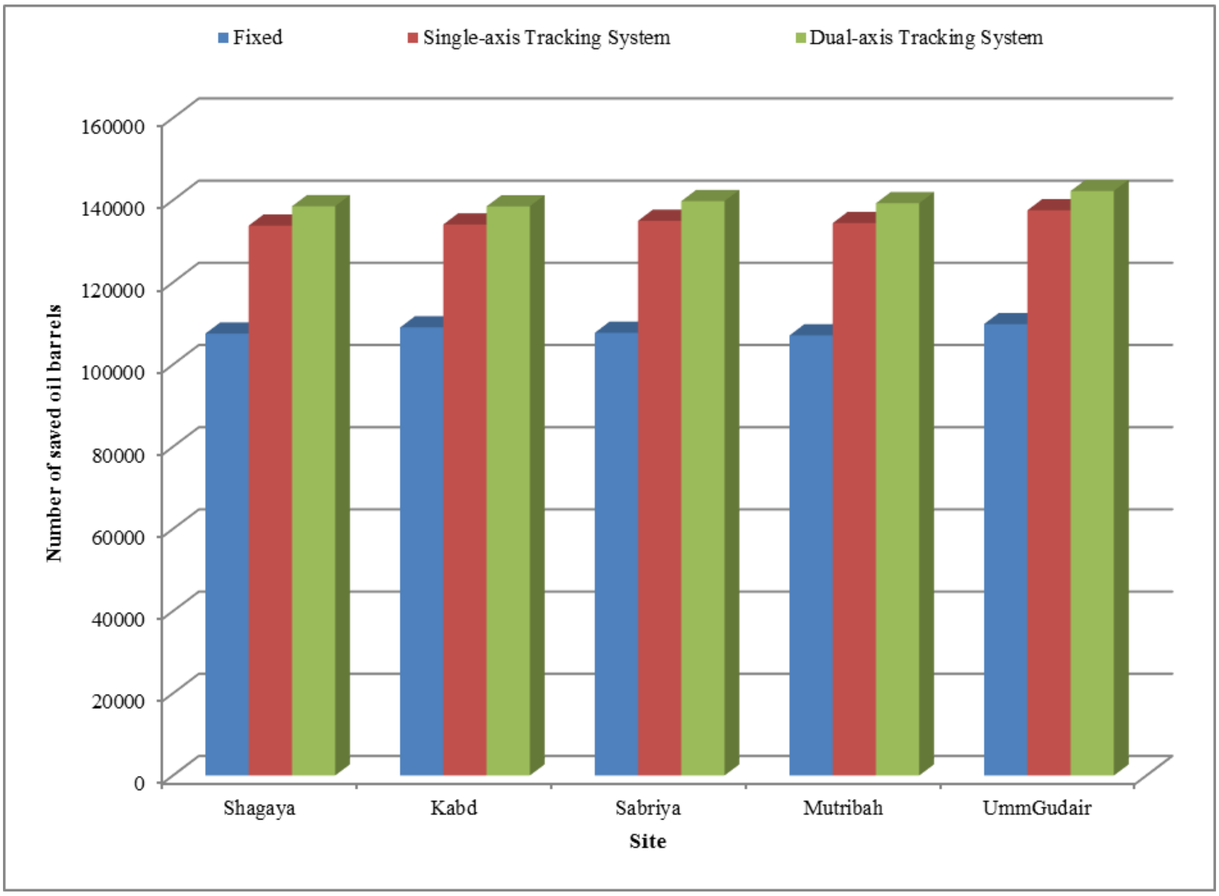


Figure 6.10 Number of oil barrels saved for the selected sites with different tracking systems

6.5 Cost of CO_2 Reduction by Implementing the Proposed PV Systems

In order to get more focus in this chapter on the economic part of this research, the amount of CO_2 saved will be represented in numeric language, in terms of money saved. CO_2 emissions have an associated cost, which ranges widely depending on several factors (Martín-Cejas, 2010).

In scientific economics, the related parameters are matched to values in order to carry out both basic and advanced analyses. In this chapter, the monetary value of the avoided CO_2 will be investigated. It is generally accepted that the CO_2 cost ranges between \$24 (£18.4)/ton and \$40 (£30.64)/ton; thus, in this study a value of \$30 (£23)/ton was used (Chel et al., 2009; Hadi et al., 2013; Johnson and Keith, 2004; Ramadhan and Naseeb, 2011). The cost of reduction in CO_2 emissions in monetary value is equal to approximately \$0.022/kWh (Hadi et al., 2013).

The amount of CO_2 emissions prevented through the use of solar energy can be calculated (EPA, 2016a) as follows:

$$\text{Annual amount saved of } CO_2 \text{ per kWh} = 7.18 \times 10^{-4} \text{ metric tons } CO_2/\text{kWh} \qquad (6.5)$$

$$\text{Cost of } CO_2 \text{ saved per kWh} = \text{Annual cost of } CO_2 \,/\, \text{PV system annual output power} \qquad (6.6)$$

The calculated costs of CO_2 for each site with different tracking systems are listed in Table 6.13. The average cost of CO_2 saved when using a fixed tracking system was \$3,796,046 (£2,910,808) at each site, and the average cost of CO_2 saved when using single-axis and dual-axis tracking systems was \$4,733,165.136 (£3,629,391) and \$4,897,368.864 (£3,755,302) for each site, respectively.

In terms of the amount of money saved by reducing CO_2 emissions as a result of utilising PV systems, the Umm Gudair site has the highest values for all of the proposed tracking systems. The Mutribah site showed the least amount of money saved (\$3,755,434.38) for the fixed tracking system, and the Shagaya site showed the least amount of money saved (\$4,692,165.9) for the single-axis tracking system. Figure 6.11 presents a comparison between the proposed sites, with different tracking systems, based on the cost of CO_2 saved by the PV system.

Table 6.13 The cost of reduction in CO_2 saved by the PV system

	Annual production (kWh/year)	**Annual amount of CO_2 reduction per kWh**	**Cost of CO_2 reduction by the PV system** ($)
Shagaya			
Fixed	175075000	125703.85	3771115.5
Single-axis Tracking System	217835000	156405.53	4692165.9
Dual-axis Tracking System	225503000	161911.154	4857334.62
Kabd			
Fixed	177519000	127458.642	3823759.26
Single-axis Tracking System	218291000	156732.938	4701988.14
Dual-axis Tracking System	225481000	161895.358	4856860.74
Sabriya			
Fixed	175378000	125921.404	3777642.12
Single-axis Tracking System	219772000	157796.296	4733888.88
Dual-axis Tracking System	227556000	163385.208	4901556.24
Mutribah			
Fixed	174347000	125181.146	3755434.38
Single-axis Tracking System	218859000	157140.762	4714222.86
Dual-axis Tracking System	226705000	162774.19	4883225.7
Umm Gudair			
Fixed	178843000	128409.274	3852278.22
Single-axis Tracking System	223935000	160785.33	4823559.9
Dual-axis Tracking System	231563000	166262.234	4987867.02

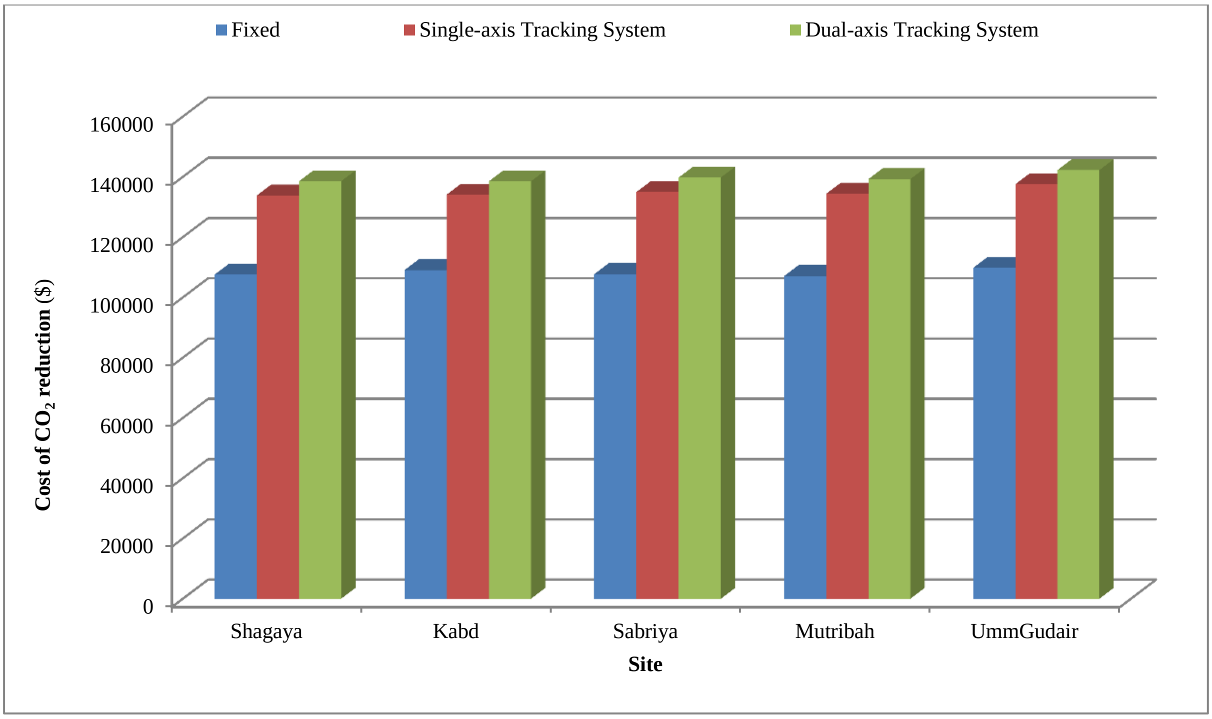


Figure 6.11 Cost of reduction in CO_2 by implementing PV systems at the selected sites

6.6 Conclusions

In this chapter, an economic evaluation of the proposed sites was conducted as a main step in this research investigating the feasibility of using solar PV systems in Kuwait. A holistic study was carried out, focusing on the following stages:

- An economic assessment of implementing PV systems
- Cost-benefit analysis
- Cost of CO_2 reduction

It was found that implementing PV systems in Kuwait is feasible, as the obtained LCOE value was less than the LCOE value for the conventional power plants in Kuwait. This was true for all types of tracking systems when the oil price was greater than $30 per barrel. It was also found that the single-axis tracking system is the best choice for all the selected sites in this study (which cover most of the country).

The average obtained LCOE value was $0.072 (£0.055) /kWh for the fixed solar tracking systems, and the average LCOE values for the single-axis and dual-axis tracking systems were $0.0625 (£0.0479) /kWh, and $0.065 (£0.050) /kWh, respectively.

The Umm Gudair site had the best values, with the lowest LCOE for all proposed tracking system types; this was expected, as the site had the highest amount of energy generated by the PV systems.

The implementation of single-axis and dual-axis tracking systems were significant. This can be clearly seen in the obtained LCOE values for the single-axis and dual-axis tracking systems, which decreased by 13.10% and 9.72%, respectively.

The single-axis tracking systems showed the best LCOE values. It should be noted that the dual-axis tracking systems increased the amount of energy produced by 28.8% and 4.8% over the fixed and single-axis tracking systems, respectively. However, the high initial costs of the dual-axis tracking systems increased the total cost, in terms of LCOE value in $/kWh.

The results of the sensitivity analysis were also encouraging, and suggest very optimistic expectations regarding the successful implementation of PV technology in Kuwait. In addition, based on the expected decrease in the cost of PV system components, and the significant development in photovoltaic technology itself, excellent results are expected.

The cost-benefit analysis found that the proposed PV systems at all selected sites are economically feasible when the oil prices are above $30 /barrel. In addition, money will be saved as a result of avoiding large amounts of CO_2 emissions. When represented in monetary values, the CO_2 savings were estimated to be $0.022 /kWh.

Overall, from an economic point view, the implementation of PV systems to generate electricity in Kuwait is feasible when oil prices are above $30 /barrel. In addition, the single-axis tracking system is the best choice for use in these systems.

Chapter 7 – Numerical Modelling

7.1 Introduction

As stated in the introduction to this thesis, the use of solar trackers in PV systems is very beneficial in terms of increasing the amount of solar irradiation that is received, by optimally following the movement of the sun. In order to determine the feasibility of using PV systems in Kuwait, which is the aim of this research, and in addition to performance parameters, environmental and economic evaluations, investigating the behaviour of the proposed solar tracker relative to varying external loads is crucial in order to obtain a holistic view of the possible implementation of such a technology for the first time in Kuwait, in which there is no previous experience or background in this field.

As identified in the literature review, although a lot of research has investigated the stability of solar trackers against wind loads, no study has yet investigated how solar trackers and ground interact with external loads. Thus, the present study will consider the ground (soil layers) in order to develop a better understanding of the behaviour of the whole proposed structure (solar tracker and foundation) in relation to external loadings. In this way, the present study will fill an identified knowledge gap, and will provide a solid base of information that can be drawn upon for future works in relevant fields. It is also important to emphasise here that the sites at which PV solar trackers are proposed to be utilised are located in free and desert areas, which typically experience frequent wind storms. Therefore, the effect of wind pressure must be taken into consideration. The wind load is a major external load that the solar tracker will be exposed to, in addition to the weight of the solar tracker structure. As stated in the introduction background, Kuwait is characterised by a desert climate which is very hot in summer and cold in winter. High temperature is an important parameter which should be considered when modelling solar trackers. The thermal loads resulting from high temperature were implicitly added in the proposed modelling as COMSOL Multiphysics software allows using multi features such as thermal stress.

In general, the purpose of design is to ensure that a proposed structure, under the worst loading conditions, will be safe. It is important to highlight here that this study will be the first study to investigate the potential use of solar trackers in Kuwait. In addition, it will be the first study in which the ground (soil layers) is included in an investigation of solar trackers.

Furthermore, this study will also investigate the problems associated with implementing PV solar trackers in Kuwait in reference to the structural and geotechnical design of both the whole structure (solar tracker and foundation), and the ground.

In order to investigate the behaviour of both the PV solar tracker and the soil in relation to the external loads, the following parameters will be considered:

- von Mises stress
- equivalent strain
- factor of safety (FOS)
- displacement

For this study, a model of dual-axis solar tracker was created to test the stability and reliability of PV solar trackers in Kuwait. The tracker was equipped with sixteen panels distributed in a 4 x 4 array (four rows and four columns). It was made by the Patriot Solar Group, and had an area of 27.4 m². A three-dimensional (3D) finite element model was created and simulated using the COMSOL Multiphysics 5.0 software.

As explained in the methodology chapter, the modelling study was carried out based on the finite elements method (FEM), using COMSOL Multiphysics software. The weight of the solar tracker itself and the design speed of the wind (40 m/s) were the main external loads examined in this study.

The effects of inclination angles of the tracker were investigated, as well as the effect of different wind directions. The elastic–perfectly plastic constitutive model (Mohr-Coulomb Model) was used to study the behaviour of the soil, where a linear elastic model has been applied for the solar structure. The validation of the FEM model will be presented in Section 7.2, and the validation of the numeric model will be presented in Section 7.3. The proposed model will be introduced in Section 7.4. The effect of wind speed on the solar tracker will be presented in Section 7.5 and finally the conclusions will be introduced in Section 7.6.

7.2 Numeric Model for Validation

7.2.1 Introduction

Validation of the proposed model is an important stage of the modelling process. In this stage, the proposed model structure is investigated and the model results, based on the given input data, are investigated to ascertain whether or not the model outputs are appropriate, and then the model results are validated using the same or similar models. In order to create an effective model in this study, the proposed model was validated using a study conducted by Lin et al. (2013).

7.2.2 Validation Case Study

Lin et al. (2013) studied the structural integrity and deformation-induced misalignment of solar radiation in a 2 kW tracking photovoltaic (PV) system using a commercial FEA code, ANSYS. The authors investigated the effects of self-weight and wind loads, using two different wind speed values (7 m/s and 12 m/s), on the structural deformation and misalignment of solar radiation. They found that the structure was stable under the applied loads, and no failure was recorded for any structural components, according to the von Mises failure criterion. The modelling simulation was carried out under a static mode.

7.2.3 Static Model

7.2.3.1 Geometry and Boundary Conditions

A 2 kW PV system was used in this study, which consisted of a 3X3 array (Figure 7.1). The PV system was 3 m in length, 2.2 m in height, and 5 m in width. Due to a lack of detail in the paper, the author of the paper was contacted, but declined to provide further details (Lin, 2016). A literature search was not able to identify the relevant details. As such, the post diameter was assumed to be 20 cm, and a square concrete foundation of 2 m in length and 1m in depth was also assumed. A fixed constraint at the bottom of the solar tracker was the main constraint of this study.

Figure 7.1 Geometry for the case study (Lin et al., 2013)

7.2.3.2 Materials

The material properties of the PV panels and mounting structure are given in Table 7.1.

Table 7.1 The material properties of the PV panels and mounting structure (Lin et al., 2013)

Material	**Young's modulus** (GPa)	**Poisson's ratio**	**Yield stress** (MPa)	**Density** (kg/m^3)
Solar glass	70	0.22	-	2500
A5052 aluminium	70.3	0.33	193	2680
A6063-T6 aluminium	68.9	0.33	214	2700
AISI 1053 steel	205	0.29	610	7850
AISI 4140 steel	205	0.29	415	7850
SUJ2 steel	205	0.29	2035	7850
SS400 steel	205	0.29	250	7750

7.2.3.3 Loading and Meshing

In the first case, only the effect of gravity was examined; in the other cases, the effects of both gravity and wind load were measured. Wind load was applied to PV modules at different inclination angles (0°, 15°, 30°, 45°, 60°, 75°); the wind direction varied from 0° to 180° with an interval of 30°, and was applied to each wind speed. The wind pressure was calculated using computational fluid dynamics (CFD) code. The wind load was based on two wind speeds, 7 m/s and 12 m/s. The mesh was created from an 8-node hexahedral and 4-node tetrahedral, with a total of 715,000 elements and 1,780,000 nodes.

7.3 Validation of the FEM Model

7.3.1 Static Model

The static model was applied in this study due to the very slow rotation of both azimuth and elevation axes. In order to validate the COMSOL Multiphysics 5.0 software, the static model created by Lin et al. (2013) was reconstructed and modelled using COMSOL Multiphysics 5.0. Due to the complexity of the geometry and the lack of certain details in the model, simplifications and assumptions were applied, taking into account that the results of the model used would not be affected.

7.3.1.1 Geometry and Boundary Conditions

A 3D model was constructed using COMSOL Multiphysics 5.0 (Figure 7.2); the solar tracker was 5 m in width, 3 m in length, and 2.2 m in height, at an elevation angle of 75°. The solar tracker consisted of nine PV panels with the following dimensions: 1668 mm x 1000 mm x 40 mm. The PV panels were supported by six aluminium beams, in turn supported by the main beam. The main beam was supported by a post. As stated above, some details were not available, such as the foundation details, and certain assumptions were made in order to conduct the study, such as the use of a square concrete foundation of 2 m in length and 1m in depth.

A fixed constraint (to prevent horizontal and vertical movement) was applied to the bottom of the foundation, while horizontal constraint roller constraints (to prevent horizontal movement) were applied to the rest of the foundation.

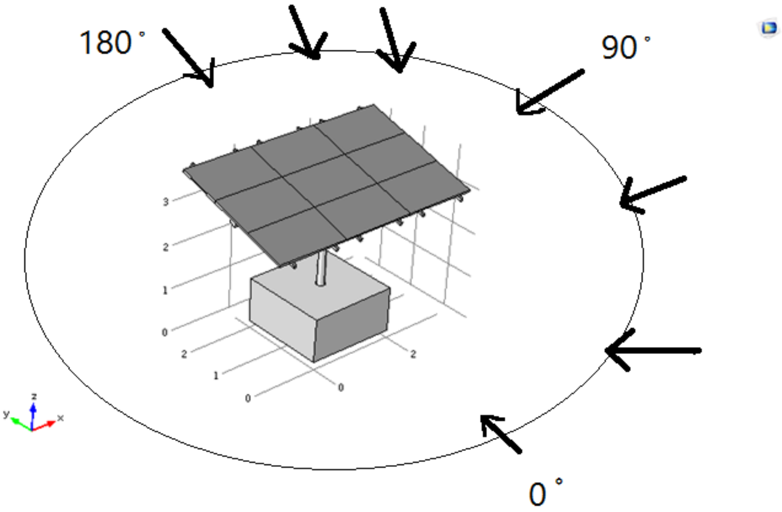


Figure 7.2 Geometric configuration created using COMSOL software

7.3.1.2 Materials

For simplicity, the material properties applied for the solar modules were assumed to be 3.5 GPa for the modulus of elasticity, and 0.33 for the Poisson’s ratio (COMSOL, 2013). Identical material properties were used for the remainder of the model components.

7.3.1.3 Loading and Meshing

Self-weight and wind load were the main loading components in this study. Two different wind loads using wind speeds of 7 m/s and 12 m/s were applied as a boundary load affecting the solar tracker on the Y-axis from a southern direction. The wind direction for each wind load, and the elevation angles of the PV modules, were applied in an identical fashion to the validation study. The self-weight of the whole structure was applied using the gravity feature of the COMSOL software. Wind loads were calculated based on the American Society of Civil Engineers (ASCE) 7-05, Minimum Design Loads for Buildings and other Structures. The wind load induced on the structure was calculated using the following equation (ASCE, 2013):

$$q_z = 0.613\ K_z\ K_{zt}\ K_d\ V^2\ I\ \ (\mathrm{N/m^2}) \qquad (7.1)$$

Where, q_z: velocity pressure

K_z = the velocity pressure exposure coefficient

K_{zt}= the topographic factor

K_d = the wind directionality factor

V = basic wind speed (m/s)

I = importance factor

Second order displacement tetrahedral elements were used for the proposed model, and the complete mesh consisted of 32,561 elements, especially with some of the assumptions has made on the properties used within the paper as the author (Lin, 2016) declined to provide any further information.

7.3.2 Results

After reconstructing the model using COMSOL Multiphysics software and setting up the complete modelling process, from defining the materials and the physics of the validating problem and ending with the run process, the obtained results were reported. It should be noted here that three different scenarios were created and tested, in order to compare the results based on the maximum von Mises stress criteria at different elevation angles (0°, 15°, 30°, 45°, 60°, 75°). In the first scenario, the effect of gravity only was tested, and in the second and third scenarios the effect of wind load, calculated based on 7 m/s and 12 m/s wind speeds, respectively, was tested. The obtained results are shown in Figures 7.3 and 7.4.

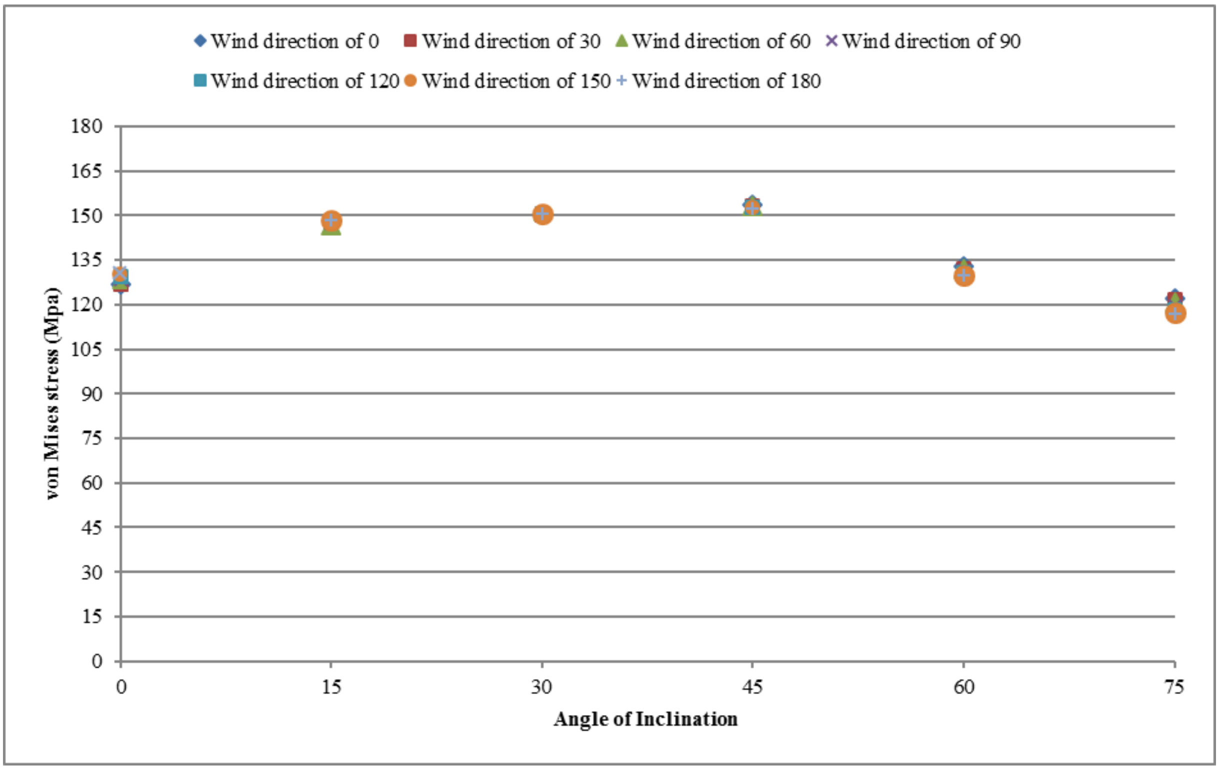


Figure 7.3 Maximum von Mises stresses for wind speed of 7 m/s

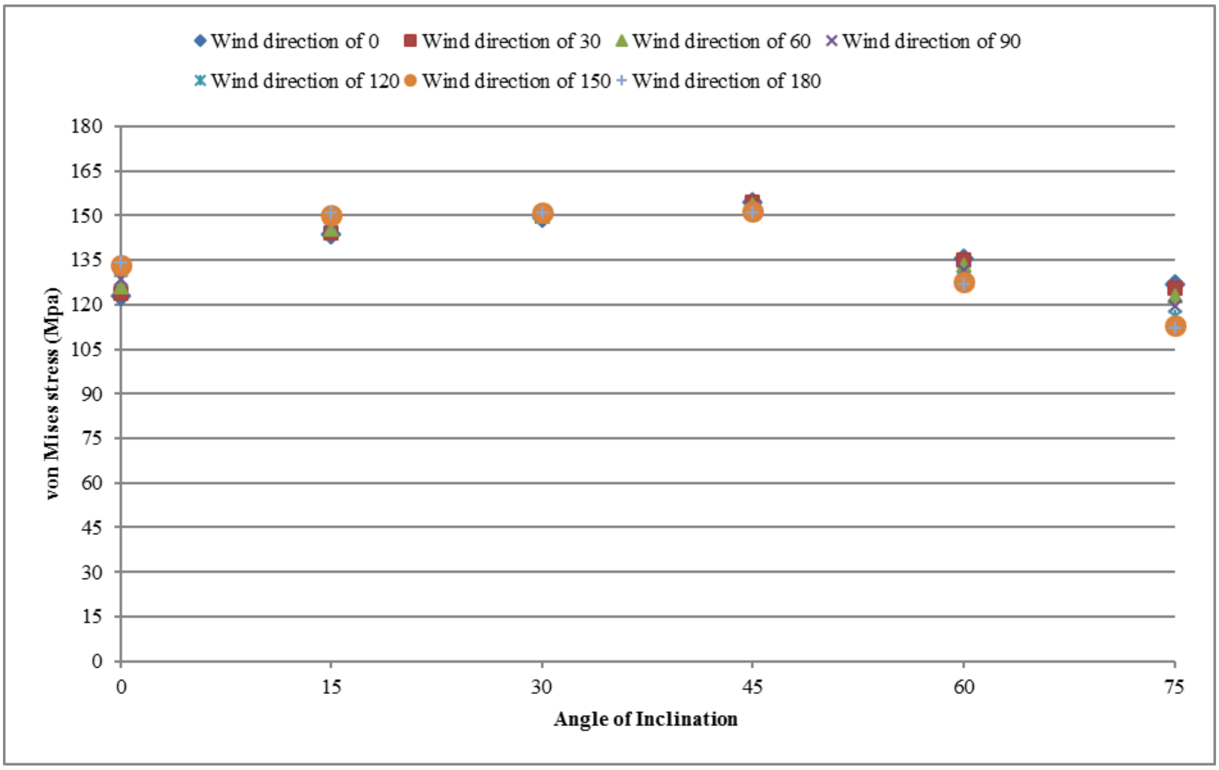


Figure 7.4 Maximum von Mises stresses for wind speed of 12 m/s

7.3.3 Validation

As stated earlier in this chapter, the validation of any proposed model or program is an important stage of the modelling process, as it provides an initial indication of the accuracy of the conducted works.

The results obtained from the validated model created using COMSOL software showed close results, in both the shape of the obtained graph and the obtained values. Three cases were then chosen for detailed comparison purposes. Tables 7.2-7.4 present a comparison of the validation study and the numerical model based on the maximum von Mises stress for the gravity only case, the 7 m/s wind speed case, and the 12 m/s wind speed case for a wind direction of 0°.

The results obtained in the present study were found to be in good agreement with the case study. In addition, the deviation of the results computed varied from between 2 and 14%, which is considered an acceptable range.

Table 7.2 Validation results for gravity load only

Angle	**Case study** **Maximum von Mises stresses** (Mpa)	**COMSOL** **Maximum von Mises stresses** **(**Mpa)	**Deviation %**
0	135	143	-5.93
15	155	147	5.16
30	145	150.3	-3.66
45	160	152.9	4.44
60	115	131	-13.91
75	135	119.53	11.46

Table 7.3 Validation results for wind speed of 7 m/s

Angle	**Case study**	**COMSOL**	**Deviation %**
0	135	126.72	6.13
15	150	146.1	2.6
30	140	150	-7.14
45	160	153.45	4.09
60	117.5	132.8	-13.02
75	125	121.2	3.04

Table 7.4 Validation results for wind speed of 12 m/s

Angle	**Case study**	**COMSOL**	**Deviation %**
0	135	123	8.89
15	155	143.7	7.29
30	140	149.4	-6.71
45	160	154.5	3.44
60	120	135.6	-13
75	130	126.67	2.56

7.4 Proposed Model for the PV Solar Tracker

7.4.1 Site Conditions

The proposed site for the numerical modelling study is Shagaya, which is located 60 km to the southwest of the city of Kuwait; Table 7.5 provides a site surface description of the Shagaya site location and topography. In general, the land of Kuwait is characterized by a flat, desert landscape, tilting towards the northeast from 270 m above sea level in Salmi, to a few metres Bubian Island (KISR, 2014). The site investigation and soil tests were performed by a private company (Gulf Inspection International Company), and the final work was submitted to KISR in the form of a report on ground investigation works for Shagaya Renewable Energy Power Plant Kuwait. Field and lab tests were performed in order to investigate the soil properties; the types and numbers of field and laboratory tests are shown in Table 7.6.

It can be noted from the results of the lab and field tests that the site is characterised by granular soil at the subsurface, and dense and very dense soil layers. The soil is mainly composed of fine sand, varying from 60 to 88%. It can be seen also that the coefficient of the permeability of the soil varied from between 5.33 x 10^{-8} and 22.0 x 10^{-8} cm/s, which indicates the low level of permeability of the soil layers, due to the high cementation bonding between the soil particles. The soil profile and the soil parameters are shown in Tables 7.7 and 7.8, respectively. It was found that the subsurface layer contains granular soil, which is classified as SP-SM/SP/SW-SM/SM/SC-SM/SC.

Table 7.5 Site surface description of the Shagaya site

Location	- Southwest of Kuwait. - The investigation site is located at approximately 60 km southwest of the city of Kuwait, and is accessible via Highway 70.
The topography	- The terrain is primarily sandy, gently undulating flat desert without any vegetation. - The area is not inhabited and has no industrial facilities.
Groundwater	- Not encountered in any of the boreholes during investigations up to a depth of 30 m.

Table 7.6 Types and number of field and laboratory tests (KISR, 2014b)

A. Field Tests		
Boreholes	50 BHs x 30.0 m	
Standard Penetration Tests		ASTM D-1586
Trial Pits	30	
Field Permeability Test	4	1377
Electrical Resistivity Test	6	ASTM G-57
Plate Load Test	20	ASTM D-1194
Cone Penetration Test	10	ASTM D-5778
B. Laboratory Tests		
Sieve Analysis	51	ASTM D-422
Moisture Content	51	ASTM D-2216
Atterberg Limits	30	ASTM D-4318
Direct Shear	11	ASTM D-3080
Bulk Density	11	
Chemical Tests	15	BS-1377 Part 3

Table 7.7 Soil profile (KISR, 2014b)

Layer No.	**Description**
Layer 1	Up to 0.3 m: top soil
Layer 2	0.3 to 2.0 m: medium dense, sand with silt
Layer 3	2.0 to 10.0 m: dense to very dense sand with silt
Layer 4	> 10.0 m: very dense sand with silt/clay

Table 7.8 Soil parameters (KISR, 2014b)

Layer No.	**Depth** (m)	**Unit Weight** (γ) (KN/m^3)	**Angle of Internal Friction** (Φ)	**Modulus of Elasticity** (E) (KN/m^2)
Layer 1	0.0 - 0.3	Top soil		
Layer 2	0.30 - 2.0	19	32	10000
Layer 3	2.0 - 10.0	20	36	40000
Layer 4	> 10.0	21	40	100000

7.4.2 Geometry

The model consisted of four parts: solar tracker, post, foundation, and the soil (which consisted of three layers, as shown in Figure 7.5). The solar tracker had an active area of 27.4 m^2. The tracker was supported by a post with a diameter of 30 cm and a length of 3 m. The post was supported by a square concrete foundation (2 m x 2 m) with a depth of 1 m.

In order to maintain the soil behaviour with proper boundary conditions and to minimise the effects of the boundries, the soil layers were modelled as 22 m x 22 m x 12 m cube, 22 m x 22 m x 8 m cube, and 22 m x 22 m x 2 m cube. In other words, a distance of five times the foundation length from all directions was applied, which is considered a minimum distance in the FEM (El-Hamalawi, 2002).

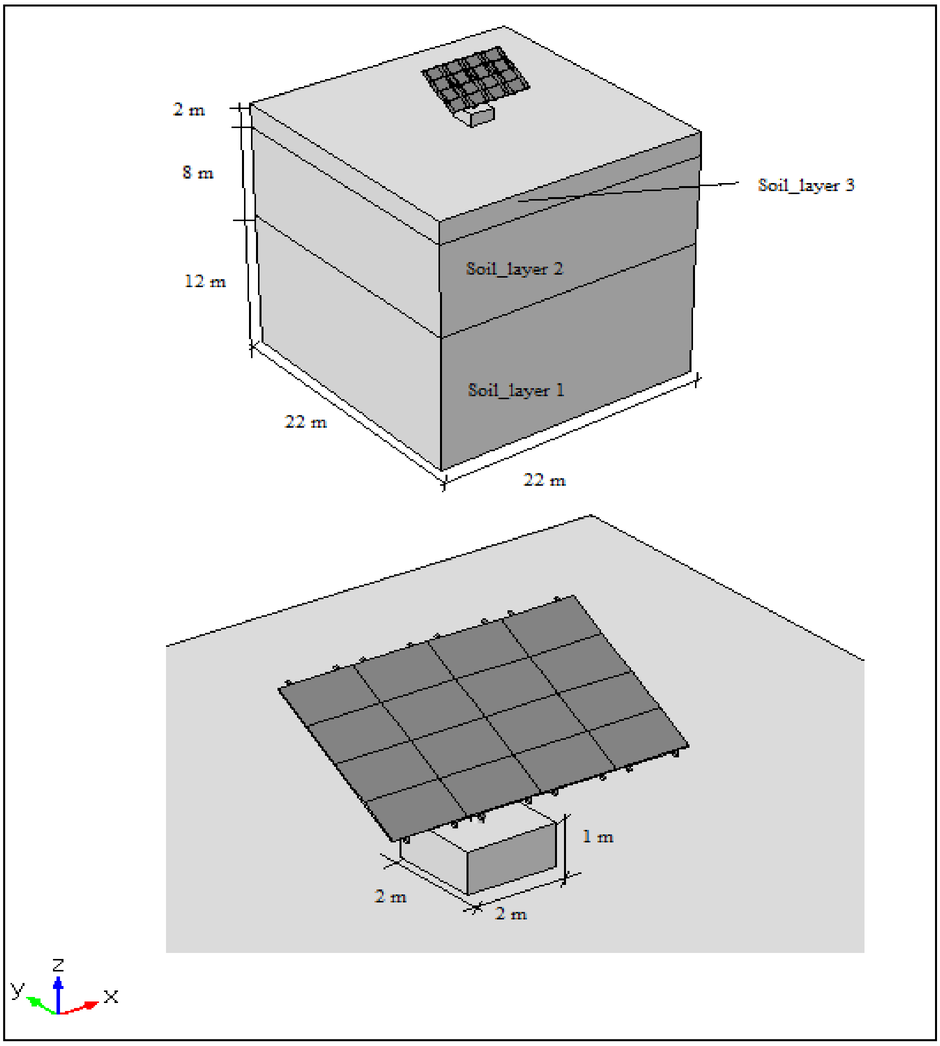


Figure 7.5 Geometric configuration

7.4.3 Material Properties

In order to conduct an efficient modelling study, the main elements of the proposed design, such as the soil layers, should be represented by the most appropriate constitutive model. As one aim of this study was to investigate the soil behaviour under the external loads, simulating the behaviour of the soils layers in this study was vital to the analysis.

As stated in the methodology chapter, the Mohr-Coulomb constitutive model, a widely used material model, was used to model the soil behaviour in this study. The required parameters when using the Mohr-Coulomb model are: Young's modulus, Poisson's ratio, angle of internal friction and cohesion. For the solar tracker structure and the foundation which have been modelled by linear elastic model, the density and the Young's modulus are the main inputs.

The material properties of the solar tracker, foundation, post and soil are shown in Table 7.9. It should be stated here that, due to the complexity of the solar module in terms of the constituted materials, and for the sake of simplicity, the material properties applied for the solar modules were assumed to be 3.5 GPa for modulus of the eleasticity and 0.33 for Poisson's ratio (COMSOL, 2013).

Table 7.9 Material properties

Material	**Density** (Kg/m^3)	**Young's modulus** (MPa)	**Poisson's Ratio** (ν)	**Cohesion** (C) (KPa)	**Angle of internal friction**(Φ)
Steel	7850	2.00E+05	0.33	-	-
Concrete	2300	2.50E+04	0.33	-	-
Soil_layer_1*	2140.7	100	0.3	19	39
Soil_layer_2**	2038.7	40	0.3	14.4	37
Soil_layer_3***	1963.8	10	0.3	5	32

* Layer_1 = medium dense, sand with silt.
** Layer_2 = dense to very dense, sand with silt.
*** Layer_3 = very dense sand with silt/clay.

7.4.4 Loading

Self-weight and wind load were the main loading elements in this study. The wind load was applied as a boundary load affecting the solar tracker. There was no code for designing wind speed available in a Kuwaiti context (Neelamani and Al-awadi, 2011).

A design wind speed is an important parameter that must be considered when evaluating solar tracker system stability. Based on the available data from KISR, and some literature specifically relating to Kuwait, this research used a design wind speed of 40 m/s (Awida, 2011; KISR, 2015; Neelamani and Al-awadi, 2011).

The wind load was applied to PV modules at different elevation angles (15°, 30°, 45°, 60°, 75°), and the wind direction varied from 0° to 180° with an interval of 30°. Wind loads were calculated based on the American Society of Civil Engineers (ASCE) 7-05. Table 7.10 shows the parameter values used in the wind load calculations.

7.4.5 Boundary Conditions

A key part of the modelling process is setting up the boundary conditions in order to ensure the proper simulation of the proposed problem. In this case, a fixed constraint (to prevent horizontal and vertical movement) was applied to the bottom of the soil layer, while a roller constraint (to prevent horizontal movement) was applied to the rest of the soil.

Table 7.10 Parameter values used in wind load calculation

Basic wind speed	V = 40 m/s	3 second gust wind speed for Kuwait
Velocity pressure exposure coefficient	Exposure D	Open area
Topographic factor	$K_{zt} = 1.0$	ASCE standard (Section 6.5.7.2)
Wind directionality	$K_d = 0.85$	ASCE standard (Section 6.5.4.4), Table 6.4
Velocity pressure exposure coefficient	$K_z = 0.85$	ASCE standard (Section 6.5.6.6), Table 6.3
Importance factor	I = 1.0	

7.4.6 Meshing

A second order displacement tetrahedral type mesh was used for the proposed model, and the complete mesh consisted of 32,561 elements; the finite element mesh is shown in Figure 7.6.

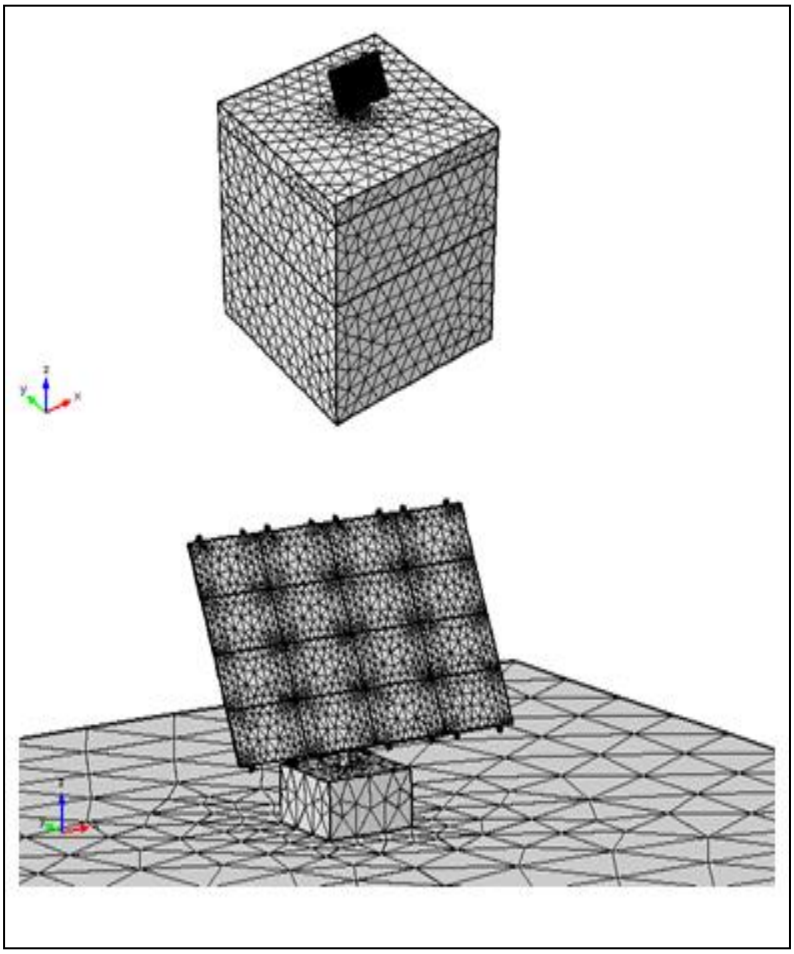


Figure 7.6 Finite elements mesh

7.4.7 Discussion and Results

As the main purpose of this study is to investigate the behaviour of the proposed solar tracker as well as the soil layers in response to external loads in the State of Kuwait, the wind load and the self-weight of the solar trackers were identified as the main parameters to be included in the analysis. In addition, the angle of inclination and the wind direction were also important parameters considered in this study. Thus, thirty-five different case scenarios were considered, and consequently thirty-five models were constructed using COMSOL Multiphysics software.

In this chapter, the behaviour of the proposed solar tracker and the soil layers were investigated in reference to the following criteria: von Mises stress, equivalent strain, displacement and the factor of safety (FOS).

The maximum von Mises stress and the maximum displacements are the most important criteria in this study, as the main purpose of conducting the numerical modelling of the solar tracker was to check its reliability and stability.

The maximum von Mises stress values varied between 57.68 and 105.74 MPa at inclination angles of 15° and 75°, respectively, with a wind direction of 0° (the south). The south direction (wind direction of 0°) was the critical case, in which the highest amount of stress was developed; this is logical, as the total wind load is assumed to affect the solar tracker from one direction, in other words, the total wind load was assumed to be a whole amount axial component.

Therefore, as the wind speed magnitude is the most important parameter in this study; in the following section (Section 7.5), further investigation will be carried out testing different wind speed magnitudes.

It can be also noted that the amount of stress increased with an increase in the inclination angles, due to the larger area exposed to wind loads. The opposite was true for the north direction (wind direction of 180°), and the east direction (wind direction of 90°) represented the lowest stresses, as a result of the relatively small areas of the solar tracker that were directly exposed to the wind load.

It can also be seen that the maximum displacement values ranged between 15.4 and 19.9 mm at inclination angles of 15° and 75°, respectively, for the wind direction of 0° (south). It can be clearly observed also that an increase in stress magnitude was represented (in the displacement criterion) as an increase in the displacement values. The variation in the displacement values can be attributed to the different stresses created as a result of assuming different inclination angles and wind directions. It can be noted that the von Mises stresses and displacements also increased with an increase in inclination angle.

Tables 7.11-7.14 present detailed results for all wind directions with five different inclination angles (15°, 30°, 45°, 60°, 75°) based on the von Mises stress, displacement, equivalent strain, and the factor of safety criteria, respectively.

Figures 7.7 and 7.8 show a comparison between the wind direction and the angle of inclination of the solar tracker, based on the maximum von Mises stress and the total displacements criteria.

In addition, the equivalent strain and the factor of safety (FOS) criteria were used in order to obtain a better understanding of the material behaviours. the factor of safety (FOS) which is an important measure of the stability of structures, was calculated using the following equation (Beer et al., 2005):

Factor of safety (FOS) = Ultimate load / Allowable load (7.2)

The maximum obtained values of the equivalent strain varied between 1.36×10^{-3} and 1.71×10^{3} for all different assumed angles of inclination and wind load directions. In terms of the factor of safety criterion, the solar tracker was stable for all of the assumed cases; the obtained factor of safety values ranged from 1.89 to 3.47. The lowest factor of safety value occurred at an angle of inclination of 75°, and the highest was at an angle of inclination of 15°. It can be observed that these obtained results are in complete agreement with the obtained results for the von Mises stress criterion; this was expected, as the FOS is a function of the applied stress and the maximum ultimate stress of the material. Figures 7.9 and 7.10 show a comparison between the wind direction and the angle of inclination of the solar tracker, based on the equivalent strain and the factor of safety (FOS) criteria.

It can be observed also that the behaviour of the solar tracker against the wind blowing from the south (at 0°) and north (at 180°) was similar, as both incur a high wind load. This was expected as a result of the highly exposed area of the solar trackers in these cases, whereas the opposite can been seen in the case of wind blowing from an easterly direction (at 90°); this was also expected, as only a small area is exposed in this case.

The critical direction of wind blowing against the solar tracker is from the south (at 0°), as indicated by the higher values of von Mises stresses and maximum displacements for this case. This is due to the large area that is exposed to the wind, which leads to large stresses in critical regions. In this study, the focus is on analysing the results of the cases where the wind is blowing from the south, based on the following criteria: von Mises stress displacement, equivalent strain, and factor of safety.

From a structural engineering perspective, it is commonly known that joints are the critical regions in which the maximum stress values occur. This fact can be observed in the results of this study, also; in the proposed model, with all different solar tracker inclination angles, the maximum von Mises stresses occurred at joints at the main connections and intersections between the post and the main beam. Figures 7.11-7.15 show the maximum von Mises stresses at different inclination angles where the wind is blowing from a southern direction (at 0°).

The maximum equivalent strain value was 1.71 $\times 10^{-3}$. This value is much less than 1.0, which refers to the elastic hypothesis (Ferroudji et al., 2014). The factor of safety of the solar trackers was calculated for different inclination angles. It is found that the factor of safety values were within a range of 1.9 to 3.5. These values indicate that the proposed structure is safe, and that the low FOS values are related to the high increase in stress induced as a result of a large area being exposed to the wind, such as where the inclination angle is equal to 75°.

On the other hand, the maximum obtained stresses and displacements in the soil layers were 39.85 kPa and 1.95 mm, respectively. These values were obtained at the south direction, with an inclination angle of 75°, which was identified above as the critical direction. These obtained results provide an important indication of the stability of the ground against the external loads induced by the self-weight of the structure and the wind loads.

It can be concluded that the effect of wind load should not be underestimated, especially when wind speed is high. Therefore, a strategy called a ‘defence position’ is generally applied in most solar trackers, in which the solar tracker is installed in a horizontal position in order to protect the structure from external forces induced by high wind speeds. This position is used to avoid very strong winds, defined by the Euro code standard as 140 km/h (Meca Solar, 2009).

Table 7.11 Maximum von Mises stress (MPa)

Wind direction	**Angle of inclination**	**Max. von Mises stress (MPa)**
Wind direction: (0°)	15	57.68
	30	76.5
	45	90.89
	60	101.34
	75	105.74
Wind direction: (30°)	15	50.11
	30	68.84
	45	78.71
	60	87.77
	75	91.57
Wind direction: (60°)	15	28.93
	30	39.74
	45	45.44
	60	50.67
	75	52.87
Wind direction: (90°)	15	28.025
	30	38.77
	45	44.42
	60	49.615
	75	51.835
Wind direction: (120°)	15	27.12
	30	37.8
	45	43.4
	60	48.56
	75	50.8
Wind direction: (150°)	15	46.96
	30	65.47
	45	75.16
	60	84.1
	75	88
Wind direction: (180°)	15	54.24
	30	75.61
	45	86.79
	60	97.11
	75	101.61

Table 7.12 Maximum displacements (mm)

Wind direction	Angle of inclination	Maximum displacements (mm)
Wind direction: (0°)	15	15.4
	30	16.6
	45	18.4
	60	18.9
	75	19.9
Wind direction: (30°)	15	13.3
	30	14.4
	45	16
	60	16.4
	75	17.2
Wind direction: (60°)	15	7.69
	30	8.3
	45	9.21
	60	9.46
	75	9.94
Wind direction: (90°)	15	7.425
	30	8.025
	45	8.925
	60	9.195
	75	9.695
Wind direction: (120°)	15	7.16
	30	7.75
	45	8.64
	60	8.93
	75	9.45
Wind direction: (150°)	15	12.4
	30	13.4
	45	15
	60	15.5
	75	16.4
Wind direction: (180°)	15	14.3
	30	15.5
	45	17.3
	60	17.9
	75	18.9

Table 7.13 Equivalent strains

Wind direction	**Angle of inclination**	**Equivalent strain**
Wind direction: (0°)	15	1.36E-03
	30	1.41E-03
	45	1.71E-03
	60	1.64E-03
	75	1.36E-03
Wind direction: (30°)	15	1.17E-03
	30	1.22E-03
	45	1.48E-03
	60	1.42E-03
	75	1.18E-03
Wind direction: (60°)	15	6.78E-04
	30	7.04E-04
	45	8.56E-04
	60	8.19E-04
	75	6.79E-04
Wind direction: (90°)	15	7.23E-04
	30	7.07E-04
	45	7.89E-04
	60	7.37E-04
	75	6.78E-04
Wind direction: (120°)	15	7.68E-04
	30	7.09E-04
	45	7.22E-04
	60	6.54E-04
	75	6.76E-04
Wind direction: (150°)	15	1.33E-03
	30	1.23E-03
	45	1.25E-03
	60	1.13E-03
	75	1.17E-03
Wind direction: (180°)	15	1.54E-03
	30	1.42E-03
	45	1.44E-03
	60	1.31E-03
	75	1.35E-03

Table 7.14 Factor of safety (FOS)

Wind direction	**Angle of inclination**	**Factor of safety (FOS)**
Wind direction: (0°)	15	3.47
	30	2.61
	45	2.20
	60	1.97
	75	1.89
Wind direction: (30°)	15	3.99
	30	2.91
	45	2.54
	60	2.28
	75	2.18
Wind direction: (60°)	15	6.91
	30	5.03
	45	4.40
	60	3.95
	75	3.78
Wind direction: (90°)	15	7.14
	30	5.16
	45	4.50
	60	4.03
	75	3.86
Wind direction: (120°)	15	7.37
	30	5.29
	45	4.61
	60	4.12
	75	3.94
Wind direction: (150°)	15	4.26
	30	3.05
	45	2.66
	60	2.38
	75	2.27
Wind direction: (180°)	15	3.69
	30	2.65
	45	2.30
	60	2.06
	75	1.97

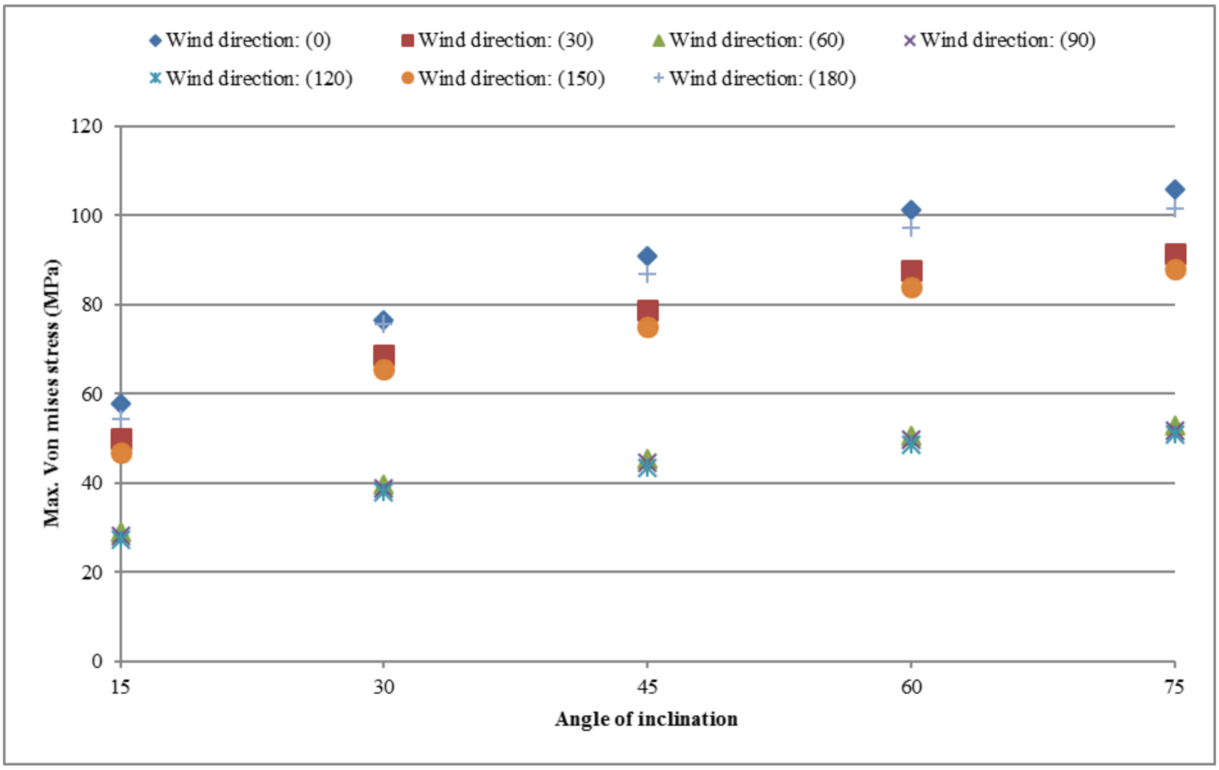


Figure 7.7 Maximum von Mises stress with different inclination angles for different wind speed magnitudes

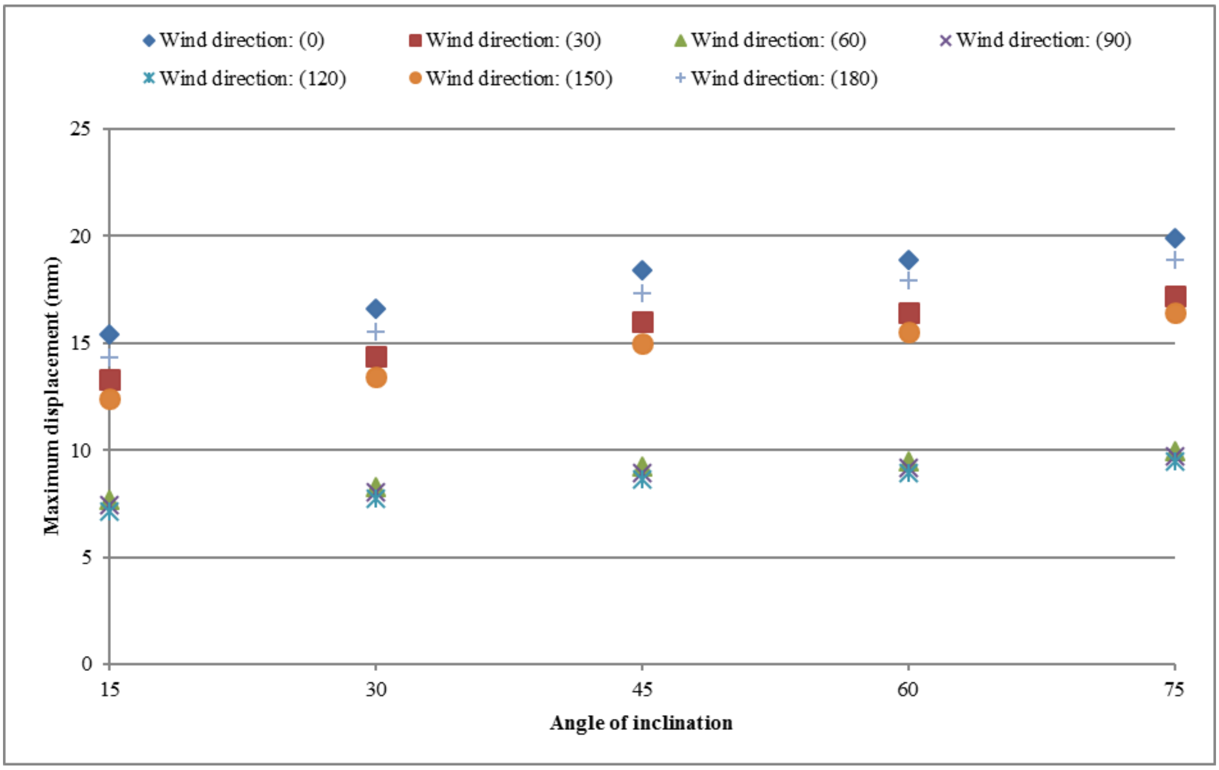


Figure 7.8 Maximum displacements with different inclination angles for different wind speed magnitudes

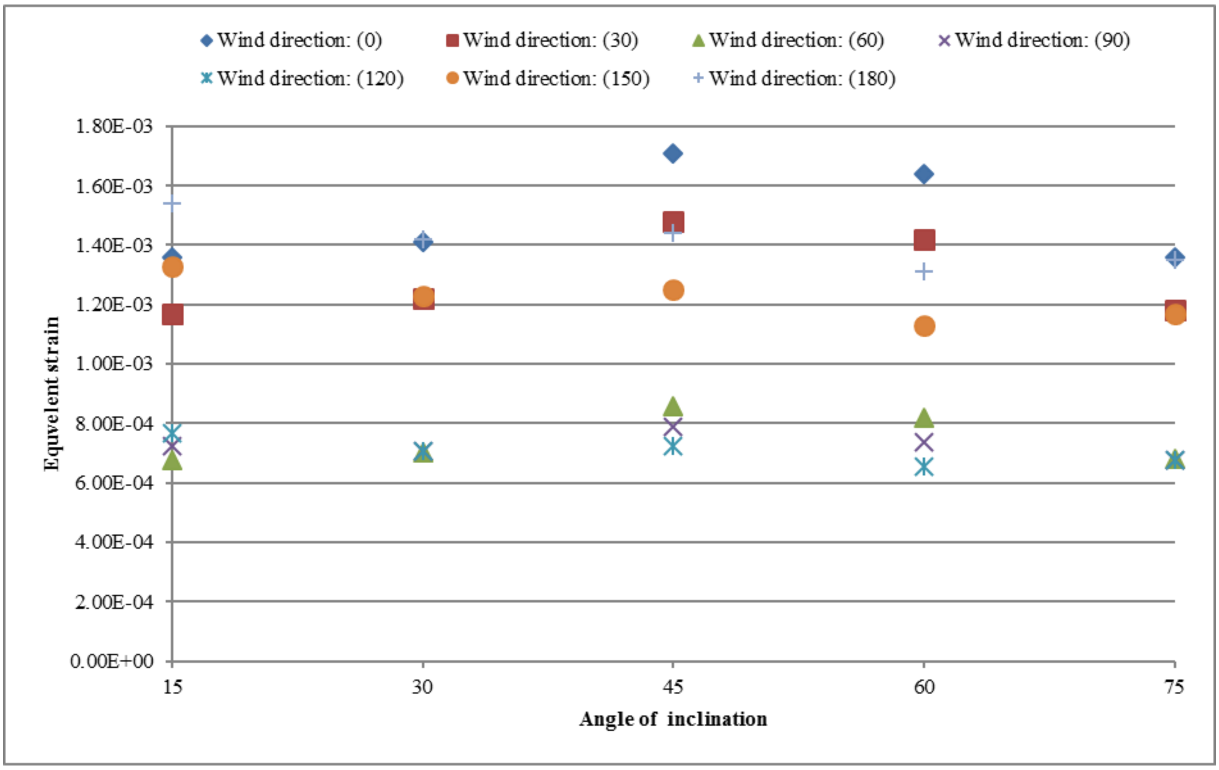


Figure 7.9 Equivalent strains with different inclination angles for different wind speed magnitudes

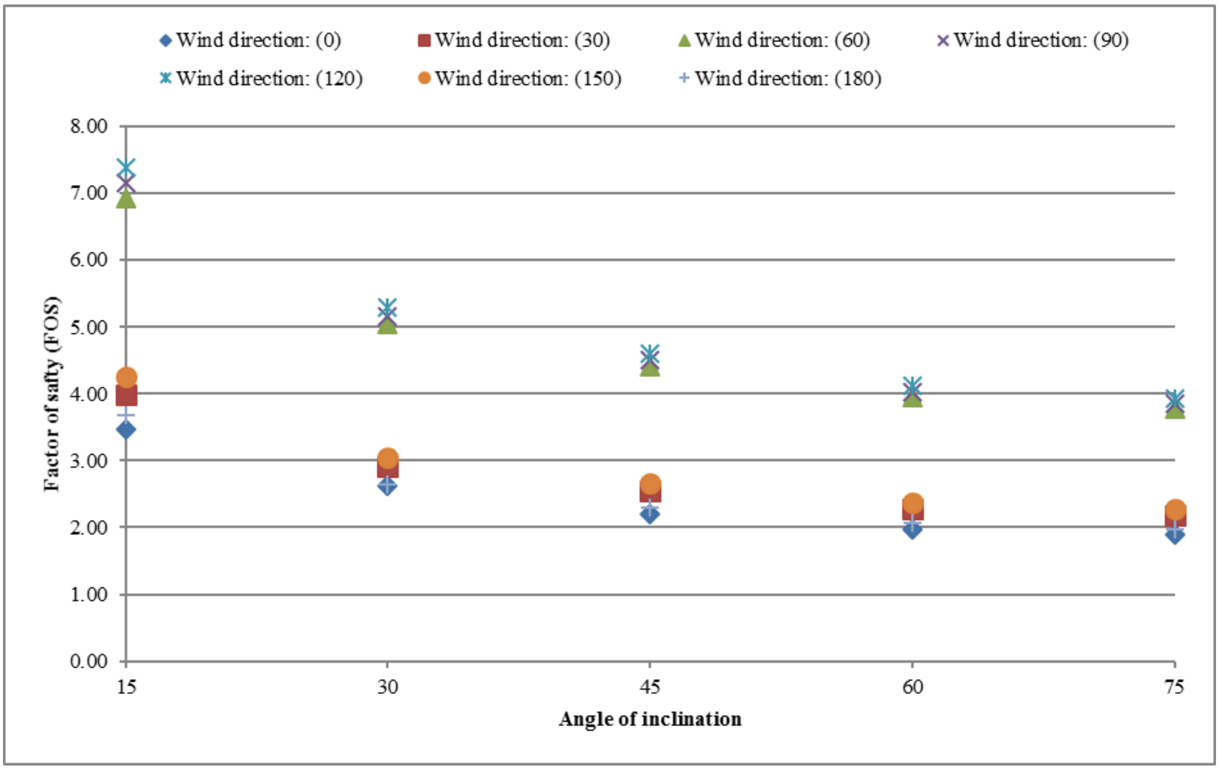


Figure 7.10 Factor of safety with different inclination angles for different wind speed magnitudes

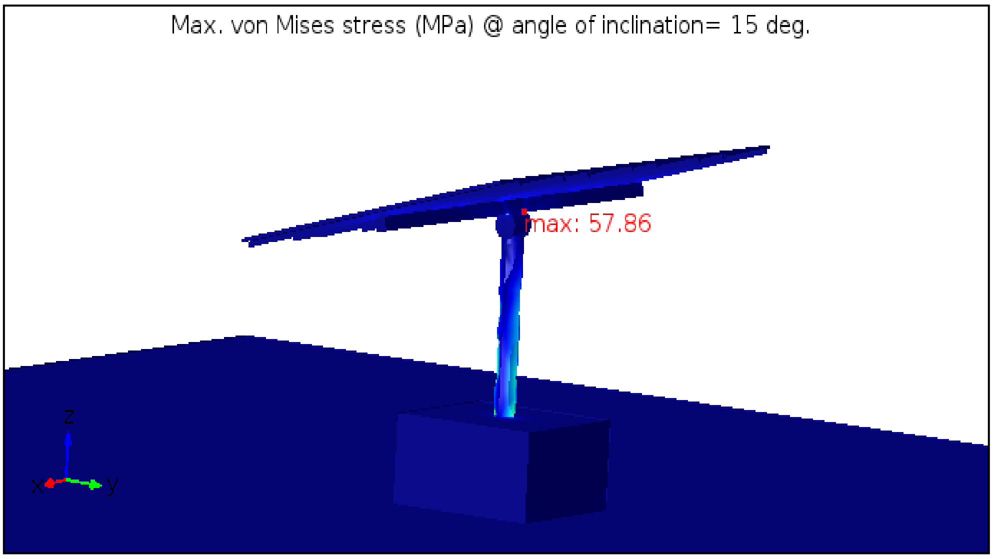


Figure 7.11 Maximum von Mises stress in MPa at inclination angle of 15°

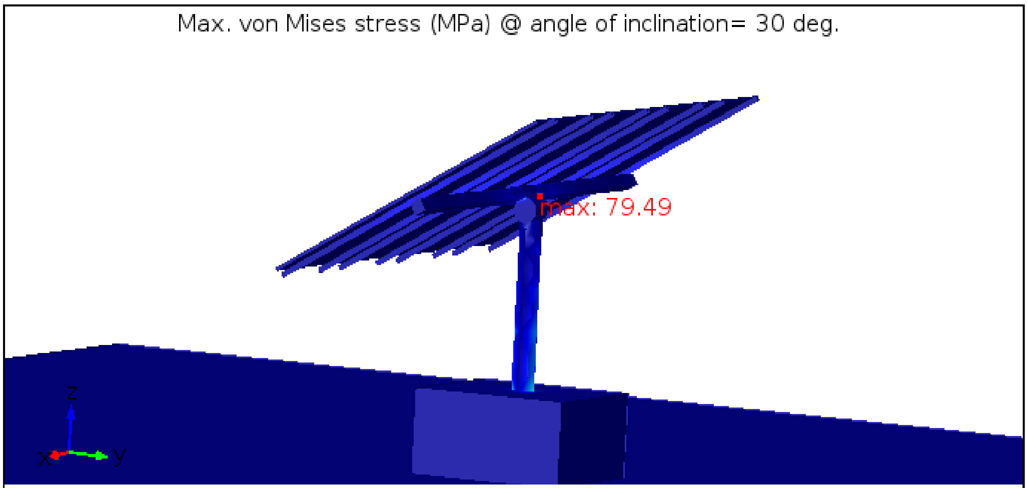


Figure 7.12 Maximum von Mises stress in MPa at inclination angle of 30°

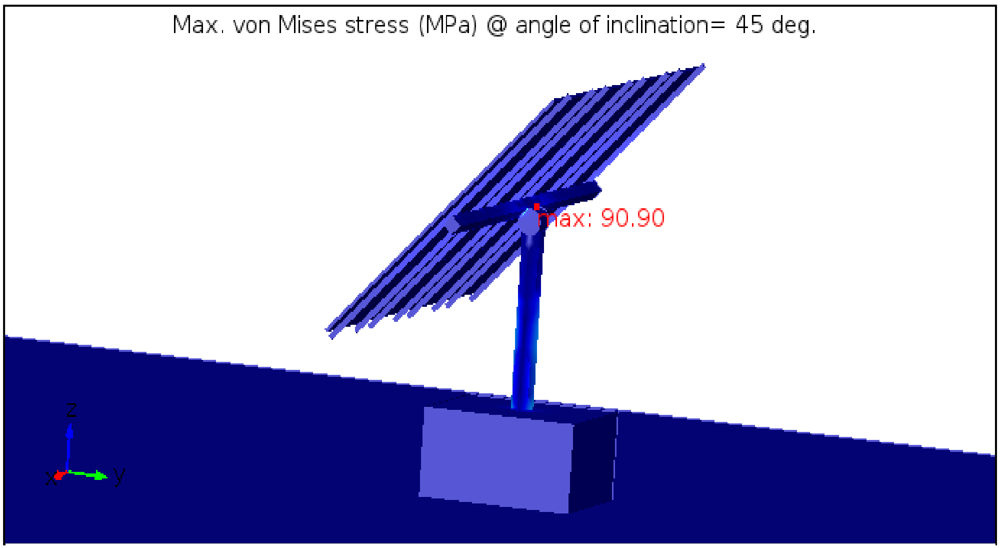


Figure 7.13 Maximum von Mises stress in MPa at inclination angle of 45°

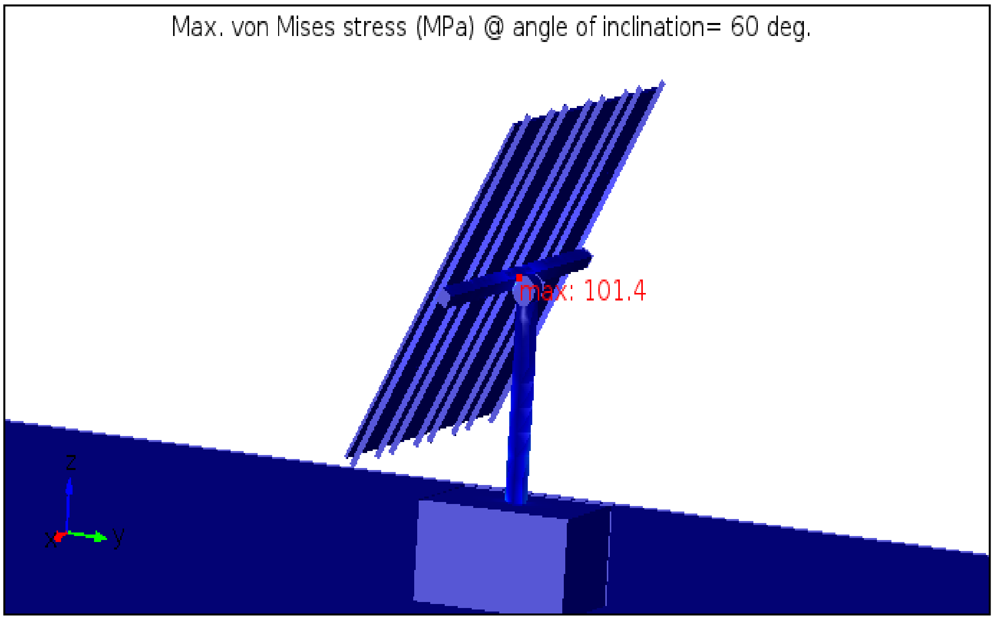


Figure 7. 14 Maximum von Mises stress in MPa at inclination angle of 60˚

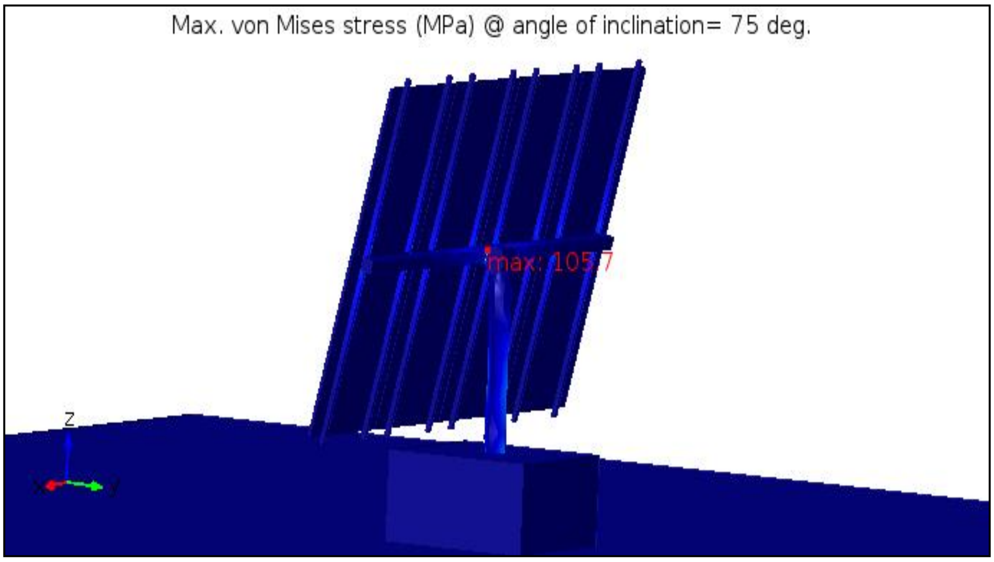


Figure 7.15 Maximum von Mises stress in MPa at inclination angle of 75˚

7.5 Effect of Wind Speed on the Proposed Solar Tracker

As mentioned in the previous section, the wind speed magnitude is the most important parameter in this study and, therefore, further analysis based on different wind speed magnitudes was undertaken in order to produce a complete picture of the effects of this parameter on the solar tracker structure.

Four different wind speed magnitudes of (30-40-50-60 m/s) were considered in the analysis. The investigation was based on the same criteria used in the main proposed solar tracker (von Mises stress, displacement, equivalent strain, and factor of safety (FOS)). The results obtained for total displacements, von Mises stress, equivalent strain, and the FOS for different wind speed magnitudes are shown in Table 7.15.

Figures 7.16 and 7.17 present a comparison between different wind speed magnitudes with different inclination angles, based on the von Mises stresses and displacements criteria. It can clearly be seen that an increase of wind speed increased the von Mises stress and displacement values for all the inclination angles. The effect of high wind speed magnitudes was significant, and can be observed in the increase in induced stresses and displacements.

It is important to recall here that the base case for this study was designed based on 40 m/s, and the results of the analysis conducted in Section 7.4 showed that the proposed solar trackers are stable and safe. In addition, it is extremely important to recall here that all solar trackers must be set up in a stationary position (safe mode) in case of high wind speed, which is estimated to be approximately 140 km/h (Meca Solar, 2009). In the safe mode, the solar tracker is applied to stow position (parallel to the ground) in order to avoid the effects of high wind speeds (Rohr et al., 2015).

The purpose of this analysis was to provide a detailed explanation of the situation in which solar trackers are exposed to high wind speed magnitudes. Failure or damage of the solar tracker is the normal expected result for this situation. From a structural point view, when the loads applied on the solar trackers exceed certain limits (the ultimate loads) the structure will be unsafe and unstable. This can be clearly observed from certain terms such as the factor of safety (FOS). From Table 7.15, it can be seen that the FOS of the solar trackers decreased to 1.2 for the case where the wind speed was 50 m/s (180 km/s), and decreased to 0.84 for a wind speed of 60 m/s and an angle of inclination of 75° and this case the solar tracker will fail.

The obtained results suggest that the use of the solar tracker becomes dangerous when the wind speed exceeds 50 m/s (215 km/s), and therefore using the safe mode is crucial in order to conserve the solar tracker and protect all of the installed PV system components, such as solar modules, from damage.

Table 7.15 Total displacement, von Mises stress, equivalent strain, and FOS for different wind speed magnitudes

Wind speed	**Angle of inclination**	**Total displacement (mm)**	**von Mises stress (MPa)**	**Equivalent strain**	**FOS**
30 m/s	15	8.6504	32.562	9.94E-04	6.1
	30	9.3405	44.733	0.001042	4.5
	45	10.366	51.149	0.0012262	3.9
	60	10.652	57.034	0.0011326	3.5
	75	11.188	59.507	9.61E-04	3.4
40 m/s	15	15.4	57.68	1.36E-03	3.5
	30	16.6	76.5	1.41E-03	2.6
	45	18.4	90.89	1.71E-03	2.2
	60	18.9	101.34	1.64E-03	2.0
	75	19.9	105.74	1.36E-03	1.9
50 m/s	15	24.029	90.451	0.0027613	2.2
	30	25.946	124.26	0.0028945	1.6
	45	28.796	142.08	0.003406	1.4
	60	29.589	158.43	0.0031462	1.3
	75	31.078	165.3	0.0026689	1.2
60 m/s	15	34.602	130.25	0.0039763	1.54
	30	37.362	178.93	0.004168	1.12
	45	41.466	204.60	0.0049047	0.98
	60	42.609	228.14	0.0045306	0.88
	75	44.752	238.03	0.0038432	0.84

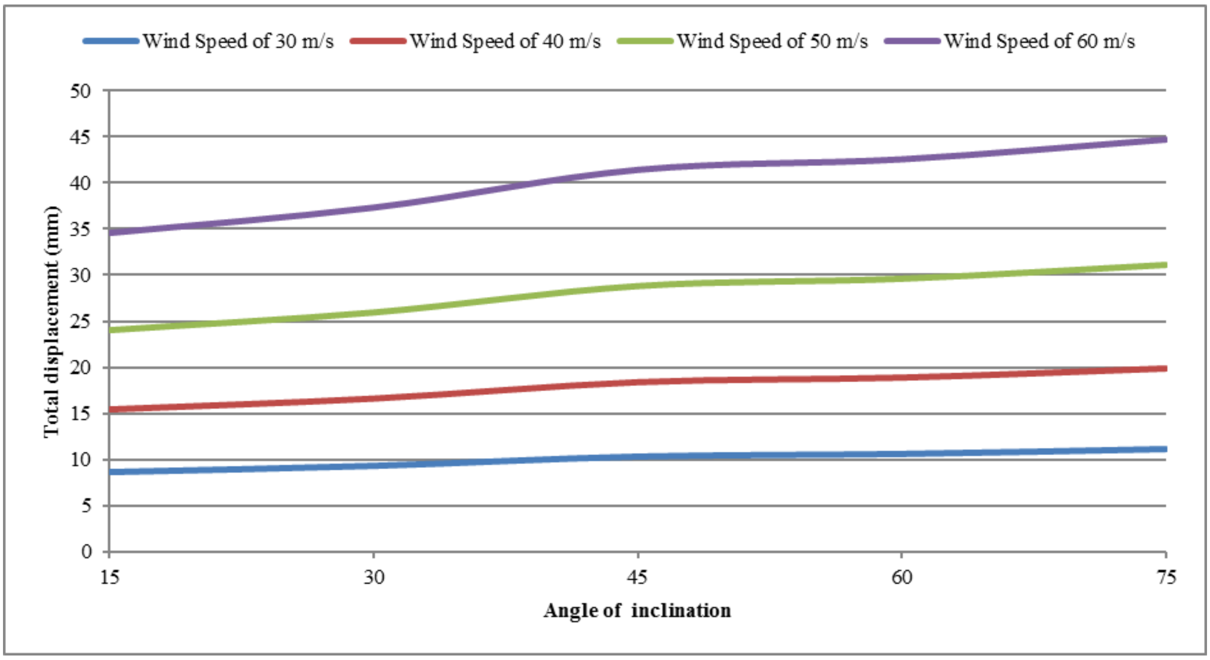


Figure 7.16 A comparison between different wind speed magnitudes with different inclination angles, based on displacement

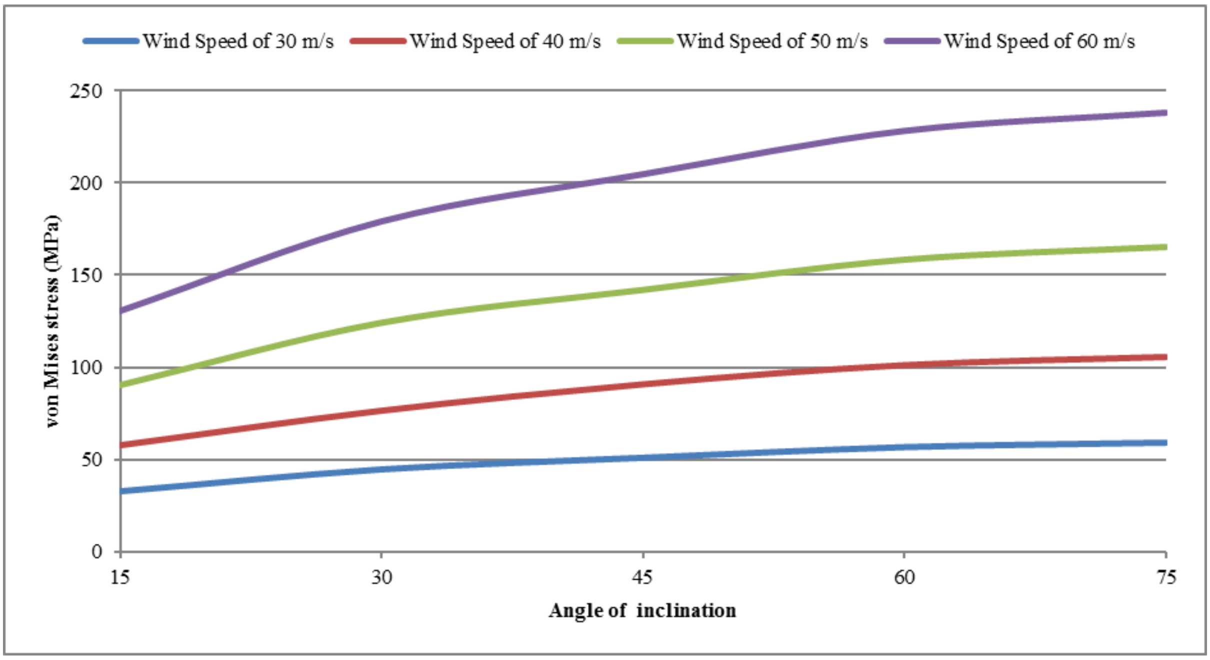


Figure 7.17 A comparison between different wind speed magnitudes with different inclination angles, based on von Mises stress

7.6 Conclusions

The location and the orientation of the solar tracker are important parameters in implementing PV systems. Kuwait is located in the northern hemisphere, and the PV solar trackers will need to face south in order to receive solar radiation. However, in this study, the effect of wind direction was investigated for five different inclination angles, and 35 scenarios were analysed.

In order to increase the amount of electricity produced by the proposed PV systems at the selected sites in Kuwait, single-axis and dual-axis PV solar trackers were investigated in this study. This study modelled a two-axis solar tracker in order to test the stability and the reliability of PV solar trackers in Kuwait. The proposed solar tracker was equipped with sixteen panels distributed in a 4 x 4 array (four rows and four columns).

The effect of wind direction was investigated for five different inclination angles, and thirty five scenarios were analysed.

The average von Mises stress was 86.43 MPa, which was less than the yield stress (200 MPa) noticed by the FOS values, which were between 1.89 (for an inclination angle of 75°) and 3.47 (for inclination angle of 15°). The average displacement was 17.84 mm, where the minimum and maximum displacement values were 15.4 mm and 19.9 mm, respectively.

From a geotechnical engineering perspective, the maximum stresses and displacements obtained revealed that the ground is safe and stable in response to external loads (self-weight of the solar tracker and wind load) except for the 60 m/s wind speed. This can be seen in the results of conducted studies in this regard that focused their analysis on the stability of solar trackers. In addition, it can be observed that solar trackers structures are more likely to suffer damage caused by high wind pressure than by other issues, such as ground failure. However, in order to determine the provisional performance of solar trackers in terms of efficiency, the movement of the solar trackers in order to follow the sun to harvest the maximum available solar irradiation will definitely be affected by the ground settlement.

The lack of past studies of solar trackers in which the ground is included as a variable may be attributed to the relatively small amounts of stresses induced in the soil layers, as these types of structures are considered relatively small in area.

It can be concluded that the effect of wind speed should not be underestimated, especially when wind speed is high. Therefore, the defence position strategy is generally applied in most solar trackers, in which the solar tracker is installed at a horizontal position in order to protect the structure from external forces induced by high wind speeds. This position is used to avoid very strong winds, defined by the Euro code standard as 140 km/h (Meca Solar, 2009).

Chapter 8 - Conclusions and Recommendations

8.1 Introduction

This chapter will present the findings and results of this research, and recommendations for future related work will also be given.

The aim of this study was to investigate the feasibility of using solar PV systems to generate electricity in Kuwait. The overall approach is shown in Figure 8.1. In order to achieve the aim of this study, the following tasks were set:

- To investigate the performance feasibility of proposed PV systems, by determining the following performance parameters for each site when using different tracking systems (fixed, single-axis and dual-axis):
  - Total energy generated
  - Final yield
  - Reference yield
  - Performance ratio
  - Capacity factor
  - System efficiency
- To conduct an environmental evaluation study including:
  - Life Cycle Assessment
  - Environmental benefits
- To conduct an economic evaluation of the proposed PV systems using LCOE to compare the proposed systems with conventional power plants in terms of electricity generation.
- To investigate the behaviour of the proposed solar tracker against the external loads using finite element software (COMSOL Multiphysics).
- To make recommendations based on the findings.

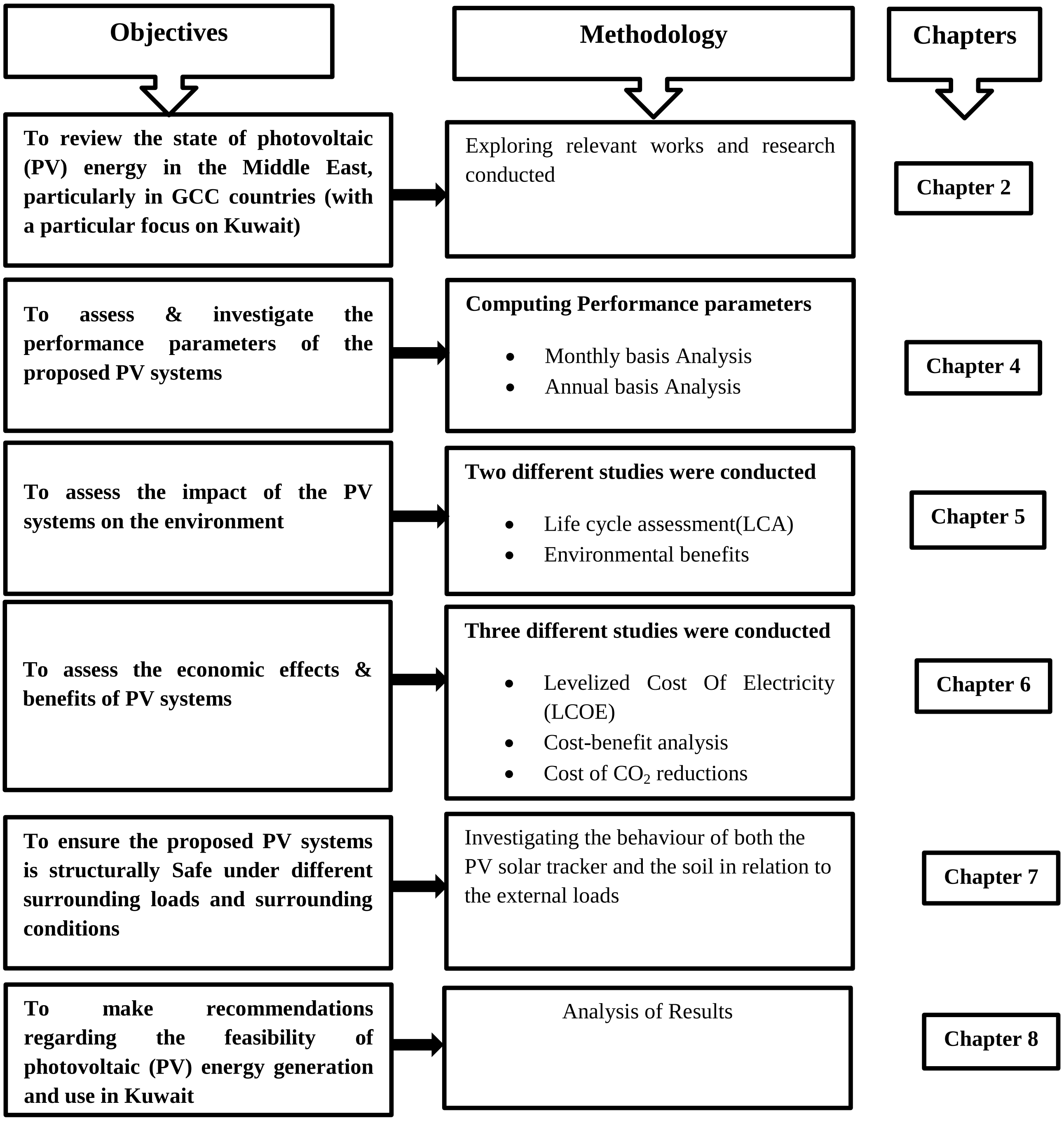


Figure 8.1 The overall approach

8.2 Summary

8.2.1 Data Collection

In order to investigate the feasibility of using solar PV systems in Kuwait, establishing the availability of data was an extremely important step. Data is a crucial part of any proposed study, as the analysis and design stages will be discussed based on the obtained results. In this thesis, four main specific tasks were set. These tasks (as stated in chapter 3) can be summarised as follows:

- Performance parameters evaluation
- Environmental evaluation
- Economic evaluation
- Numerical modelling study

In order to carry out the aforementioned tasks, metrological, structural, and geotechnical data was required. Two types of metrological data, satellite and ground station data, were collected from KISR. This was done in order to validate the data used, and also to ensure a greater range of referenced data sources for Kuwaiti sites. Detailed geotechnical data was also collected from KISR. The data for the proposed PV system components and the proposed solar trackers was collected from the relevant companies via their official websites.

8.2.2 Selected Sites

In order to investigate the feasibility of using solar PV systems in Kuwait, it was extremely important to select not only the most appropriate locations, but also to study a minimum number of sites that would be most representative of the whole country. In addition to recommending the best locations for implementing the PV systems in Kuwait, this study aimed to build up a solid base of information, whereby the whole country was included in the scope of the research. Based on the site selection process, which consisted of three stages (see Chapter 3), the following sites were selected:

- Shagaya
- Kabd
- Sabria
- Mutribah
- Umm Gudair

The selected sites are located in different areas of the country; the Mutribah site in northern Kuwait; Umm Gudair in the southern region, Shagaya in the west, and Kabd in the east. The Sabria site is the nearest to the largest islands in Kuwait, and was considered to be the best representative site for the islands. As mentioned in the discussion of the site selection process (see Section 3.2), the availability of data was an important parameter in the site selection. The selected sites consequently represent the whole country, and the Shagaya site was used for the numerical modelling study, due to site investigation data availability.

8.2.3 Results

At the end of each chapter, detailed results and discussions of the main findings of each task have been presented.

Some background introduction regarding the need for renewable energy was presented in Chapter 1. It also introduced important information about the location, climate, the electricity demand and the current state of renewable energy in the State of Kuwait. In addition, the main problems associated with a large increase in the use of fossil fuels were explained, along with the expected contribution of this research to resolving these issues.

The need for renewable resources, which is clean and sustainable, is becoming a worthy target and a key goal in order to satisfy the high increase rate of electricity demand in Kuwait and in order to minimise the impact of fossil fuel emissions on the environment

Solar photovoltaic energy was chosen as the renewable energy source to be implemented in because Kuwait has a high solar energy potential. Kuwait has approximately nine hours of sunshine a day, on average, and annual solar irradiation of approximately 2100 kW/m^2/year. Moreover, the low levels of rainfall and cloud cover, as well as the large area of uninhabited desert, are also important factors affecting the use of solar photovoltaic systems.

Chapter 2 presented studies conducted in the photovoltaic energy field, focusing on the evaluation indices of this technology, such as performance and environmental evaluation studies. It was concluded from the literature review that there is a lack of research conducted in GCC countries, and in Kuwait in particular, investigating the feasibility of implementing PV systems in detail, covering all the areas related to this technology.

It was identified that no studies of PV systems using single-axis and dual-axis tracking systems in Kuwait have been conducted. Moreover, in most of the conducted studies, the method used to calculate the output energy was imperfect, for various reasons, including:

- Assuming the whole country as similar to one site, and hence using non-representative data leading to inaccurate results.
- Few studies used specialist PV system programs; most applied a very simple mathematical equation for calculation purposes.
- No studies considered tracking systems.
- No study took into account the ground (soil layers) when modelling the behaviour of the solar trackers against external loads.

The methodology followed in this research was discussed in Chapter 3, which introduced in detail the site selection and data collection processes used in this study. The main specified tasks and objectives (performance, environmental, economic evaluations, as well as the numerical modelling of the proposed solar trackers) were also described in this chapter.

In Chapter 4, in order to evaluate the performance of the proposed PV systems, the performance parameters of the proposed PV systems at the selected sites were determined. The investigation was conducted based on monthly basis for the selected sites, and then an investigation was carried out based on an annual basis in order to compare the obtained results with different studies from the literature.

The amount of produced energy ranged between 174347 and 178843 MWh for the fixed tracking systems, and from 217835 and 223935 MWh and 225481 and 231563 MWh for the single-axis and dual-axis tracking systems, respectively. It was established that the variance in the annual production energy between the proposed sites was 2.58 % for the fixed tracking systems, and 2.80 and 2.70 % for the single-axis and dual-axis tracking systems, respectively. This indicates that the effect of location is insignificant for the state of Kuwait, as the country is relatively small in area. However, these small degrees of variation in the results have a significant influence when it comes to accuracy and research undertaken in a professional manner, in particular for large-scale projects.

The implementation of solar tracking systems led to this increasing by 24.7% and 29%. In addition, there was a significant increase in CF and YF values of approximately 24% and 28.8%, related to the use of single-axis and dual-axis systems, respectively. However, despite the encouraging results gained by the use of single-axis and dual-axis PV systems, lower performance values were obtained for tracking systems, due to the high energy loss resulting from overheating of PV modules as a result of high summer temperatures. This current study established that the performance parameters values obtained by using tracking systems are highly beneficial to electricity generation in Kuwait, as an alternative source to conventional power plants.

Chapter 5 presented the environmental evaluation study. The study consisted of two main parts; the first part was the Life Cycle Assessment (LCA), in which the main LCA evaluation indices, such as the energy payback time (EPBT), were determined. The second part was the environmental benefits evaluation, in which the amounts of GHGs saved were computed.

Although photovoltaic technology itself produces zero emissions, some emissions, which should not be underestimated, are produced throughout its lifecycle. It was identified that the manufacturing stage of PV system components is a critical stage in this regard, as a high volume of emissions are produced due to the large amounts of energy consumed in manufacturing and fabricating PV systems components.

The average EPBTs and EYR s obtained in the present study are encouraging, and show that shorter periods can be achieved by using single-axis and dual-axis tracking systems. It was found that the transportation stage, which has been included as a boundary condition in this study, had an insignificant effect on the total CO_2 emission rate of the proposed PV systems at the selected sites, compared with other stages. However, including the emissions produced in the transportation stage in the LCA provided more realistic results.

The average total CO_2 emission rate was estimated at 56.94 g-CO_2,eq/kWh for the fixed tracking system, and 47.56 g-CO_2,eq/kWh and 46.38 g-CO_2,eq/kWh for single-axis and dual-axis tracking systems, respectively. The importance of implementing tracking systems can be clearly seen in the percentage reduction in total CO_2 emission rates, which was calculated at 19.72% and 22.78% when using single-axis and dual-axis tracking systems, respectively.

It was also found that the emissions resulting from photovoltaic solar energy are relatively low compared with fossil fuel based technologies such as coal and oil, but are relatively high when compared with other renewable technologies, such as wind energy. This was attributed to the large amounts of energy consumed in the manufacturing and fabrication of the solar modules.

Based on the environmental benefits analysis, a large amount of GHG emissions, as stated above, would be avoided by implementing PV systems to generate electricity in Kuwait. This would constitute a positive contribution to helping minimise certain environmental issues, such as global warming.

The economic evaluation was presented in Chapter 6, using the levelized cost of electricity (LCOE) approach. A sensitivity analysis of the main LCOE approach, with input parameters such as installation cost, was performed in order to ensure that the study covered a wide range of different variables, which are highly dependent on market prices as well as financial issues related to this technology.

The average obtained LCOE value was \$0.072 (£0.055) /kWh for the fixed solar tracking systems, and the average LCOE values for the single-axis and dual-axis tracking systems were \$0.0625 (£0.0479) /kWh, and \$0.065 (£0.050) /kWh, respectively.

The results of the sensitivity analysis were also encouraging, and suggest very optimistic expectations regarding the successful implementation of PV technology in Kuwait. In addition, based on the expected decrease in the cost of PV system components, and the significant development in photovoltaic technology itself, excellent results are expected.

The implementation of single-axis and dual-axis tracking systems were significant. This can be clearly seen in the obtained LCOE values for the single-axis and dual-axis tracking systems, which decreased by 13.10% and 9.72%, respectively. The single-axis tracking systems showed the best LCOE values. It should be noted that the dual-axis tracking systems increased the amount of energy produced by 28.8% and 4.8% over the fixed and single-axis tracking systems, respectively. However, the high initial costs of the dual-axis tracking systems increased the total cost, in terms of LCOE value in \$/kWh.

The cost-benefit analysis found that the proposed PV systems at all selected sites are economically feasible when the oil prices are above \$30 /barrel. In addition, money will be saved as a result of avoiding large amounts of CO_2 emissions. When represented in monetary values.

In Chapter 7, a numerical modelling study was conducted in order to investigate the behaviour of the proposed solar models against the external loads. The study was carried out by means of the FEM, using the COMSOL Multiphysics software. It also identified that the wind load is the most important criteria applied in this study. The foundation and soil layers were included in the numerical modelling, in order to gain a better understanding of the interaction between the solar tracker and soil. The average von Mises stress was 86.43 MPa, which was less than the yield stress (200 MPa) noticed by the FOS values, which were between 1.89 (for an inclination angle of 75°) and 3.47 (for inclination angle of 15°). The average displacement was 17.84 mm, where the minimum and maximum displacement values were 15.4 mm and 19.9 mm, respectively.

From a geotechnical engineering perspective, the maximum stresses and displacements obtained revealed that the ground is safe and stable in response to external loads (self-weight of the solar tracker and wind load) except for the 60 m/s wind speed.

It can be concluded that the effect of wind speed should not be underestimated, especially when wind speed is high. Therefore, the defence position strategy is generally applied in most solar trackers, in which the solar tracker is installed at a horizontal position in order to protect the structure from external forces induced by high wind speeds. This position is used to avoid very strong winds.

8.3 Discussion

As stated in the background and introduction, the continuing population increase, economic and social development, as well the large-scale and unbalanced use of natural resources are serious indications of a future crisis in terms of both energy use and environmental issues. In addition to the fact that oil, which is one of the finite natural resources, will eventually finish.

The need to utilise sustainable energy resources such as wind and solar is essential to satisfy the accelerating energy demand across the world. Recently, there has been more interest in using renewable energy, which is clean and free.

The location of Kuwait means there is a high potential to implement solar technology in the country. This is clearly evident from the high rate of annual solar irradiation the country receives, which is estimated to be approximately 2100 $kW/m^2/year$. In addition, the relatively long daylight hours (approximately nine hours) and the low levels of rainfall and cloud cover are further advantages that suggest the chances of success of using such technology will be high.

Solar photovoltaic energy was chosen as the renewable energy source to be implemented in this study. The author strongly recommends the use of solar photovoltaic systems, as a promising technology for generating electricity in Kuwait, instead of increasing the capacity of the existing conventional power plants.

It is extremely important to explain the decision-making process integrating the identified criteria in this research. It was previously stated in the aim and objectives sections of this research that the feasibility of using PV systems in Kuwait would be investigated based on the following main tasks:

- Performance parameters assessment of the proposed PV systems;
- Environmental evaluation;
- Economic evaluation; and
- A numerical modelling study of the proposed PV systems.

These tasks are vital, and have a considerable influence on the final results of the feasibility study of this research; Table 8.1 lists the significance of the criteria used in this research.

Based on the methodology of this research, the first objective consists of the performance parameters of the proposed PV systems, as it is pointless to continue to evaluate a proposed system that is not technically feasible, or able to satisfy the minimum range of the required or expected results. This is particularly so when the proposed project gives clear initial indications that the expected power production will not satisfy the minimum standards required of this type of technology. It is therefore more effective, from the basic principle of feasibility, to focus on improving the proposed system with a detailed re-assessment, or simply rejecting the proposal and seeking different alternatives.

The economic and environmental evaluation tasks are highly dependent on the results obtained from the study of the performance parameters, i.e. these results determine the assessment of the lifecycle and amount of avoidable greenhouse gas emissions undertaken in the environmental evaluation study. Alternatively, the political and health factors are important as Kuwait signed many international agreements such as the Kyoto protocol. The physical stability of the proposed solar tracker is extremely important as based on it, the site would be prepared, and the underlying soil treated accordingly, in addition the structure supporting the tracker being appropriately designed and built. This would also affect the feasibility analysis through the economic criterion.

Overall, it can be concluded that the performance parameters criteria is the most critical factor compared with the other criteria. However, a proper evaluation by means of comparing all the set criteria would be recommended based on the main purpose of the proposed solar PV system.

Table 8.1 Significance of the criteria used in this research

Criteria	Importance
Performance Parameters	Determines the technical performance of the proposed PV systems in generating electricity.
Environmental Evaluation	Implementing solar PV systems in Kuwait would be a significant step towards increasing the use of renewable energy to minimise the effects of global warming, especially that Kuwait has signed relevant international agreements.
Economic Evaluation	Compares the cost of the proposed PV systems with conventional power plants in generating electricity.
Numerical Modelling Study	Check the stability and reliability of the proposed solar tracker against the external loads.

The performance parameters stated by the International Energy Agency (IEA) were employed in order to investigate the technical feasibility of the proposed PV systems. For the fixed tracking systems, the average energy output per month and performance ratio were 14,257 MW and 78.17%, respectively. These values provide some indication of the performance of the proposed PV systems in terms of the amount of energy that would be introduced, and the amount of energy that would be lost by implementing these systems.

The effect of using tracking systems is significant. The amounts of energy produced increased by 23.55% and 30.52% by implementing single-axis and dual-axis tracking systems, respectively. However, the performance ratios decreased by 1.09% and 2.0%. This decrease in performance ratio values is due to the amount of energy lost, and can be primarily attributed to high temperatures in the summer.

In the second part of the performance parameters evaluation, the calculations and the results were done on an annual basis in order to provide a better understanding of the performance of the proposed PV systems, by comparing them with different countries that are mature and leading in the photovoltaic energy field, such as Germany and Italy.

The average annual production of the proposed PV systems was 176,232.4 MW with a performance ratio of 77.5%. This is a good indication of the amount of solar irradiation that was harvested at the selected sites.

The capacity factors of the selected sites ranged from 19.9% to 20.42%, and the obtained yield factor values ranged from 1,743.47 and 1,813.27 kWh/kW/year. These values are encouraging when compared with leading countries in the photovoltaic energy field across the world.

In addition, the effect of using tracking systems was considerable; the annual produced energy increased by 24.7% and 29% as a result of implementing single-axis and dual-axis tracking systems, respectively. Moreover, the capacity factors and the yield factors also increased by 24% and 28.8%, respectively. However, the performance ratios decreased to 76.4% and 76.2% as a result of using single-axis and dual-axis tracking systems, respectively. This can be attributed to the high loss of energy resulting from the excessive heating of solar modules in high temperatures, particularly in the summer.

The impact of implementing PV systems in Kuwait on the environment is an important consideration that has been investigated in this research. It is very important to emphasise here that the claim that photovoltaic energy is clean and environmentally friendly requires some clarification. It is true that PV systems generate electricity with zero emissions, and this is achieved simply by converting solar irradiation into electricity. However, as stated in Chapter 5, a large amount of energy is used in the manufacturing of the PV system components; for instance, a lot of energy is consumed in the process of refining and purifying of the raw material (silicon). This is clearly evident from the results of the Life Cycle Assessment (LCA) study that was conducted in Chapter 5. It can be observed that GHG emissions occur at different stages (production stage, installation and maintenance stage, transportation and recycling stage). Most of GHG emissions are reported at the production stage, and this can be attributed to the large amount of energy used in this stage, whereas an insignificant amount was reported at the transportation stage.

As stated in the literature review, photovoltaic energy is a relatively immature technology, and there is no available data on the recycling processes of PV systems.

The LCA study evaluation indices (EPBT, EYR, and CO_2 emission rate) were computed in order to provide a complete understanding of the impact of the proposed PV systems on the environment. The average EPBT and EYR values for the proposed sites using fixed tracking systems were 1.77 year and 14.12 year, respectively, and the average CO_2 rate was 56.94 g-CO_2,eq/kWh.

The importance of utilising tracking systems is significant and can be clearly seen from the decrease in EPBT values, by 19.66% and 22.145% as a result of implementing the single-axis and dual-axis tracking systems, respectively. Moreover, an increase of 24.53% and 28.53% in the EYR values was obtained through the use of single-axis and dual-axis tracking systems, respectively. The effect of using tracking systems can also be observed in the 16.47% and 18.55% decrease in the CO_2 rate that was achieved by implementing single-axis and dual-axis tracking systems, respectively.

Large amounts of GHG emissions, estimated at 105,739.4 tons of CO_2, 176.234 tons of SO_2 and 264.348 tons of NO_x would be avoided by implementing the PV systems in the selected sites in Kuwait. In addition, these estimated amounts would increase to 131,843 and 136,417.2 tons of CO_2, 219.74 and 227.362 tons of SO_2 and 329.61 and 341.04 tons of NO_x if utilising single-axis and dual-axis tracking systems, respectively.

From an economic perspective, the implementation of PV systems in Kuwait will constitute a significant contribution to saving the money consumed by burning fossil fuels to generate electricity in conventional power plants in Kuwait. The results of the LCOE show that the values of the selected sites were less than the LCOE values for the conventional power plants. In other words, a large amount of money will be saved as a result of using PV systems to generate electricity in Kuwait.

The amount of money saved depends on the tracking system used. For example, although more electricity is generated using the dual-axis tracking systems, the results revealed that single-axis tracking systems are more appropriate for use in Kuwait. This can be seen by comparing the amount of energy that would be introduced with each tracking system with the LCOE value of each system. The amount of electricity that would be generated by implementing single-axis and dual-axis systems increases by 24.7% and 29%, respectively, where the single-axis tracker produces better LCOE values. This can mainly be attributed to the expense of the dual-axis solar tracking systems.

It should be emphasised here that the LCOE approach is highly dependent on the parameters used to calculate the LCOE values, such as installation cost and lifetime cycle of PV system components. This can be observed from the results of the sensitivity study, in which a wide range of different variables were tested in order to understand the effect of each variable on the LCOE value.

The cost-benefit study that was conducted focused on the amount of money that would be saved by implementing PV systems in Kuwait. The price of oil was an important factor in this study, and the equivalent cost of the amount of oil saved was computed. Fluctuation in oil prices was considered by assuming wide range of oil prices in order to cover all possible situations that might occur in the future. Based on the obtained results, the oil price of $30 (£23) per barrel was identified as a critical point, and single-axis tracking systems produced the lowest LCOE values at all of the selected sites.

The behaviour of the proposed solar trackers can be observed in the numerical modelling study that was conducted in Chapter 7. The behaviour of the solar tracker and the soil can be seen in the equivalent stress, displacement, equivalent strain, and factor of safety results that were achieved.

It was found that the proposed PV solar tracker would be stable under the design speed (40 m/s), and the critical case of the proposed model occurs when the inclination angle of the solar tracker was at 75° with the wind blowing from a southern direction. It was also found that all the minimum factor of safety (FOS) values for the models were greater than 1.89, and relatively small displacement values varied from 15.4 to 19.9 mm, for the solar structure and the foundation. There was relatively small equivalent strains, between 1.36×10^{-3} and 1.71×10^{-3}, and von Mises stress values varied between 58 and 107 MPa, which was less than the yield values of the solar tracker materials, for the critical case.

It can be concluded that the effect of wind speed should not be underestimated, especially when wind speed is high. Therefore, the defence position strategy is generally applied in most solar trackers, in which the solar tracker is installed at a horizontal position in order to protect the structure from external forces produced by high wind speeds.

8.4 Overall Conclusion

There is no doubt that renewable energy will play a substantial role in helping to minimize the currently high reliance on fossil fuels based technology, such as conventional power plants. Since the peak time in terms of electricity demand in Kuwait coincides with the peak production time of PV systems, this is another clear reason why solar PV systems would be the best choice amongst other renewable energy technologies.

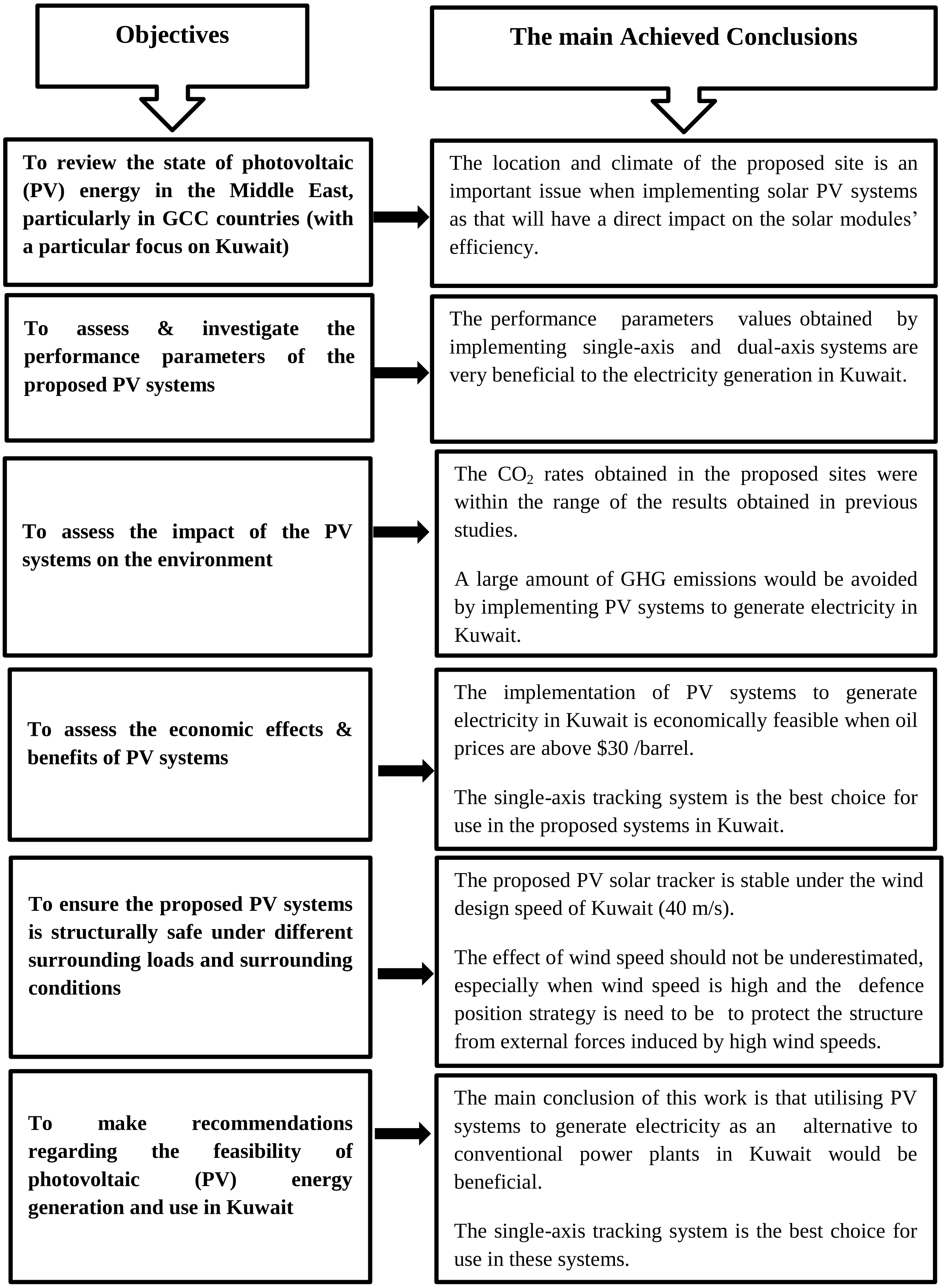
The main findings of this study (Figure 8.2), which has considered four elements of the ‘feasibility’ of using PV systems in Kuwait, encourage the use of PV systems in Kuwait to produce electricity. Single-axis tracking systems are recommended as the better option to be implemented in the state of Kuwait.

In terms of the performance evaluation, a large amount of energy would be generated by such systems, which would significantly contribute to minimizing the pressure resulting from the high demand for electricity, especially in the summer months. The results related to the performance of the proposed PV systems were excellent by the means of achieved results of the performance parameters. The effect of utilising tracking systems, either single-axis or dual-axis tracking systems, is significant, as these increased the amount of energy produced, as well as reducing the amount of greenhouse emissions produced.

The results of the environmental analysis showed that a large volume of greenhouse gases would be avoided, which will contribute significantly to minimizing environmental problems, such as global warming. It was found also that the proposed PV systems are economically feasible compared with conventional power plants when oil prices are greater than $30 (£23)/barrel. The implementation of PV systems in Kuwait will save a lot of money, as it will be possible to sell fossil fuels instead of using them as fuel for conventional power plants.

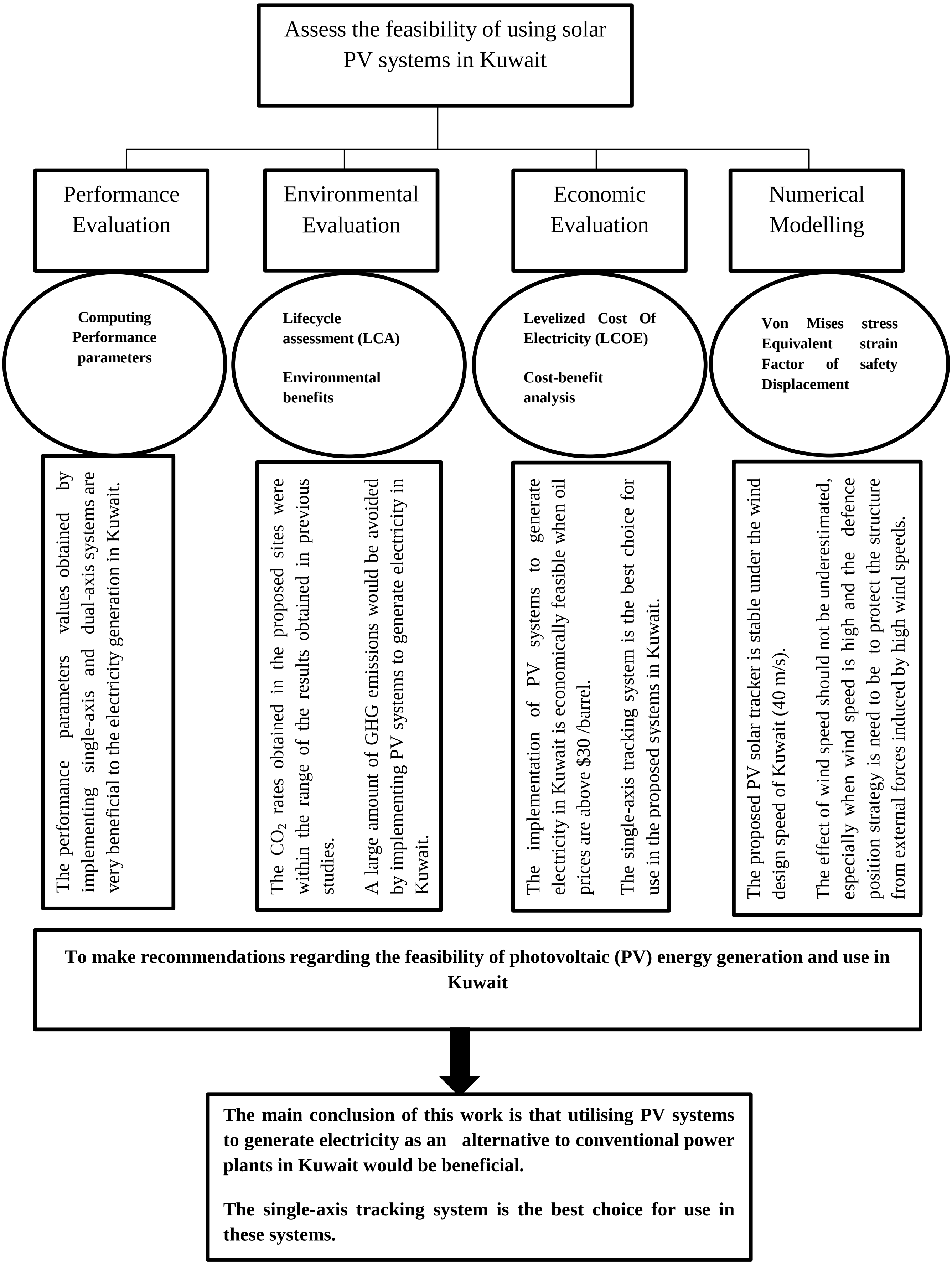
The numerical modelling study found that the behaviour of the proposed solar tracker and the ground against the external loads would be safe and stable under the used design criteria. However, the effects of high wind speed magnitudes should not be ignored, and solar trackers should be put into a defence state in high wind speeds.

Overall, based on the results of this research, the implementation of PV systems in Kuwait is recommended. Utilising PV systems will contribute significantly to addressing economical and environment concerns. Use of a single-axis tracking system is also recommended; Figure 8.3 shows the road map of the research and the overall conclusion.



Objectives	The main Achieved Conclusions
To review the state of photovoltaic (PV) energy in the Middle East, particularly in GCC countries (with a particular focus on Kuwait)	The location and climate of the proposed site is an important issue when implementing solar PV systems as that will have a direct impact on the solar modules' efficiency.
To assess & investigate the performance parameters of the proposed PV systems	The performance parameters values obtained by implementing single-axis and dual-axis systems are very beneficial to the electricity generation in Kuwait.
To assess the impact of the PV systems on the environment	The CO_2 rates obtained in the proposed sites were within the range of the results obtained in previous studies. A large amount of GHG emissions would be avoided by implementing PV systems to generate electricity in Kuwait.
To assess the economic effects & benefits of PV systems	The implementation of PV systems to generate electricity in Kuwait is economically feasible when oil prices are above $30 /barrel. The single-axis tracking system is the best choice for use in the proposed systems in Kuwait.
To ensure the proposed PV systems is structurally safe under different surrounding loads and surrounding conditions	The proposed PV solar tracker is stable under the wind design speed of Kuwait (40 m/s). The effect of wind speed should not be underestimated, especially when wind speed is high and the defence position strategy is need to be to protect the structure from external forces induced by high wind speeds.
To make recommendations regarding the feasibility of photovoltaic (PV) energy generation and use in Kuwait	The main conclusion of this work is that utilising PV systems to generate electricity as an alternative to conventional power plants in Kuwait would be beneficial. The single-axis tracking system is the best choice for use in these systems.

Figure 8.2 The main achieved conclusions



The performance parameters values obtained by implementing single-axis and dual-axis systems are very beneficial to the electricity generation in Kuwait.

The CO_2 rates obtained in the proposed sites were within the range of the results obtained in previous studies.

A large amount of GHG emissions would be avoided by implementing PV systems to generate electricity in Kuwait.

The implementation of PV systems to generate electricity in Kuwait is economically feasible when oil prices are above $30 /barrel.

The single-axis tracking system is the best choice for use in the proposed systems in Kuwait.

The proposed PV solar tracker is stable under the wind design speed of Kuwait (40 m/s).

The effect of wind speed should not be underestimated, especially when wind speed is high and the defence position strategy is need to be to protect the structure from external forces induced by high wind speeds.

To make recommendations regarding the feasibility of photovoltaic (PV) energy generation and use in Kuwait

The main conclusion of this work is that utilising PV systems to generate electricity as an alternative to conventional power plants in Kuwait would be beneficial.

The single-axis tracking system is the best choice for use in these systems.

Figure 8.3 The road map of the research and the overall conclusion

8.5 Contributions to Knowledge

This thesis provides an important contribution to knowledge in terms of understanding the feasibility of solar photovoltaic energy in Kuwait from technical, environmental and economic perspectives. Moreover, from engineering perspective, it will provide a better understanding of the behaviour of the solar tracker and the ground against the external loads such as wind.

This study would be considered as a solid base of information and a benchmark for any future implementation of solar energy in Kuwait and GCC countries. This research has investigated the utilisation of solar energy in terms of the high data quality and covers all of Kuwait by selecting the most representative sites.

This high quality data was obtained by means of using two different sources; satellite and ground station data. The performance parameters have been analysed and computed using well-researched software for photovoltaic systems (PVsyst). Moreover, the effect of using tracking systems (single-axis and dual-axis) has been examined and is the first time this has been done in depth.

The study significantly contributed in filling the knowledge gap by including the ground (soil layers) in the numerical modelling which will give a clear and better understanding of the soil-structure interaction under external loads, in addition to the effects of a self-weight of the solar tracker on the soil. This is especially important as any expected or unexpected settlement will have a direct effect on the efficiency of the PV system by means of the orientation and the inclination angle of the solar trackers.

8.6 Recommendations for Future Work

It is crucial to increase the awareness and perceived importance of sustainable energy systems in terms of the vital role that renewable energy technologies can play in overcoming a number of economic and environmental issues. In order to enhance and encourage all stakeholders in the use of renewable energy, and in particular solar photovoltaic technology, more specialized programmes and workshops are needed. This will enable investors and decision-makers to have a better understanding of the technology, and will provide a solid base of reference information related to investment in the solar photovoltaic field.

Although much effort was made to select appropriate site locations, some sites were excluded from this study, such as landfill sites, due to a lack of information related to security issues, such as gas leakages, fire incidents, and also the unavailability of the soil properties of these sites. It would be beneficial to conduct more detailed investigations, including a full site survey study to provide details regarding soil properties and gas leakage at these sites.

As stated in Chapter 4, a large amount of energy is lost as a result of heating solar modules, especially in the summer months; hence, it would be beneficial to investigate new recommended techniques, such as frequent cleaning, for the purpose of both cleaning and cooling the solar modules.

As the economic perspective is most important to investors, serious effort is needed from the government in Kuwait to support and encourage the use of such technology, by offering incentives and more reliable and flexible financial credit sources.

The focus of this research was on implementing large-scale PV systems, which require large land areas in the State of Kuwait; it would be very beneficial for a future study to investigate small-scale PV systems in order to provide useful background data for smaller companies or even individuals who might be interested in this technology.

As stated in the introduction, Kuwait has high potential for utilising both solar and wind energy, and as there is on-going research on wind energy, it would be beneficial to evaluate the use of a combined system, what is known as a combination solar-wind power system, which could increase the amount of energy generated and would also be the best option for generating electricity in rainy weather (when there is little or no sunlight).

Finally, the decision-making process integrating the identified criteria is an important concept that has to be considered by means of conducting further studies in order to combine the effect of each individually used criterion with all other criteria.

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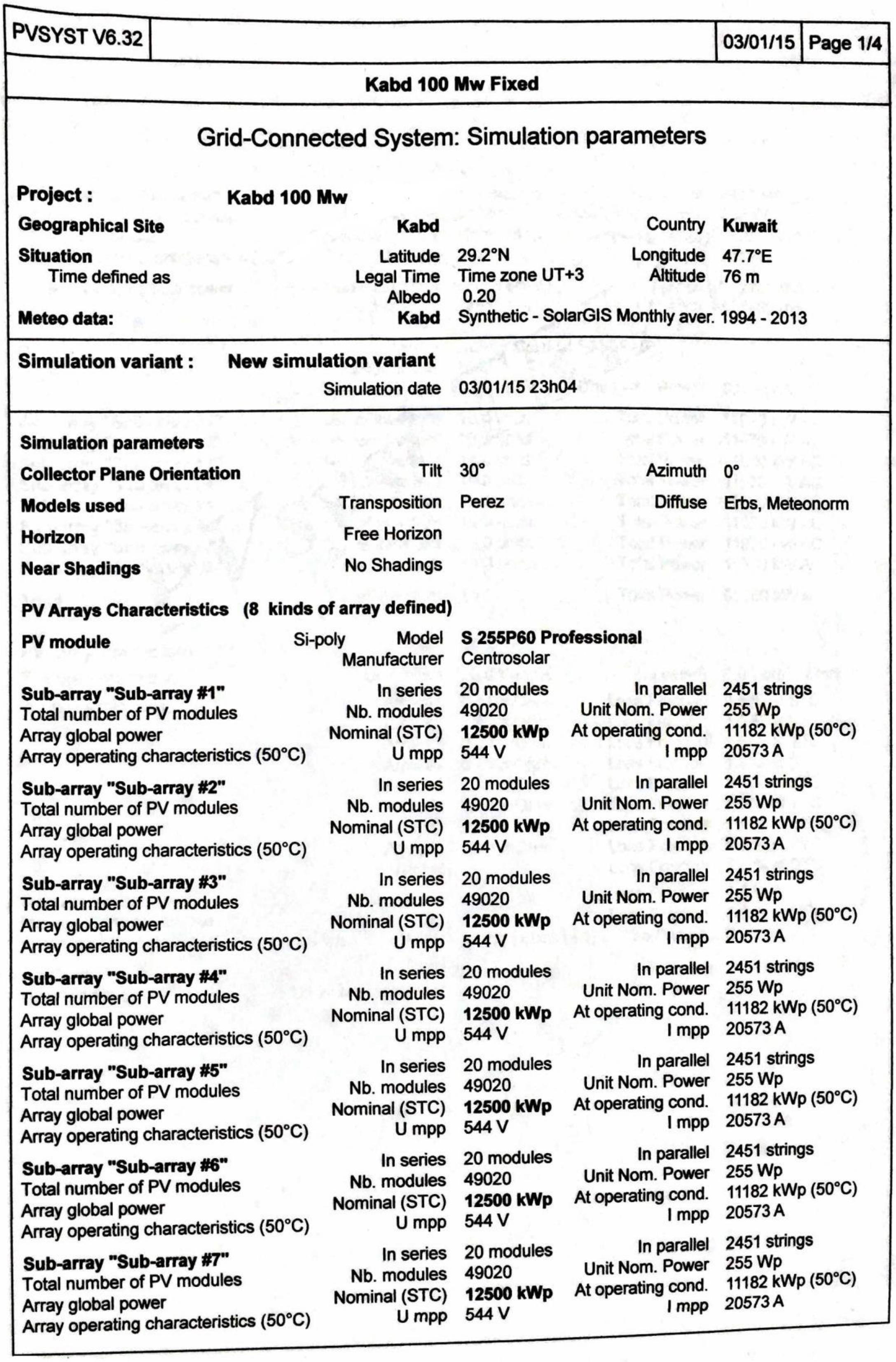
LIST OF APPENDICES

APPENDIX A – A Sample from the Performance Evaluation Analysis



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Kabd 100 Mw Fixed

Grid-Connected System: Simulation parameters

Project :	**Kabd 100 Mw**			
Geographical Site	**Kabd**		Country	**Kuwait**
Situation	Latitude	29.2°N	Longitude	47.7°E
Time defined as	Legal Time	Time zone UT+3	Altitude	76 m
	Albedo	0.20		
Meteo data:	**Kabd**	Synthetic - SolarGIS Monthly aver. 1994 - 2013		

Simulation variant :	**New simulation variant**	
	Simulation date	03/01/15 23h04

Simulation parameters

Collector Plane Orientation	Tilt	30°	Azimuth	0°
Models used	Transposition	Perez	Diffuse	Erbs, Meteonorm
Horizon	Free Horizon			
Near Shadings	No Shadings			

PV Arrays Characteristics (8 kinds of array defined)

PV module	Si-poly	Model	**S 255P60 Professional**		
		Manufacturer	Centrosolar		
Sub-array "Sub-array #1"		In series	20 modules	In parallel	2451 strings
Total number of PV modules		Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power		Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)
Array operating characteristics (50°C)		U mpp	544 V	I mpp	20573 A
Sub-array "Sub-array #2"		In series	20 modules	In parallel	2451 strings
Total number of PV modules		Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power		Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)
Array operating characteristics (50°C)		U mpp	544 V	I mpp	20573 A
Sub-array "Sub-array #3"		In series	20 modules	In parallel	2451 strings
Total number of PV modules		Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power		Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)
Array operating characteristics (50°C)		U mpp	544 V	I mpp	20573 A
Sub-array "Sub-array #4"		In series	20 modules	In parallel	2451 strings
Total number of PV modules		Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power		Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)
Array operating characteristics (50°C)		U mpp	544 V	I mpp	20573 A
Sub-array "Sub-array #5"		In series	20 modules	In parallel	2451 strings
Total number of PV modules		Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power		Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)
Array operating characteristics (50°C)		U mpp	544 V	I mpp	20573 A
Sub-array "Sub-array #6"		In series	20 modules	In parallel	2451 strings
Total number of PV modules		Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power		Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)
Array operating characteristics (50°C)		U mpp	544 V	I mpp	20573 A
Sub-array "Sub-array #7"		In series	20 modules	In parallel	2451 strings
Total number of PV modules		Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power		Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)
Array operating characteristics (50°C)		U mpp	544 V	I mpp	20573 A

Grid-Connected System: Simulation parameters (continued)

Sub-array "Sub-array #8"	In series	20 modules	In parallel	2451 strings
Total number of PV modules	Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power	Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)
Array operating characteristics (50°C)	U mpp	544 V	I mpp	20573 A
Total Arrays global power	Nominal (STC)	**100001 kWp**	Total	392160 modules
	Module area	**644476 m²**	Cell area	558499 m²

Inverter	Model	**Sunny Central 630CP-JP**		
	Manufacturer	SMA		
	Operating Voltage	500-850 V	Unit Nom. Power	630 kW AC
Sub-array "Sub-array #1"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Sub-array "Sub-array #2"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Sub-array "Sub-array #3"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Sub-array "Sub-array #4"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Sub-array "Sub-array #5"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Sub-array "Sub-array #6"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Sub-array "Sub-array #7"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Sub-array "Sub-array #8"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Total	Nb. of inverters	152	Total Power	95760 kW AC

PV Array loss factors

Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss	Array#1	0.44 mOhm	Loss Fraction	1.5 % at STC
	Array#2	0.44 mOhm	Loss Fraction	1.5 % at STC
	Array#3	0.44 mOhm	Loss Fraction	1.5 % at STC
	Array#4	0.44 mOhm	Loss Fraction	1.5 % at STC
	Array#5	0.44 mOhm	Loss Fraction	1.5 % at STC
	Array#6	0.44 mOhm	Loss Fraction	1.5 % at STC
	Array#7	0.44 mOhm	Loss Fraction	1.5 % at STC
	Array#8	0.44 mOhm	Loss Fraction	1.5 % at STC
	Global		Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	1.5 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05

User's needs : Unlimited load (grid)

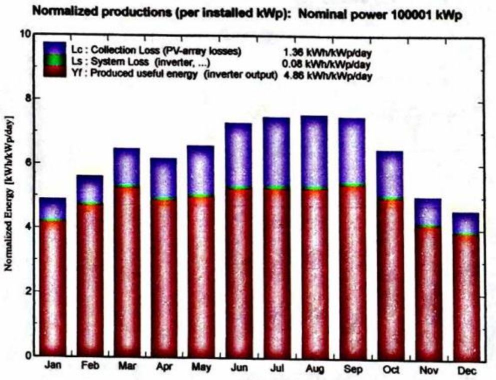
Grid-Connected System: Main results

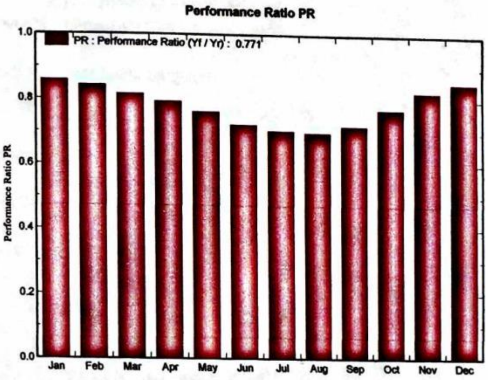
Project : **Kabd 100 Mw Two axis**

Simulation variant : **New simulation variant**

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	30°	azimuth	0°
PV modules	Model	S 255P60 Professional	Pnom	255 Wp
PV Array	Nb. of modules	392160	Pnom total	**100001 kWp**
Inverter	Model	Sunny Central 630CP-JP	Pnom	630 kW ac
Inverter pack	Nb. of units	152.0	Pnom total	**95760 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**177519 MWh/year**	Specific prod.	1775 kWh/kWp/year
	Performance Ratio PR	77.1 %		





New simulation variant

Balances and main results

	GlobHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	EffArrR %	EffSysR %
January	108.3	13.10	151.5	147.9	13207	12994	13.52	13.31
February	123.5	15.41	157.0	153.1	13440	13216	13.28	13.06
March	175.1	20.13	200.4	195.2	16616	16349	12.86	12.66
April	182.6	26.10	185.1	179.6	14915	14676	12.50	12.30
May	217.7	32.64	203.7	197.1	15764	15514	12.01	11.82
June	243.4	37.09	218.5	211.8	16049	15787	11.40	11.21
July	254.6	38.45	232.0	225.1	16629	16351	11.12	10.94
August	237.3	38.21	234.2	228.0	16646	16376	11.03	10.85
September	202.9	34.19	224.8	219.6	16452	16191	11.35	11.17
October	162.3	28.53	200.8	195.9	15731	15490	12.16	11.97
November	112.1	20.32	150.7	147.0	12653	12443	13.03	12.81
December	99.7	14.67	142.1	138.6	12333	12132	13.47	13.25
Year	2119.5	26.63	2301.0	2238.8	180436	177519	12.17	11.97

Legends:				
GlobHor	Horizontal global irradiation		EArray	Effective energy at the output of the array
T Amb	Ambient Temperature		E_Grid	Energy injected into grid
GlobInc	Global incident in coll. plane		EffArrR	Effic. Eout array / rough area
GlobEff	Effective Global, corr. for IAM and shadings		EffSysR	Effic. Eout system / rough area

Kabd 100 Mw Fixed

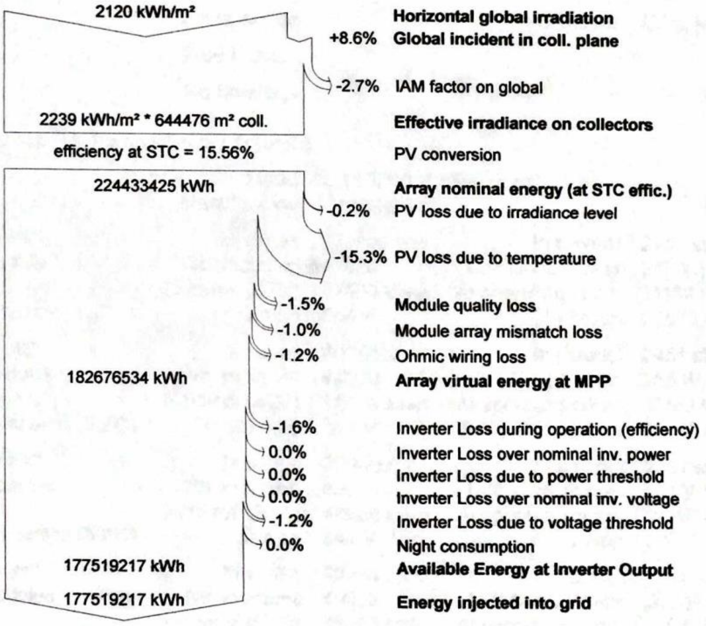
Grid-Connected System: Loss diagram

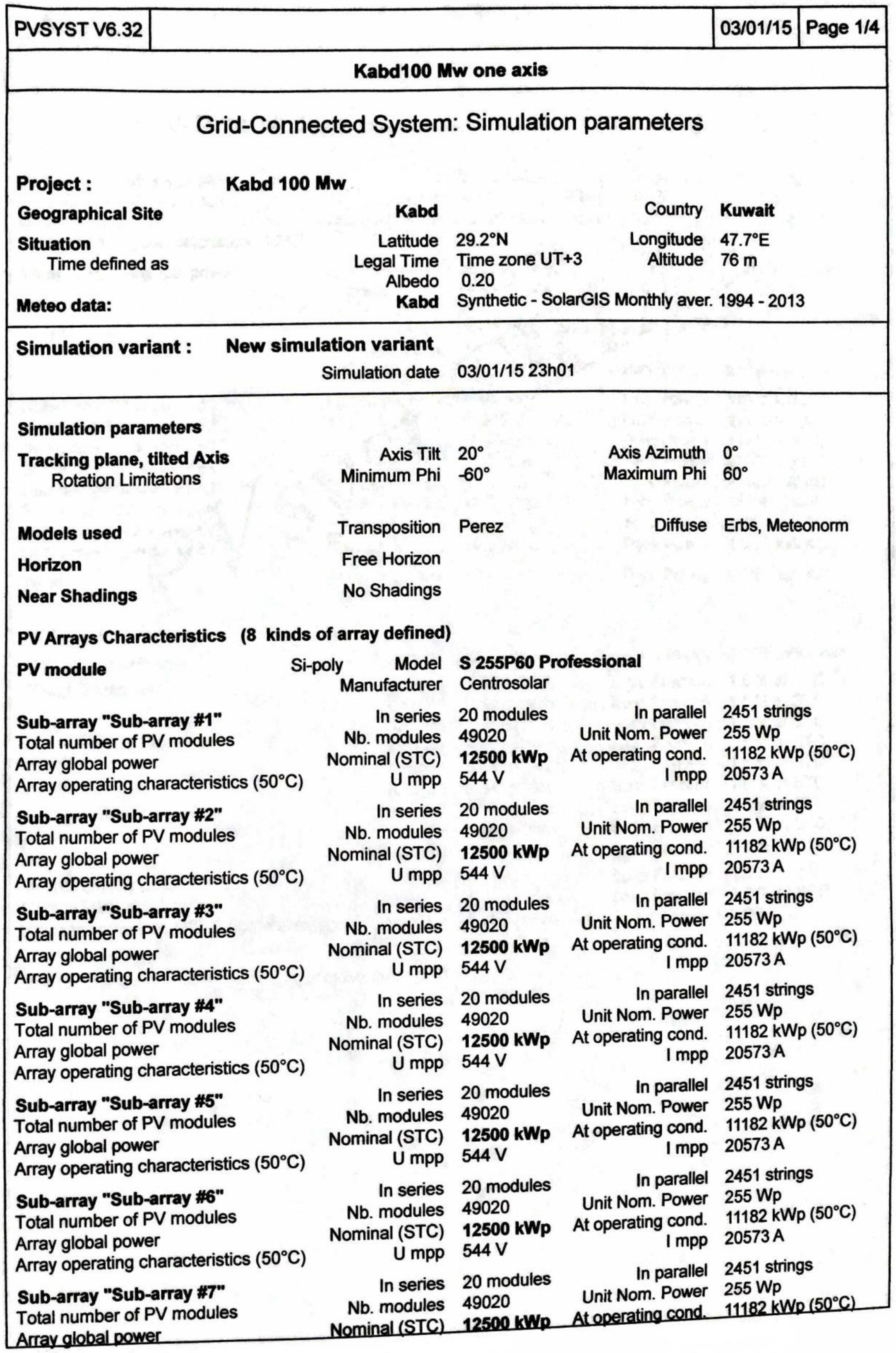
Project : **Kabd 100 Mw**

Simulation variant : **New simulation variant**

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tilt	30°	azimuth	0°
PV modules	Model	S 255P60 Professional	Pnom	255 Wp
PV Array	Nb. of modules	392160	Pnom total	**100001 kWp**
Inverter	Model	Sunny Central 630CP-JP	Pnom	630 kW ac
Inverter pack	Nb. of units	152.0	Pnom total	**95760 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year





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Kabd100 Mw one axis

Grid-Connected System: Simulation parameters

Project : **Kabd 100 Mw**

Geographical Site	**Kabd**		Country	**Kuwait**
Situation	Latitude	29.2°N	Longitude	47.7°E
Time defined as	Legal Time	Time zone UT+3	Altitude	76 m
	Albedo	0.20		
Meteo data:	**Kabd**	Synthetic - SolarGIS Monthly aver. 1994 - 2013		

Simulation variant : **New simulation variant**

Simulation date 03/01/15 23h01

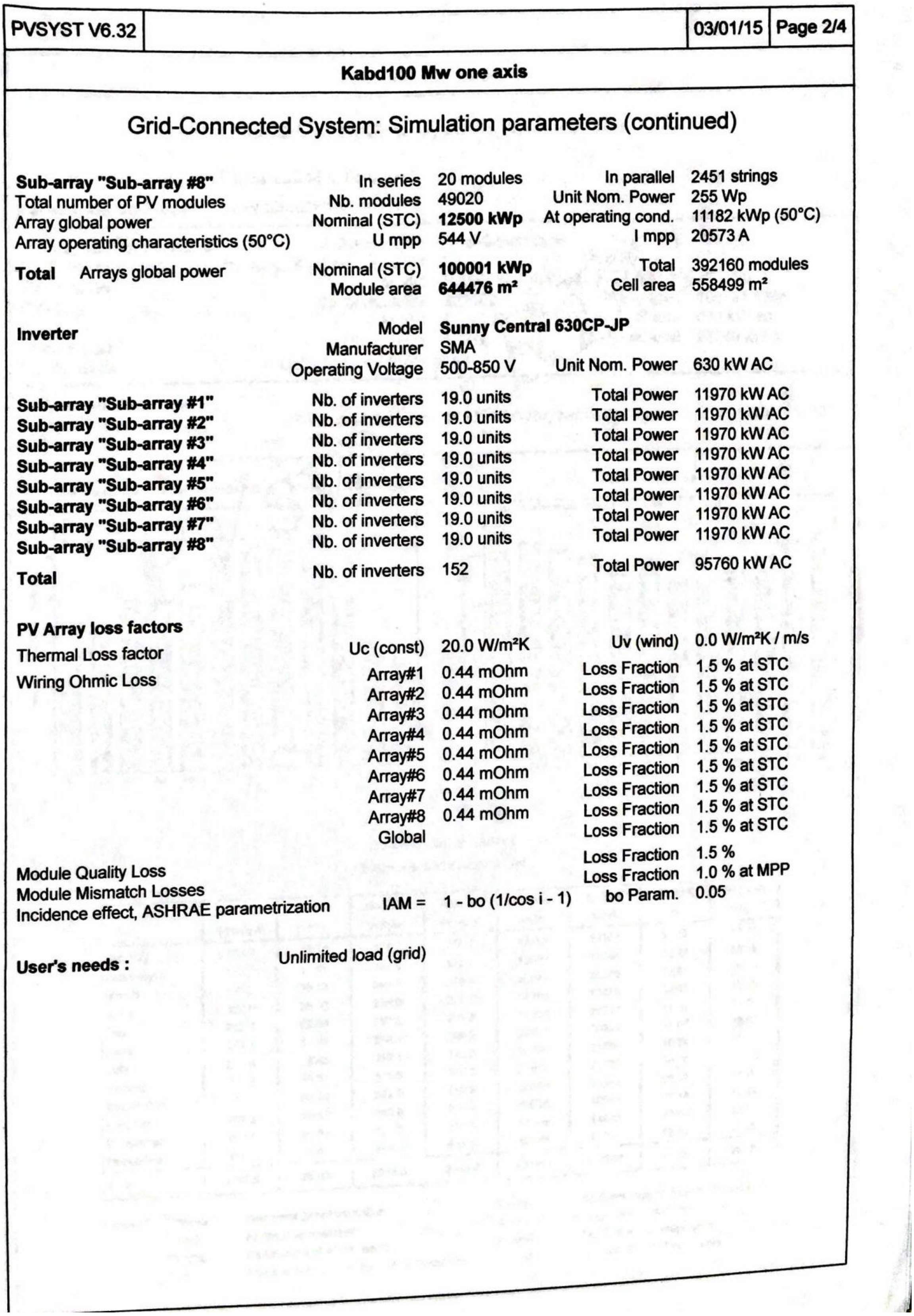
Simulation parameters

Tracking plane, tilted Axis	Axis Tilt	20°	Axis Azimuth	0°
Rotation Limitations	Minimum Phi	-60°	Maximum Phi	60°
Models used	Transposition	Perez	Diffuse	Erbs, Meteonorm
Horizon	Free Horizon			
Near Shadings	No Shadings			

PV Arrays Characteristics (8 kinds of array defined)

PV module	Si-poly	Model	**S 255P60 Professional**		
		Manufacturer	Centrosolar		

Sub-array "Sub-array #1"	In series	20 modules	In parallel	2451 strings
Total number of PV modules	Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power	Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)
Array operating characteristics (50°C)	U mpp	544 V	I mpp	20573 A
Sub-array "Sub-array #2"	In series	20 modules	In parallel	2451 strings
Total number of PV modules	Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power	Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)
Array operating characteristics (50°C)	U mpp	544 V	I mpp	20573 A
Sub-array "Sub-array #3"	In series	20 modules	In parallel	2451 strings
Total number of PV modules	Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power	Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)
Array operating characteristics (50°C)	U mpp	544 V	I mpp	20573 A
Sub-array "Sub-array #4"	In series	20 modules	In parallel	2451 strings
Total number of PV modules	Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power	Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)
Array operating characteristics (50°C)	U mpp	544 V	I mpp	20573 A
Sub-array "Sub-array #5"	In series	20 modules	In parallel	2451 strings
Total number of PV modules	Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power	Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)
Array operating characteristics (50°C)	U mpp	544 V	I mpp	20573 A
Sub-array "Sub-array #6"	In series	20 modules	In parallel	2451 strings
Total number of PV modules	Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power	Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)
Array operating characteristics (50°C)	U mpp	544 V	I mpp	20573 A
Sub-array "Sub-array #7"	In series	20 modules	In parallel	2451 strings
Total number of PV modules	Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power	Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)



Grid-Connected System: Simulation parameters (continued)

Sub-array "Sub-array #8"	In series	20 modules	In parallel	2451 strings
Total number of PV modules	Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power	Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)
Array operating characteristics (50°C)	U mpp	544 V	I mpp	20573 A
Total Arrays global power	Nominal (STC)	**100001 kWp**	Total	392160 modules
	Module area	**644476 m²**	Cell area	558499 m²

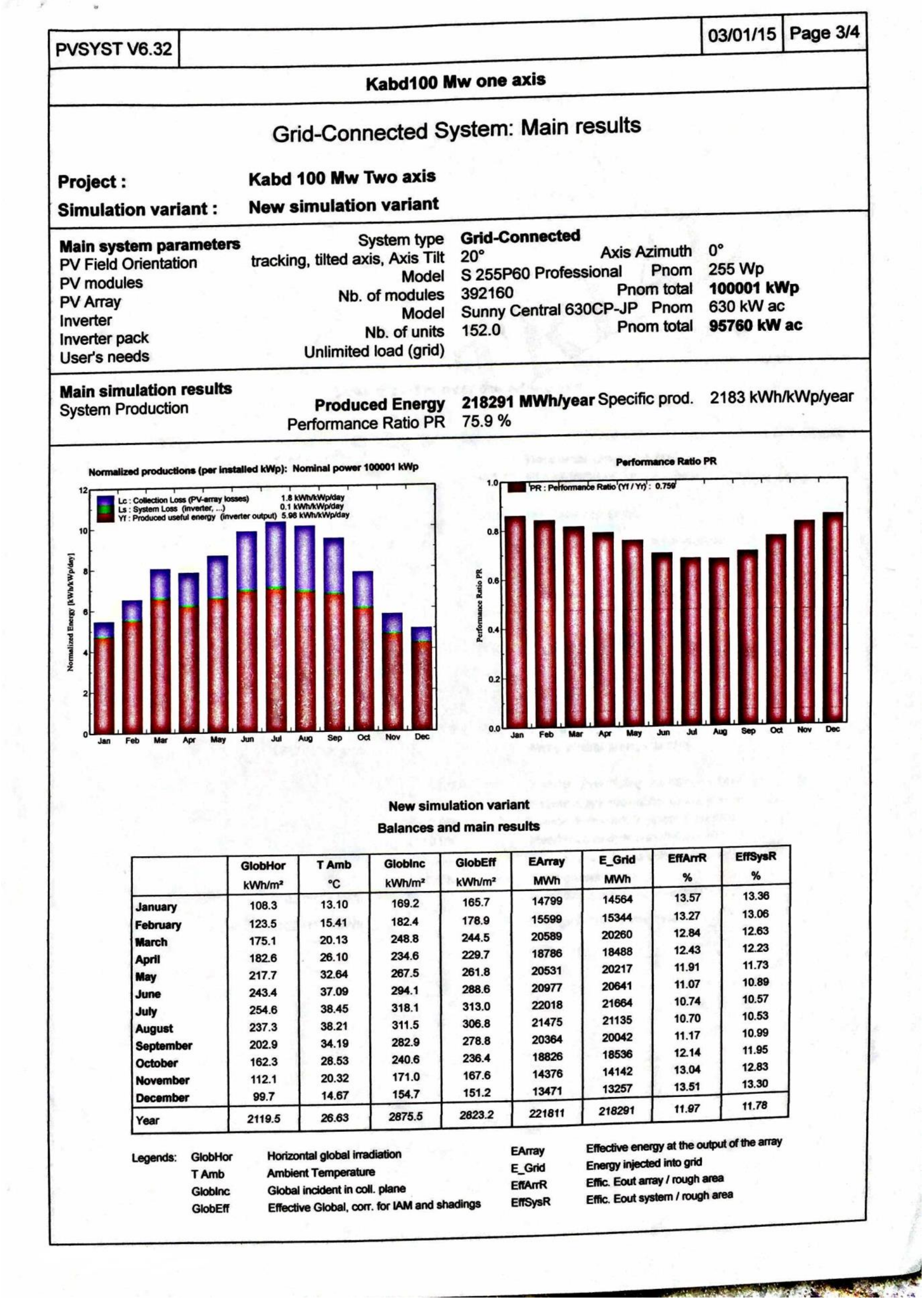
Inverter	Model	**Sunny Central 630CP-JP**		
	Manufacturer	SMA		
	Operating Voltage	500-850 V	Unit Nom. Power	630 kW AC

Sub-array "Sub-array #1"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Sub-array "Sub-array #2"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Sub-array "Sub-array #3"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Sub-array "Sub-array #4"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Sub-array "Sub-array #5"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Sub-array "Sub-array #6"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Sub-array "Sub-array #7"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Sub-array "Sub-array #8"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Total	Nb. of inverters	152	Total Power	95760 kW AC

PV Array loss factors

Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss	Array#1	0.44 mOhm	Loss Fraction	1.5 % at STC
	Array#2	0.44 mOhm	Loss Fraction	1.5 % at STC
	Array#3	0.44 mOhm	Loss Fraction	1.5 % at STC
	Array#4	0.44 mOhm	Loss Fraction	1.5 % at STC
	Array#5	0.44 mOhm	Loss Fraction	1.5 % at STC
	Array#6	0.44 mOhm	Loss Fraction	1.5 % at STC
	Array#7	0.44 mOhm	Loss Fraction	1.5 % at STC
	Array#8	0.44 mOhm	Loss Fraction	1.5 % at STC
	Global		Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	1.5 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05

User's needs : Unlimited load (grid)



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Kabd100 Mw one axis

Grid-Connected System: Main results

Project : **Kabd 100 Mw Two axis**
Simulation variant : **New simulation variant**

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tracking, tilted axis, Axis Tilt	20°	Axis Azimuth	0°
PV modules	Model	S 255P60 Professional	Pnom	255 Wp
PV Array	Nb. of modules	392160	Pnom total	**100001 kWp**
Inverter	Model	Sunny Central 630CP-JP	Pnom	630 kW ac
Inverter pack	Nb. of units	152.0	Pnom total	**95760 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**218291 MWh/year**	Specific prod.	2183 kWh/kWp/year
	Performance Ratio PR	75.9 %		

New simulation variant

Balances and main results

	GlobHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	EffArrR %	EffSysR %
January	108.3	13.10	169.2	165.7	14799	14564	13.57	13.36
February	123.5	15.41	182.4	178.9	15599	15344	13.27	13.06
March	175.1	20.13	248.8	244.5	20589	20260	12.84	12.63
April	182.6	26.10	234.6	229.7	18786	18488	12.43	12.23
May	217.7	32.64	267.5	261.8	20531	20217	11.91	11.73
June	243.4	37.09	294.1	288.6	20977	20641	11.07	10.89
July	254.6	38.45	318.1	313.0	22018	21664	10.74	10.57
August	237.3	38.21	311.5	306.8	21475	21135	10.70	10.53
September	202.9	34.19	282.9	278.8	20364	20042	11.17	10.99
October	162.3	28.53	240.6	236.4	18826	18536	12.14	11.95
November	112.1	20.32	171.0	167.6	14376	14142	13.04	12.83
December	99.7	14.67	154.7	151.2	13471	13257	13.51	13.30
Year	2119.5	26.63	2875.5	2823.2	221811	218291	11.97	11.78

Legends:				
	GlobHor	Horizontal global irradiation	EArray	Effective energy at the output of the array
	T Amb	Ambient Temperature	E_Grid	Energy injected into grid
	GlobInc	Global incident in coll. plane	EffArrR	Effic. Eout array / rough area
	GlobEff	Effective Global, corr. for IAM and shadings	EffSysR	Effic. Eout system / rough area

Kabd100 Mw one axis

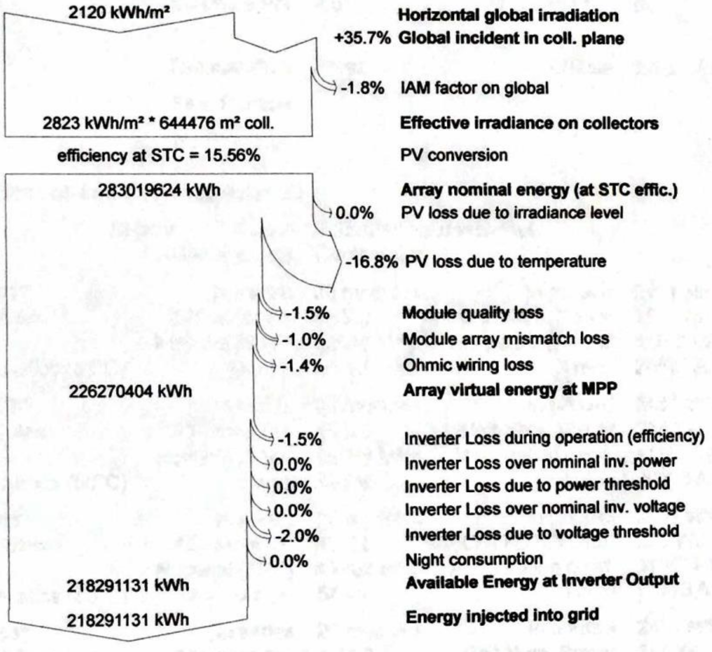
Grid-Connected System: Loss diagram

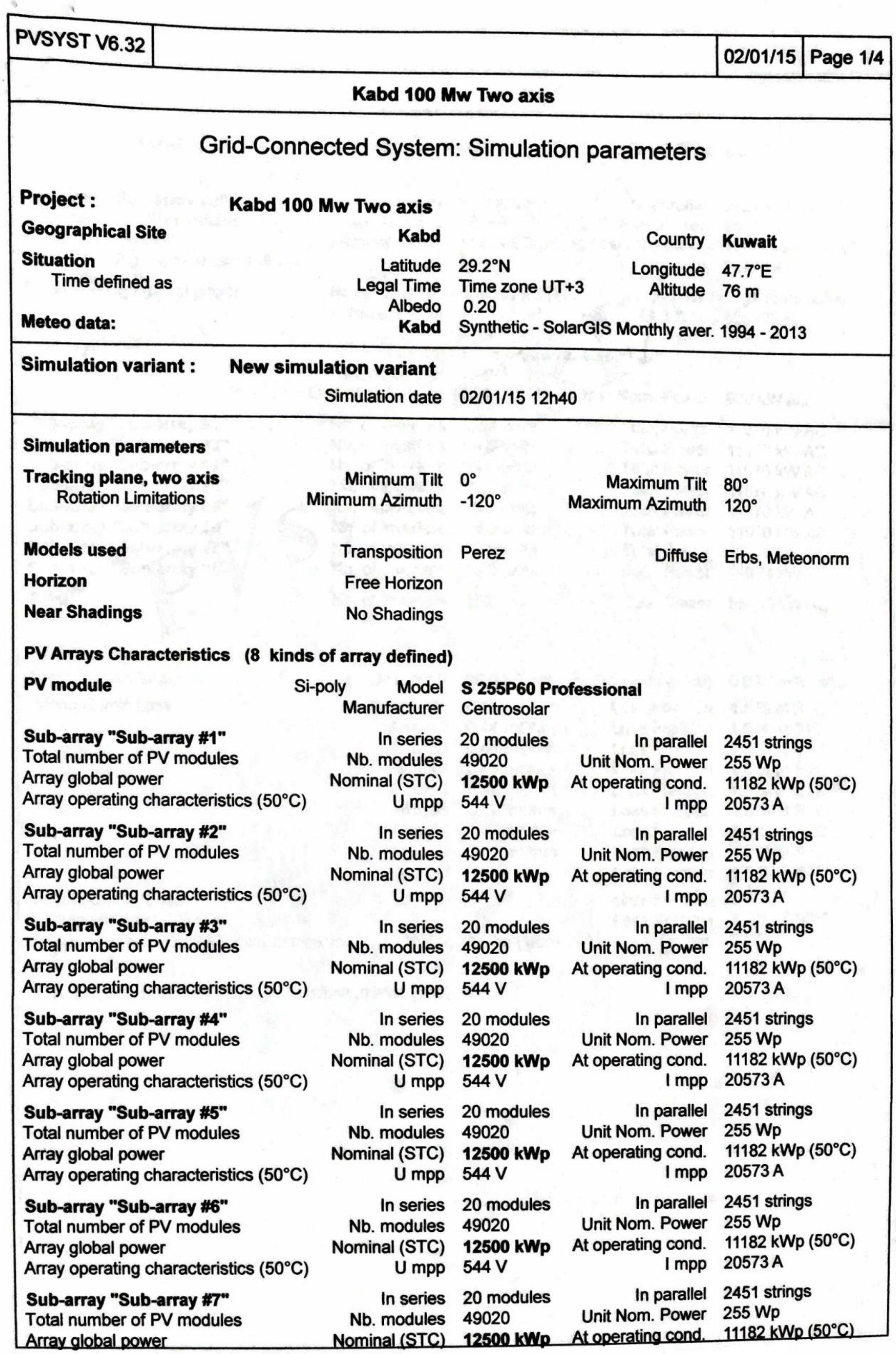
Project : **Kabd 100 Mw Two axis**

Simulation variant : **New simulation variant**

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	tracking, tilted axis, Axis Tilt	20°	Axis Azimuth	0°
PV modules	Model	S 255P60 Professional	Pnom	255 Wp
PV Array	Nb. of modules	392160	Pnom total	**100001 kWp**
Inverter	Model	Sunny Central 630CP-JP	Pnom	630 kW ac
Inverter pack	Nb. of units	152.0	Pnom total	**95760 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year





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Kabd 100 Mw Two axis

Grid-Connected System: Simulation parameters

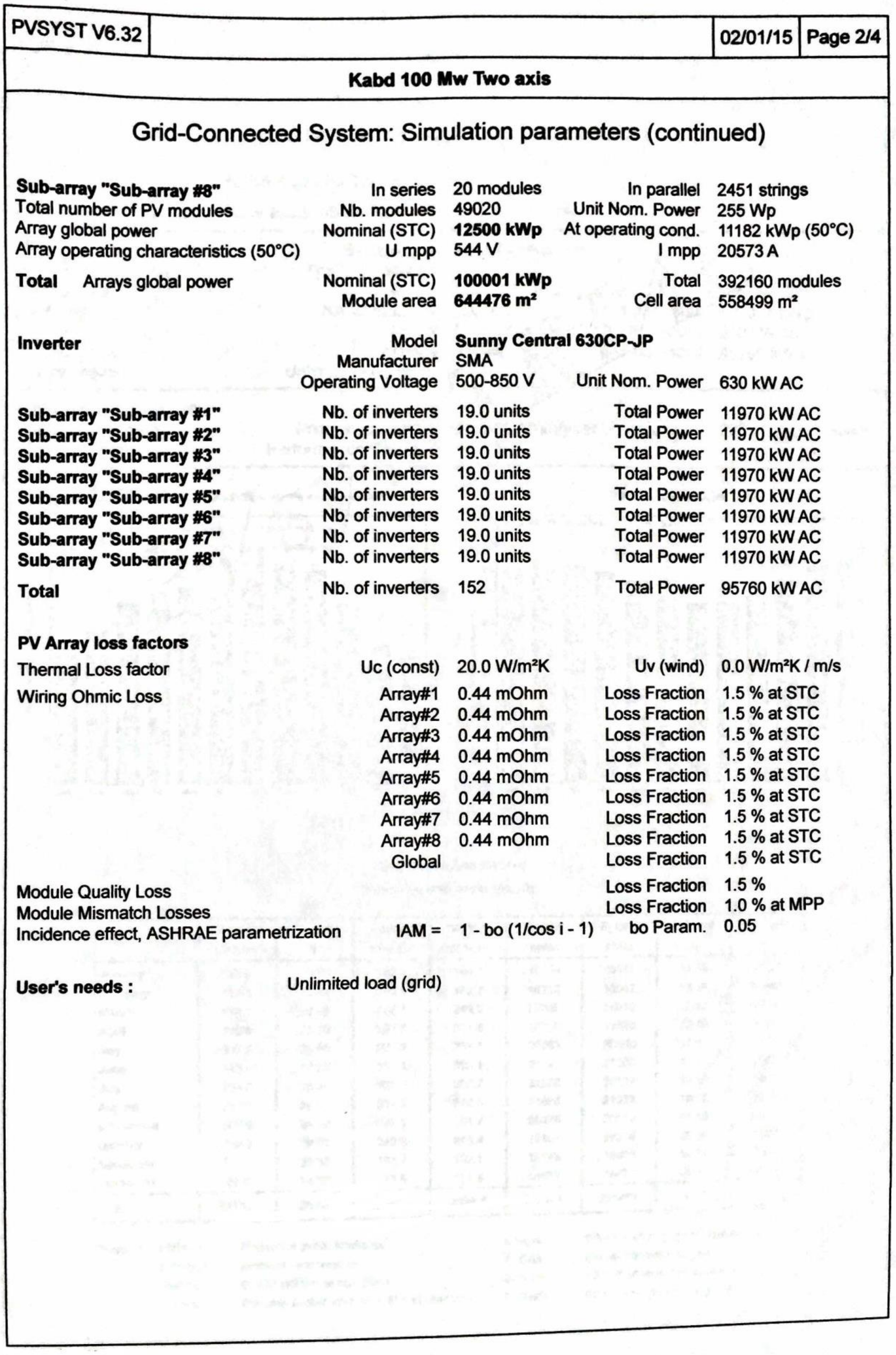
Project :	**Kabd 100 Mw Two axis**			
Geographical Site		**Kabd**	Country	**Kuwait**
Situation	Latitude	29.2°N	Longitude	47.7°E
Time defined as	Legal Time	Time zone UT+3	Altitude	76 m
	Albedo	0.20		
Meteo data:	**Kabd**	Synthetic - SolarGIS Monthly aver. 1994 - 2013		

Simulation variant :	**New simulation variant**			
	Simulation date	02/01/15 12h40		

Simulation parameters				
Tracking plane, two axis	Minimum Tilt	0°	Maximum Tilt	80°
Rotation Limitations	Minimum Azimuth	-120°	Maximum Azimuth	120°
Models used	Transposition	Perez	Diffuse	Erbs, Meteonorm
Horizon	Free Horizon			
Near Shadings	No Shadings			

PV Arrays Characteristics (8 kinds of array defined)

PV module Si-poly	Model	**S 255P60 Professional**		
	Manufacturer	Centrosolar		
Sub-array "Sub-array #1"	In series	20 modules	In parallel	2451 strings
Total number of PV modules	Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power	Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)
Array operating characteristics (50°C)	U mpp	544 V	I mpp	20573 A
Sub-array "Sub-array #2"	In series	20 modules	In parallel	2451 strings
Total number of PV modules	Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power	Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)
Array operating characteristics (50°C)	U mpp	544 V	I mpp	20573 A
Sub-array "Sub-array #3"	In series	20 modules	In parallel	2451 strings
Total number of PV modules	Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power	Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)
Array operating characteristics (50°C)	U mpp	544 V	I mpp	20573 A
Sub-array "Sub-array #4"	In series	20 modules	In parallel	2451 strings
Total number of PV modules	Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power	Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)
Array operating characteristics (50°C)	U mpp	544 V	I mpp	20573 A
Sub-array "Sub-array #5"	In series	20 modules	In parallel	2451 strings
Total number of PV modules	Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power	Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)
Array operating characteristics (50°C)	U mpp	544 V	I mpp	20573 A
Sub-array "Sub-array #6"	In series	20 modules	In parallel	2451 strings
Total number of PV modules	Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power	Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)
Array operating characteristics (50°C)	U mpp	544 V	I mpp	20573 A
Sub-array "Sub-array #7"	In series	20 modules	In parallel	2451 strings
Total number of PV modules	Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power	Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)



Grid-Connected System: Simulation parameters (continued)

Sub-array "Sub-array #8"	In series	20 modules	In parallel	2451 strings
Total number of PV modules	Nb. modules	49020	Unit Nom. Power	255 Wp
Array global power	Nominal (STC)	**12500 kWp**	At operating cond.	11182 kWp (50°C)
Array operating characteristics (50°C)	U mpp	544 V	I mpp	20573 A
Total Arrays global power	Nominal (STC)	**100001 kWp**	Total	392160 modules
	Module area	**644476 m²**	Cell area	558499 m²

Inverter	Model	**Sunny Central 630CP-JP**		
	Manufacturer	SMA		
	Operating Voltage	500-850 V	Unit Nom. Power	630 kW AC

Sub-array "Sub-array #1"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Sub-array "Sub-array #2"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Sub-array "Sub-array #3"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Sub-array "Sub-array #4"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Sub-array "Sub-array #5"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Sub-array "Sub-array #6"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Sub-array "Sub-array #7"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Sub-array "Sub-array #8"	Nb. of inverters	19.0 units	Total Power	11970 kW AC
Total	Nb. of inverters	152	Total Power	95760 kW AC

PV Array loss factors

Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss	Array#1	0.44 mOhm	Loss Fraction	1.5 % at STC
	Array#2	0.44 mOhm	Loss Fraction	1.5 % at STC
	Array#3	0.44 mOhm	Loss Fraction	1.5 % at STC
	Array#4	0.44 mOhm	Loss Fraction	1.5 % at STC
	Array#5	0.44 mOhm	Loss Fraction	1.5 % at STC
	Array#6	0.44 mOhm	Loss Fraction	1.5 % at STC
	Array#7	0.44 mOhm	Loss Fraction	1.5 % at STC
	Array#8	0.44 mOhm	Loss Fraction	1.5 % at STC
	Global		Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	1.5 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05

User's needs : Unlimited load (grid)

Kabd 100 Mw Two axis

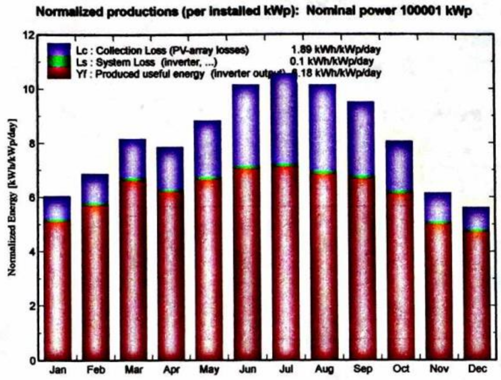
Grid-Connected System: Main results

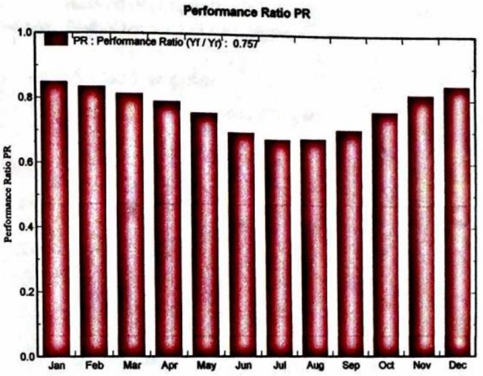
Project : **Kabd 100 Mw Two axis**

Simulation variant : **New simulation variant**

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	Tracking two axis			
PV modules	Model	S 255P60 Professional	Pnom	255 Wp
PV Array	Nb. of modules	392160	Pnom total	**100001 kWp**
Inverter	Model	Sunny Central 630CP-JP	Pnom	630 kW ac
Inverter pack	Nb. of units	152.0	Pnom total	**95760 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**225481 MWh/year**	Specific prod.	2255 kWh/kWp/year
	Performance Ratio PR	75.7 %		



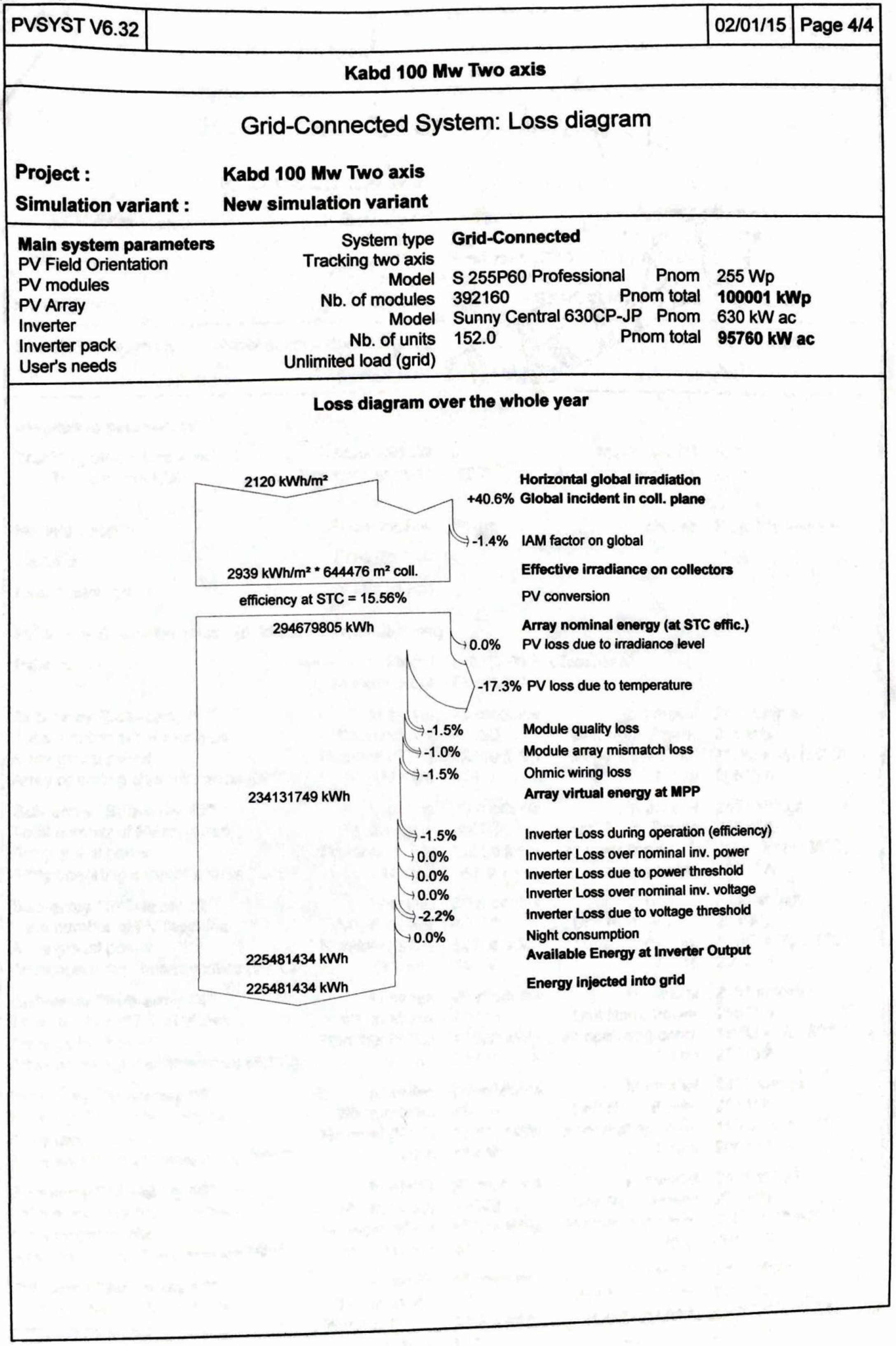


New simulation variant

Balances and main results

	GlobHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	EffArrR %	EffSysR %
January	108.3	13.10	187.2	184.7	16154	15889	13.39	13.17
February	123.5	15.41	192.1	189.3	16312	16042	13.18	12.96
March	175.1	20.13	252.7	249.0	20897	20562	12.83	12.63
April	182.6	26.10	235.8	231.8	18937	18638	12.46	12.26
May	217.7	32.64	273.3	268.7	20985	20664	11.91	11.73
June	243.4	37.09	304.4	300.1	21543	21200	10.98	10.81
July	254.6	38.45	327.5	323.7	22506	22144	10.66	10.49
August	237.3	38.21	314.4	310.6	21683	21342	10.70	10.53
September	202.9	34.19	285.1	281.7	20476	20152	11.15	10.97
October	162.3	28.53	249.8	246.4	19381	19079	12.04	11.85
November	112.1	20.32	184.7	182.1	15346	15093	12.89	12.68
December	99.7	14.67	173.8	171.3	14922	14677	13.32	13.11
Year	2119.5	26.63	2980.6	2939.5	229143	225481	11.93	11.74

Legends:				
GlobHor	Horizontal global irradiation		EArray	Effective energy at the output of the array
T Amb	Ambient Temperature		E_Grid	Energy injected into grid
GlobInc	Global incident in coll. plane		EffArrR	Effic. Eout array / rough area
GlobEff	Effective Global, corr. for IAM and shadings		EffSysR	Effic. Eout system / rough area



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Kabd 100 Mw Two axis

Grid-Connected System: Loss diagram

Project : **Kabd 100 Mw Two axis**

Simulation variant : **New simulation variant**

Main system parameters	System type	**Grid-Connected**		
PV Field Orientation	Tracking two axis			
PV modules	Model	S 255P60 Professional	Pnom	255 Wp
PV Array	Nb. of modules	392160	Pnom total	**100001 kWp**
Inverter	Model	Sunny Central 630CP-JP	Pnom	630 kW ac
Inverter pack	Nb. of units	152.0	Pnom total	**95760 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year

2120 kWh/m² **Horizontal global irradiation**

+40.6% **Global incident in coll. plane**

-1.4% IAM factor on global

2939 kWh/m² * 644476 m² coll. **Effective irradiance on collectors**

efficiency at STC = 15.56% PV conversion

294679805 kWh **Array nominal energy (at STC effic.)**

0.0% PV loss due to irradiance level

-17.3% PV loss due to temperature

-1.5% Module quality loss

-1.0% Module array mismatch loss

-1.5% Ohmic wiring loss

234131749 kWh **Array virtual energy at MPP**

-1.5% Inverter Loss during operation (efficiency)

0.0% Inverter Loss over nominal inv. power

0.0% Inverter Loss due to power threshold

0.0% Inverter Loss over nominal inv. voltage

-2.2% Inverter Loss due to voltage threshold

0.0% Night consumption

225481434 kWh **Available Energy at Inverter Output**

225481434 kWh **Energy injected into grid**

APPENDIX B – A sample from the Numerical Modelling Analysis

A Sample Report for one Case of the Conducted Studies in this Thesis

Global

Global settings

Name	21_2_2017.mph
Path	C:\Users\Abdulla\Desktop\21_2_2017.mph
Program	COMSOL 5.0 (Build: 243)
Unit system	SI

Used products

COMSOL Multiphysics
CAD Import Module
Structural Mechanics Module

Definitions

Parameters 1

Parameters

Name	Expression	Value	Description
theta	30[deg]	0.52360 rad	

Component 1

Component settings

Unit system	SI
Geometry shape order	automatic

Definitions

Coordinate Systems

Chapter 2 Boundary System 1

Coordinate system type	Boundary system
Tag	sys1

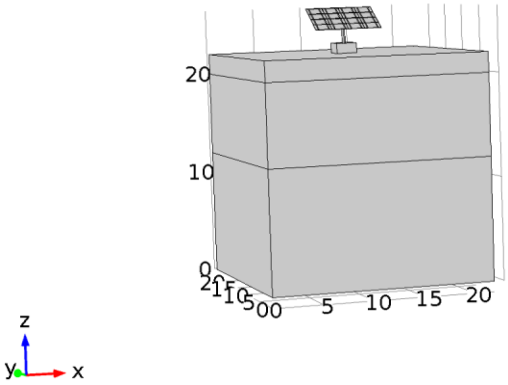
Settings

First (t1)	Second (t2)	Third (n)
t1	t2	n

Settings

Name	Value
Create first tangent direction from	Global Cartesian (spatial)

Geometry 1



Geometry 1

Units

Length unit	m
Angular unit	deg

Geometry statistics

Property	Value
Space dimension	3
Number of domains	34
Number of boundaries	277
Number of edges	541
Number of vertices	294

Block 1 (Soil Layer_1)

Position

Name	Value
Position	{0, 0, 0}

Axis

Name	Value
Axis type	z - axis

Size and shape

Name	Value
Width	22
Depth	22
Height	12

Block 2 (Soil Layer_2)

Position

Name	Value
Position	{0, 0, 12}

Axis

Name	Value
Axis type	z - axis

Size and shape

Name	Value
Width	22
Depth	22
Height	8

Block 3 (Soil Layer_3)

Position

Name	Value
Position	{0, 0, 20}

Axis

Name	Value
Axis type	z - axis

Size and shape

Name	Value
Width	22
Depth	22
Height	2

Work Plane 1

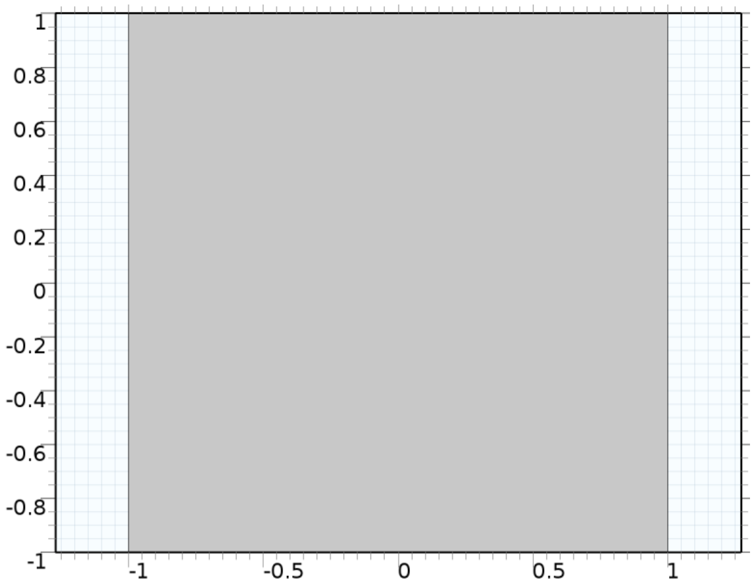
Plane definition

Name	Value
Plane type	Face parallel

Unite objects

Name	Value
Unite objects	On

Chapter 3 Foundation (wp1)



Foundation

Foundation (r1)

Position

Name	Value
Position	{0, 0}
Base	Center

Size

Name	Value
Width	2
Height	2

Extrude 1 (ext1)

Settings

Name	Value
Work plane	Work Plane 1

Distances from plane

Name	Value
Distances	1

Scales

Scales xw	Scales yw
1	1

Displacements

Displacements xw (m)	Displacements yw (m)
0	0

Twist angles

Name	Value
Twist_angles	0

Post (wp2)

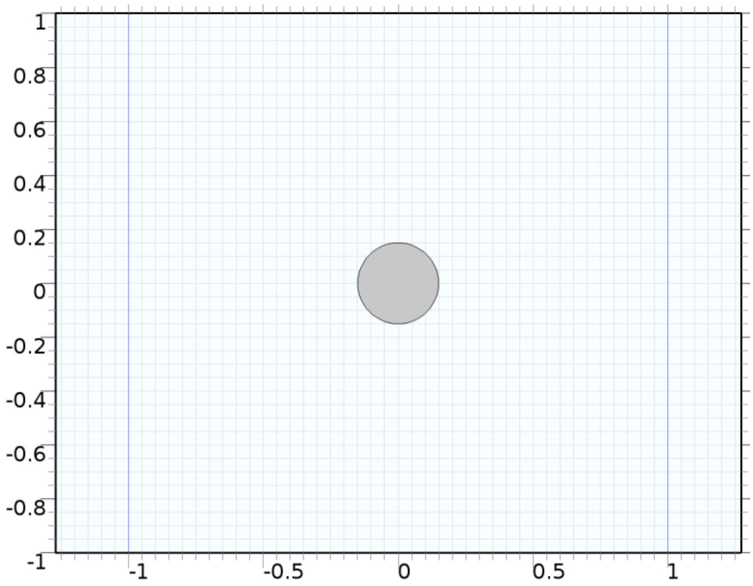
Plane definition

Name	Value
Plane type	Face parallel

Unite objects

Name	Value
Unite objects	On

Plane Geometry (wp2)



Plane Geometry

Circle 1 (c1)

Position

Name	Value
Position	{0, 0}

Size and shape

Name	Value
Radius	0.15

Extrude 2 (ext2)

Settings

Name	Value
Work plane	Post

Distances from plane

Name	Value
Distances	2.7

Scales

Scales xw	Scales yw
1	1

Displacements

Displacements xw (m)	Displacements yw (m)
0	0

Twist angles

Name	Value
Twist_angles	0

Move 1 (mov1)

Selections of resulting entities

Name	Value
x	0
y	0
z	-0.7

Cylinder 1

Position

Name	Value
Position	{10.80, 11, 25.1}

Rotation angle

Name	Value
Rotation	90

Axis

Name	Value
Axis type	x - axis

Size and shape

Name	Value
Radius	0.15
Height	0.4

Block 4 (blk4)

Position

Name	Value
Position	{11, 11, 25.3}
Base	Center

Axis

Name	Value
Axis type	z - axis

Size and shape

Name	Value
Width	6.3
Depth	0.15
Height	0.15

Work Plane 4 (wp4)

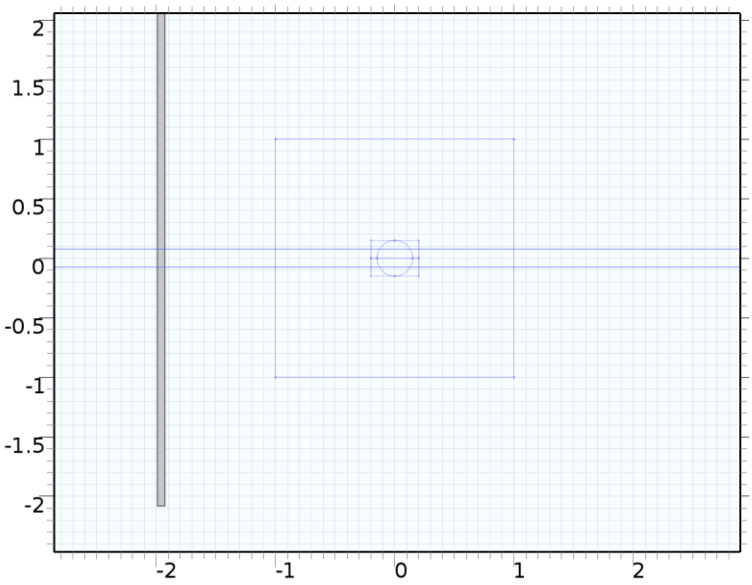
Plane definition

Name	Value
Plane type	Face parallel

Unite objects

Name	Value
Unite objects	On

Plane Geometry (wp4)



Plane Geometry

Rectangle 1 (r1)

Position

Name	Value
Position	{-3.02, 0}
Base	Center

Size

Name	Value
Width	0.06
Height	4.16

Rectangle 2 (r2)

Position

Name	Value
Position	{-1.96, 0}
Base	Center

Size

Name	Value
Width	0.06
Height	4.16

Extrude 4 (ext4)

Settings

Name	Value
Work plane	Work Plane 4

Distances from plane

Name	Value
Distances	0.06

Scales

Scales xw	Scales yw
1	1

Displacements

Displacements xw (m)	Displacements yw (m)
0	0

Twist angles

Name	Value
Twist_angles	0

Work Plane 5 (wp5)

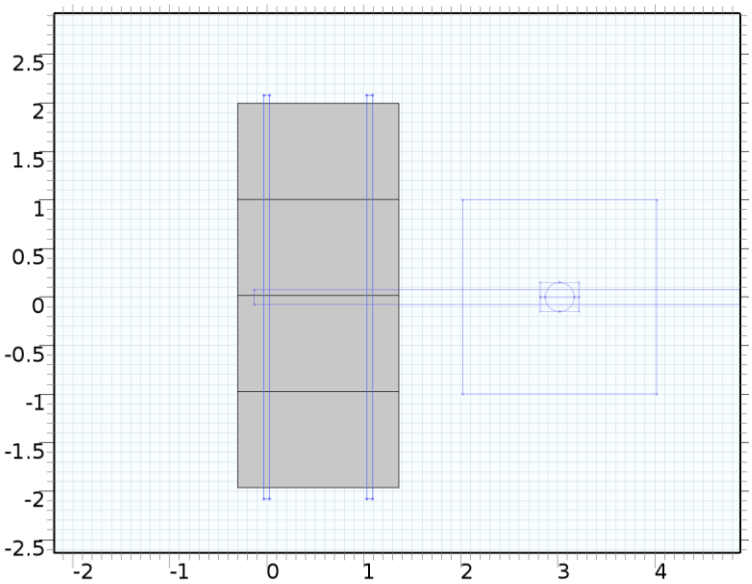
Plane definition

Name	Value
Plane type	Face parallel

Unite objects

Name	Value
Unite objects	On

Plane Geometry (wp5)



Plane Geometry

Rectangle 1 (r1)

Position

Name	Value
Position	{0.53, 1.5}
Base	Center

Size

Name	Value
Width	1.66
Height	0.99

Array 1 (arr1)

Settings

Name	Value
Size	{1, 4}
Full size	{1, 4}
Displacement	{0, -0.99}

Extrude 5 (ext5)

Settings

Name	Value
Work plane	Work Plane 5

Distances from plane

Name	Value
Distances	0.04

Scales

Scales xw	Scales yw
1	1

Displacements

Displacements xw (m)	Displacements yw (m)
0	0

Twist angles

Name	Value
Twist_angles	0

Array 1 (arr1)

Selections of resulting entities

Name	Value
Size	{4, 1, 1}
Full size	{4, 1, 1}
Displacement	{-1.66, 0, 0}

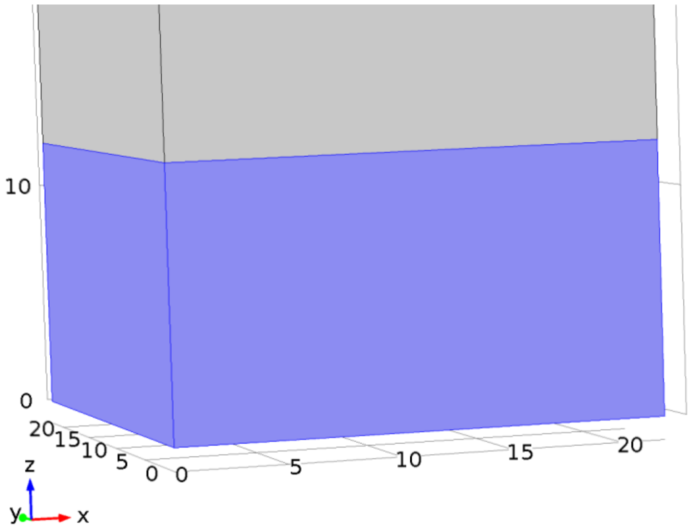
Rotate 1 (rot1)

Selections of resulting entities

Name	Value
Rotation	30
Point on axis of rotation	{11, 11, 25.1}
Axis type	x - axis

Materials

Soil Layer_1



Soil Layer_1

Selection

Geometric entity level	Domain
Selection	Domain 1

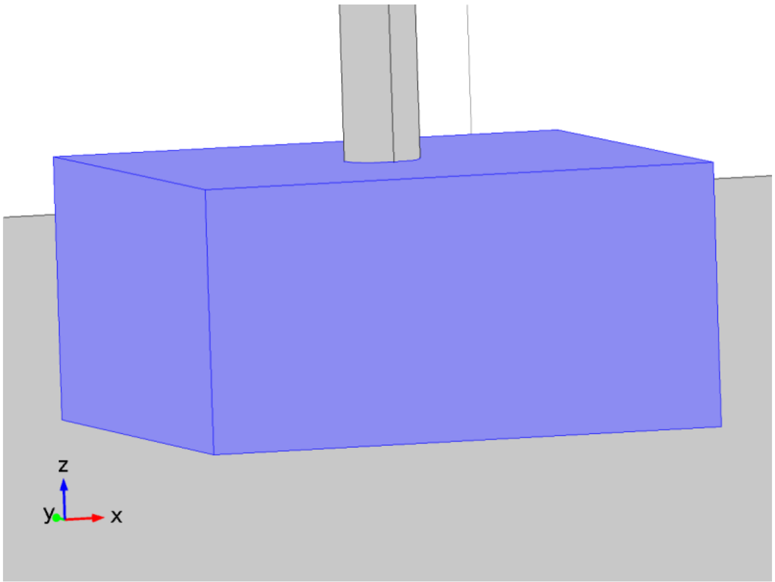
Material parameters

Name	Value	Unit
Young's modulus	1e8	Pa
Poisson's ratio	0.3	1
Density	2140.7	kg/m^3

Basic Settings

Description	Value
Young's modulus	1e8
Poisson's ratio	0.3
Density	2140.7

Concrete



Concrete

Selection

Geometric entity level	Domain
Selection	Domain 16

Material parameters

Name	Value	Unit
Density	2300[kg/m^3]	kg/m^3
Young's modulus	25e9[Pa]	Pa
Poisson's ratio	0.33	1

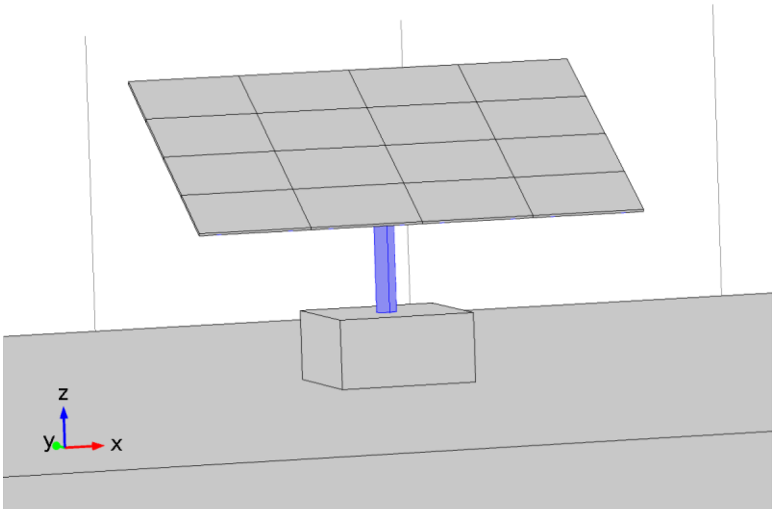
Basic Settings

Description	Value
Coefficient of thermal expansion	{{10e-6[1/K], 0, 0}, {0, 10e-6[1/K], 0}, {0, 0, 10e-6[1/K]}}
Density	2300[kg/m^3]
Thermal conductivity	{{1.8[W/(m*K)], 0, 0}, {0, 1.8[W/(m*K)], 0}, {0, 0, 1.8[W/(m*K)]}}
Heat capacity at constant pressure	880[J/(kg*K)]

Young's modulus and Poisson's ratio Settings

Description	Value
Young's modulus	25e9[Pa]
Poisson's ratio	0.33

Structural steel



Structural steel

Selection

Geometric entity level	Domain
Selection	Domains 8–10, 15, 17–22, 27–28, 33–34

Material parameters

Name	Value	Unit
Heat capacity at constant pressure	475[J/(kg*K)]	J/(kg*K)
Thermal conductivity	44.5[W/(m*K)]	W/(m*K)
Coefficient of thermal expansion	12.3e-6[1/K]	1/K
Density	7850[kg/m^3]	kg/m^3
Young's modulus	200e9[Pa]	Pa
Poisson's ratio	0.33	1

Basic Settings

Description	Value
Relative permeability	{{1, 0, 0}, {0, 1, 0}, {0, 0, 1}}
Heat capacity at constant pressure	475[J/(kg*K)]
Thermal conductivity	{{44.5[W/(m*K)], 0, 0}, {0, 44.5[W/(m*K)], 0}, {0, 0, 44.5[W/(m*K)]}}
Electrical conductivity	{{4.032e6[S/m], 0, 0}, {0, 4.032e6[S/m], 0}, {0, 0, 4.032e6[S/m]}}
Relative permittivity	{{1, 0, 0}, {0, 1, 0}, {0, 0, 1}}
Coefficient of thermal expansion	{{12.3e-6[1/K], 0, 0}, {0, 12.3e-6[1/K], 0}, {0, 0, 12.3e-6[1/K]}}

Description	Value
Density	7850[kg/m^3]

Young's modulus and Poisson's ratio Settings

Description	Value
Young's modulus	200e9[Pa]
Poisson's ratio	0.33

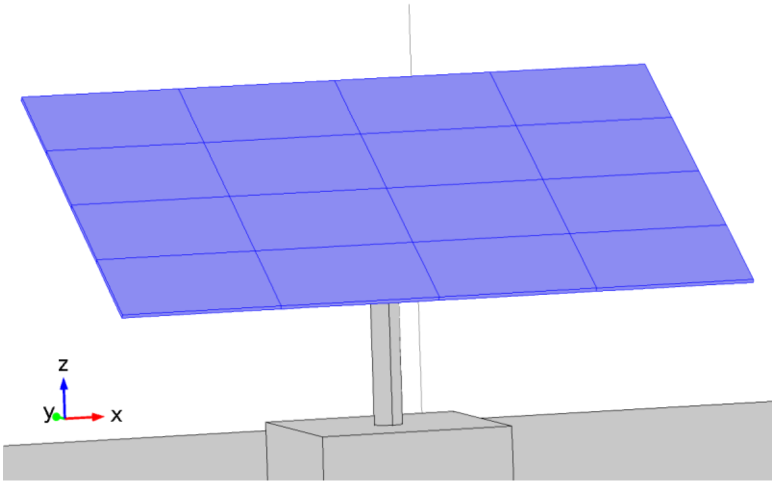
Murnaghan Settings

Description	Value
Murnaghan third-order elastic moduli	-3.0e11[Pa]
Murnaghan third-order elastic moduli	-6.2e11[Pa]
Murnaghan third-order elastic moduli	-7.2e11[Pa]

Lamé parameters Settings

Description	Value
Lamé parameter λ	1.5e11[Pa]
Lamé parameter μ	7.5e10[Pa]

Solar modules



Solar modules

Selection

Geometric entity level	Domain
Selection	Domains 4–7, 11–14, 23–26, 29–32

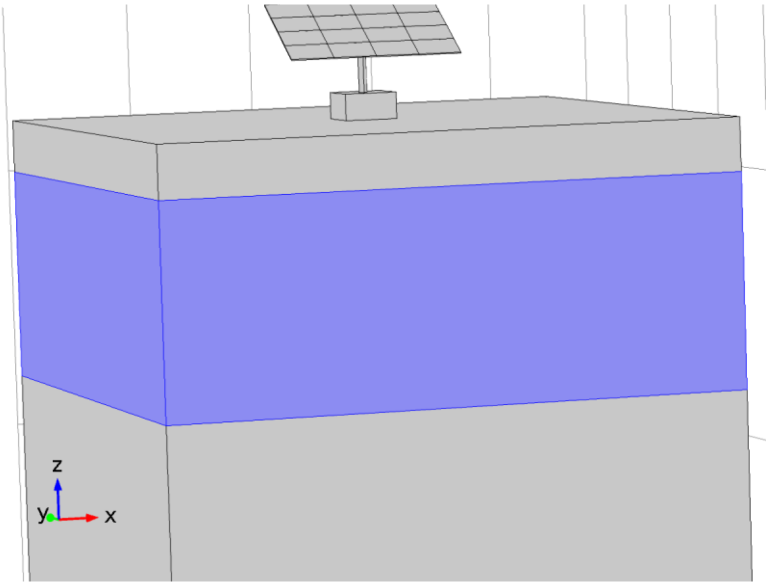
Material parameters

Name	Value	Unit
Young's modulus	3.5e9[Pa]	Pa
Poisson's ratio	0.33	1

Young's modulus and Poisson's ratio Settings

Description	Value
Young's modulus	3.5e9[Pa]
Poisson's ratio	0.33

Soil layer_2



Soil Layer_2

Selection

Geometric entity level	Domain
Selection	Domain 2

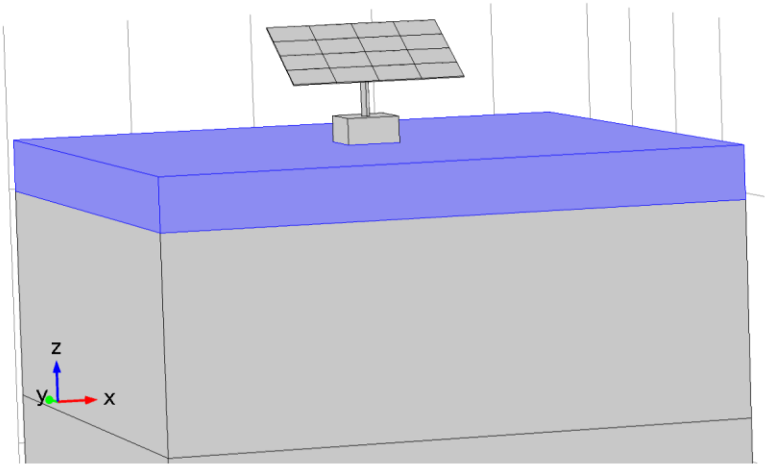
Material parameters

Name	Value	Unit
Young's modulus	4e7	Pa
Poisson's ratio	0.3	1
Density	2038.7	kg/m^3

Basic Settings

Description	Value
Young's modulus	4e7
Poisson's ratio	0.3
Density	2038.7

Soil Layer_3



Soil Layer_3

Selection

Geometric entity level	Domain
Selection	Domain 3

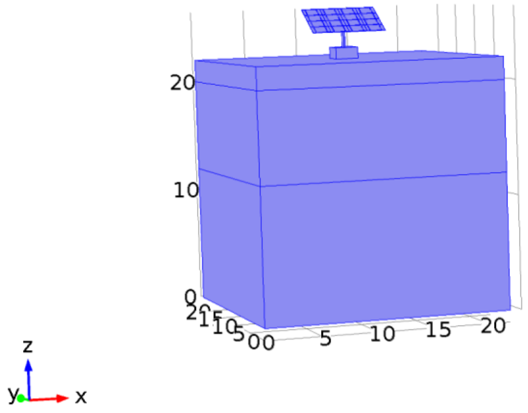
Material parameters

Name	Value	Unit
Young's modulus	1e7	Pa
Poisson's ratio	0.3	1
Density	1963.8	kg/m^3

Basic Settings

Description	Value
Young's modulus	1e7
Poisson's ratio	0.3
Density	1963.8

Solid Mechanics



Solid Mechanics

Selection

Geometric entity level	Domain
Selection	Domains 1–34

Settings

Description	Value
Displacement field	Quadratic
Compute boundary fluxes	Off
Value type when using splitting of complex variables	Complex
Structural transient behavior	Quasi - static
Reference point for moment computation, x component	0
Reference point for moment computation, y component	0
Reference point for moment computation, z component	0
Typical wave speed for perfectly matched layers	solid.cp

Variables

Name	Expression	Unit	Description	Selection
solid.nX	nX	1	Normal vector, X component	Boundaries 6, 9, 19, 23, 27, 40–43, 45, 58–61, 63, 72, 76–77, 80–81, 84–85, 93–96, 98, 109, 116–119, 121, 133–138, 141–143, 146–151, 154, 158–159, 162–163, 166, 168, 170–171, 175–176, 178, 184–187, 189, 203–206, 208, 217, 221–222, 225–226, 229–230, 238–241, 243, 256–259, 261
solid.nY	nY	1	Normal vector, Y component	Boundaries 6, 9, 19, 23, 27, 40–43, 45, 58–61, 63, 72, 76–77, 80–81, 84–85, 93–96, 98, 109, 116–119, 121, 133–138, 141–143, 146–151, 154, 158–159, 162–163, 166, 168, 170–171, 175–176, 178, 184–187, 189, 203–206, 208, 217, 221–222, 225–226, 229–230, 238–241, 243, 256–259, 261
solid.nZ	nZ	1	Normal vector, Z component	Boundaries 6, 9, 19, 23, 27, 40–43, 45, 58–61, 63, 72, 76–77, 80–81, 84–85, 93–96, 98, 109, 116–119, 121, 133–138, 141–143, 146–151, 154, 158–159, 162–163, 166, 168, 170–171, 175–176, 178, 184–187, 189, 203–206, 208, 217, 221–222, 225–226, 229–230, 238–241, 243, 256–259, 261
solid.nX	dnX	1	Normal vector, X component	Boundaries 1–5, 7–8, 10–18, 20–22, 24–26, 28–39, 44, 46–57, 62, 64–71, 73–75, 78–79, 82–83, 86–92, 97, 99–108, 110–115, 120, 122–132, 139–140, 144–145, 152–153,

Name	Expression	Unit	Description	Selection
				155–157, 160–161, 164–165, 167, 169, 172–174, 177, 179–183, 188, 190–202, 207, 209–216, 218–220, 223–224, 227–228, 231–237, 242, 244–255, 260, 262–277
solid.nY	dnY	1	Normal vector, Y component	Boundaries 1–5, 7–8, 10–18, 20–22, 24–26, 28–39, 44, 46–57, 62, 64–71, 73–75, 78–79, 82–83, 86–92, 97, 99–108, 110–115, 120, 122–132, 139–140, 144–145, 152–153, 155–157, 160–161, 164–165, 167, 169, 172–174, 177, 179–183, 188, 190–202, 207, 209–216, 218–220, 223–224, 227–228, 231–237, 242, 244–255, 260, 262–277
solid.nZ	dnZ	1	Normal vector, Z component	Boundaries 1–5, 7–8, 10–18, 20–22, 24–26, 28–39, 44, 46–57, 62, 64–71, 73–75, 78–79, 82–83, 86–92, 97, 99–108, 110–115, 120, 122–132, 139–140, 144–145, 152–153, 155–157, 160–161, 164–165, 167, 169, 172–174, 177, 179–183, 188, 190–202, 207, 209–216, 218–220, 223–224, 227–228, 231–237, 242, 244–255, 260, 262–277
solid.nx	nx	1	Normal vector, x component	Boundaries 6, 9, 19, 23, 27, 40–43, 45, 58–61, 63, 72, 76–77, 80–81, 84–85, 93–96, 98, 109, 116–119, 121, 133–138, 141–143, 146–151, 154, 158–159, 162–163, 166, 168, 170–171, 175–176,

Name	Expression	Unit	Description	Selection
				178, 184–187, 189, 203–206, 208, 217, 221–222, 225–226, 229–230, 238–241, 243, 256–259, 261
solid.ny	ny	1	Normal vector, y component	Boundaries 6, 9, 19, 23, 27, 40–43, 45, 58–61, 63, 72, 76–77, 80–81, 84–85, 93–96, 98, 109, 116–119, 121, 133–138, 141–143, 146–151, 154, 158–159, 162–163, 166, 168, 170–171, 175–176, 178, 184–187, 189, 203–206, 208, 217, 221–222, 225–226, 229–230, 238–241, 243, 256–259, 261
solid.nz	nz	1	Normal vector, z component	Boundaries 6, 9, 19, 23, 27, 40–43, 45, 58–61, 63, 72, 76–77, 80–81, 84–85, 93–96, 98, 109, 116–119, 121, 133–138, 141–143, 146–151, 154, 158–159, 162–163, 166, 168, 170–171, 175–176, 178, 184–187, 189, 203–206, 208, 217, 221–222, 225–226, 229–230, 238–241, 243, 256–259, 261
solid.nx	dnx	1	Normal vector, x component	Boundaries 1–5, 7–8, 10–18, 20–22, 24–26, 28–39, 44, 46–57, 62, 64–71, 73–75, 78–79, 82–83, 86–92, 97, 99–108, 110–115, 120, 122–132, 139–140, 144–145, 152–153, 155–157, 160–161, 164–165, 167, 169, 172–174, 177, 179–183, 188, 190–202, 207, 209–216, 218–220, 223–224, 227–228, 231–237, 242, 244–255, 260, 262–277
solid.ny	dny	1	Normal vector, y	Boundaries 1–5, 7–8,

Name	Expression	Unit	Description	Selection
			component	10–18, 20–22, 24–26, 28–39, 44, 46–57, 62, 64–71, 73–75, 78–79, 82–83, 86–92, 97, 99–108, 110–115, 120, 122–132, 139–140, 144–145, 152–153, 155–157, 160–161, 164–165, 167, 169, 172–174, 177, 179–183, 188, 190–202, 207, 209–216, 218–220, 223–224, 227–228, 231–237, 242, 244–255, 260, 262–277
solid.nz	dnz	1	Normal vector, z component	Boundaries 1–5, 7–8, 10–18, 20–22, 24–26, 28–39, 44, 46–57, 62, 64–71, 73–75, 78–79, 82–83, 86–92, 97, 99–108, 110–115, 120, 122–132, 139–140, 144–145, 152–153, 155–157, 160–161, 164–165, 167, 169, 172–174, 177, 179–183, 188, 190–202, 207, 209–216, 218–220, 223–224, 227–228, 231–237, 242, 244–255, 260, 262–277
solid.nXmesh	root.nXmesh	1	Normal vector (mesh), X component	Boundaries 6, 9, 19, 23, 27, 40–43, 45, 58–61, 63, 72, 76–77, 80–81, 84–85, 93–96, 98, 109, 116–119, 121, 133–138, 141–143, 146–151, 154, 158–159, 162–163, 166, 168, 170–171, 175–176, 178, 184–187, 189, 203–206, 208, 217, 221–222, 225–226, 229–230, 238–241, 243, 256–259, 261
solid.nYmesh	root.nYmesh	1	Normal vector (mesh), Y component	Boundaries 6, 9, 19, 23, 27, 40–43, 45, 58–61, 63, 72, 76–77, 80–81, 84–85, 93–96, 98, 109,

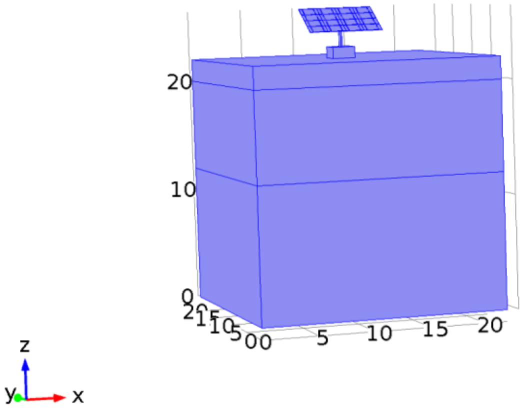
Name	Expression	Unit	Description	Selection
				116–119, 121, 133–138, 141–143, 146–151, 154, 158–159, 162–163, 166, 168, 170–171, 175–176, 178, 184–187, 189, 203–206, 208, 217, 221–222, 225–226, 229–230, 238–241, 243, 256–259, 261
solid.nZmesh	root.nZmesh	1	Normal vector (mesh), Z component	Boundaries 6, 9, 19, 23, 27, 40–43, 45, 58–61, 63, 72, 76–77, 80–81, 84–85, 93–96, 98, 109, 116–119, 121, 133–138, 141–143, 146–151, 154, 158–159, 162–163, 166, 168, 170–171, 175–176, 178, 184–187, 189, 203–206, 208, 217, 221–222, 225–226, 229–230, 238–241, 243, 256–259, 261
solid.nXmesh	root.dnXmesh	1	Normal vector (mesh), X component	Boundaries 1–5, 7–8, 10–18, 20–22, 24–26, 28–39, 44, 46–57, 62, 64–71, 73–75, 78–79, 82–83, 86–92, 97, 99–108, 110–115, 120, 122–132, 139–140, 144–145, 152–153, 155–157, 160–161, 164–165, 167, 169, 172–174, 177, 179–183, 188, 190–202, 207, 209–216, 218–220, 223–224, 227–228, 231–237, 242, 244–255, 260, 262–277
solid.nYmesh	root.dnYmesh	1	Normal vector (mesh), Y component	Boundaries 1–5, 7–8, 10–18, 20–22, 24–26, 28–39, 44, 46–57, 62, 64–71, 73–75, 78–79, 82–83, 86–92, 97, 99–108, 110–115, 120, 122–132, 139–140, 144–145, 152–153, 155–157, 160–161, 164–165, 167, 169,

Name	Expression	Unit	Description	Selection
				172–174, 177, 179–183, 188, 190–202, 207, 209–216, 218–220, 223–224, 227–228, 231–237, 242, 244–255, 260, 262–277
solid.nZmesh	root.dnZmesh	1	Normal vector (mesh), Z component	Boundaries 1–5, 7–8, 10–18, 20–22, 24–26, 28–39, 44, 46–57, 62, 64–71, 73–75, 78–79, 82–83, 86–92, 97, 99–108, 110–115, 120, 122–132, 139–140, 144–145, 152–153, 155–157, 160–161, 164–165, 167, 169, 172–174, 177, 179–183, 188, 190–202, 207, 209–216, 218–220, 223–224, 227–228, 231–237, 242, 244–255, 260, 262–277
solid.nxmesh	root.nxmesh	1	Normal vector (mesh), x component	Boundaries 6, 9, 19, 23, 27, 40–43, 45, 58–61, 63, 72, 76–77, 80–81, 84–85, 93–96, 98, 109, 116–119, 121, 133–138, 141–143, 146–151, 154, 158–159, 162–163, 166, 168, 170–171, 175–176, 178, 184–187, 189, 203–206, 208, 217, 221–222, 225–226, 229–230, 238–241, 243, 256–259, 261
solid.nymesh	root.nymesh	1	Normal vector (mesh), y component	Boundaries 6, 9, 19, 23, 27, 40–43, 45, 58–61, 63, 72, 76–77, 80–81, 84–85, 93–96, 98, 109, 116–119, 121, 133–138, 141–143, 146–151, 154, 158–159, 162–163, 166, 168, 170–171, 175–176, 178, 184–187, 189, 203–206, 208, 217, 221–222, 225–226, 229–230, 238–241, 243, 256–259, 261

Name	Expression	Unit	Description	Selection
solid.nzmesh	root.nzmesh	1	Normal vector (mesh), z component	Boundaries 6, 9, 19, 23, 27, 40–43, 45, 58–61, 63, 72, 76–77, 80–81, 84–85, 93–96, 98, 109, 116–119, 121, 133–138, 141–143, 146–151, 154, 158–159, 162–163, 166, 168, 170–171, 175–176, 178, 184–187, 189, 203–206, 208, 217, 221–222, 225–226, 229–230, 238–241, 243, 256–259, 261
solid.nxmesh	root.dnxmesh	1	Normal vector (mesh), x component	Boundaries 1–5, 7–8, 10–18, 20–22, 24–26, 28–39, 44, 46–57, 62, 64–71, 73–75, 78–79, 82–83, 86–92, 97, 99–108, 110–115, 120, 122–132, 139–140, 144–145, 152–153, 155–157, 160–161, 164–165, 167, 169, 172–174, 177, 179–183, 188, 190–202, 207, 209–216, 218–220, 223–224, 227–228, 231–237, 242, 244–255, 260, 262–277
solid.nymesh	root.dnymesh	1	Normal vector (mesh), y component	Boundaries 1–5, 7–8, 10–18, 20–22, 24–26, 28–39, 44, 46–57, 62, 64–71, 73–75, 78–79, 82–83, 86–92, 97, 99–108, 110–115, 120, 122–132, 139–140, 144–145, 152–153, 155–157, 160–161, 164–165, 167, 169, 172–174, 177, 179–183, 188, 190–202, 207, 209–216, 218–220, 223–224, 227–228, 231–237, 242, 244–255, 260, 262–277
solid.nzmesh	root.dnzmesh	1	Normal vector (mesh), z component	Boundaries 1–5, 7–8, 10–18, 20–22, 24–26, 28–39, 44, 46–57, 62,

Name	Expression	Unit	Description	Selection
				64–71, 73–75, 78–79, 82–83, 86–92, 97, 99–108, 110–115, 120, 122–132, 139–140, 144–145, 152–153, 155–157, 160–161, 164–165, 167, 169, 172–174, 177, 179–183, 188, 190–202, 207, 209–216, 218–220, 223–224, 227–228, 231–237, 242, 244–255, 260, 262–277
solid.refpntx	0	m	Reference point for moment computation, x component	Global
solid.refpnty	0	m	Reference point for moment computation, y component	Global
solid.refpntz	0	m	Reference point for moment computation, z component	Global
solid.cref	solid.cp	m/s	Typical wave speed for perfectly matched layers	Domains 1–34
xt	d(x,TIME)	m/s	Mesh velocity, x component	Global
yt	d(y,TIME)	m/s	Mesh velocity, y component	Global
zt	d(z,TIME)	m/s	Mesh velocity, z component	Global

Linear Elastic Material 1



Linear Elastic Material 1

Selection

Geometric entity level	Domain
Selection	Domains 1–34

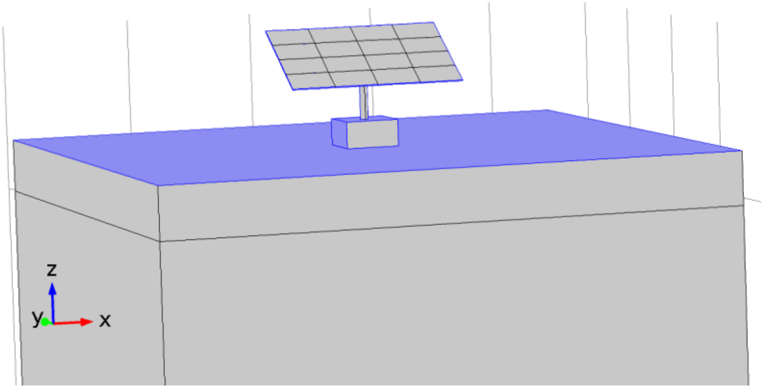
Settings

Description	Value
Solid model	Isotropic
Force linear strains	Off
Nearly incompressible material	Off
Specify	Young's modulus and Poisson's ratio
Calculate dissipated energy	Off
Young's modulus	From material
Poisson's ratio	From material
Elasticity matrix	{{0, 0, 0, 0, 0, 0}, {0, 0, 0, 0, 0, 0}, {0, 0, 0, 0, 0, 0}, {0, 0, 0, 0, 0, 0}, {0, 0, 0, 0, 0, 0}, {0, 0, 0, 0, 0, 0}}
Elasticity matrix, Voigt notation	{{0, 0, 0, 0, 0, 0}, {0, 0, 0, 0, 0, 0}, {0, 0, 0, 0, 0, 0}, {0, 0, 0, 0, 0, 0}, {0, 0, 0, 0, 0, 0}, {0, 0, 0, 0, 0, 0}}
Density	From material

Properties from material

Property	Material	Property group
Young's modulus	Material 1	Basic
Poisson's ratio	Material 1	Basic
Density	Material 1	Basic
Young's modulus	Concrete	Young's modulus and Poisson's ratio
Poisson's ratio	Concrete	Young's modulus and Poisson's ratio
Density	Concrete	Basic
Young's modulus	Structural steel	Young's modulus and Poisson's ratio
Poisson's ratio	Structural steel	Young's modulus and Poisson's ratio
Density	Structural steel	Basic
Young's modulus	Si - Polycrystalline Silicon	Young's modulus and Poisson's ratio
Poisson's ratio	Si - Polycrystalline Silicon	Young's modulus and Poisson's ratio
Density	Si - Polycrystalline Silicon	Basic
Young's modulus	Material 5	Basic
Poisson's ratio	Material 5	Basic
Density	Material 5	Basic
Young's modulus	Material 6	Basic
Poisson's ratio	Material 6	Basic
Density	Material 6	Basic

Free 1

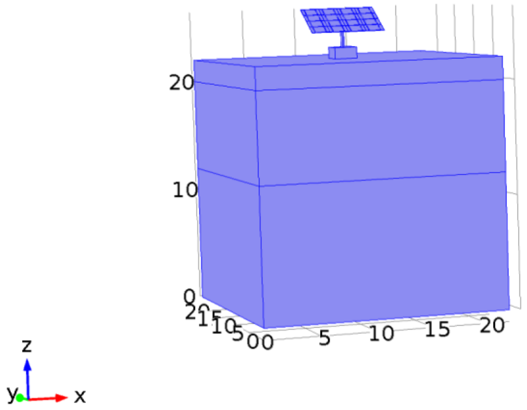


Free 1

Selection

Geometric entity level	Boundary
Selection	Boundaries 10, 14–15, 17–18, 21–22, 25–26, 29–39, 44, 46–57, 62, 64–71, 73, 75, 79, 83, 87–92, 97, 99–107, 110–115, 120, 122–132, 139–140, 145, 152–153, 155, 157, 161, 165, 169, 173–174, 177, 179–183, 188, 190–202, 207, 209–216, 218, 220, 224, 228, 232–237, 242, 244–255, 260, 262–274

Initial Values 1



Initial Values 1

Selection

Geometric entity level	Domain
Selection	Domains 1–34

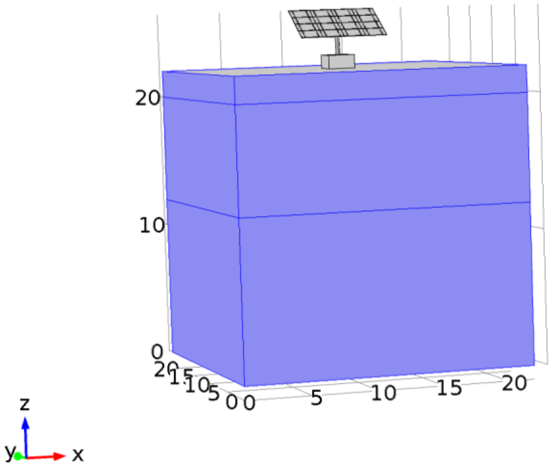
Settings

Description	Value
Displacement field	{0, 0, 0}
Structural velocity field	{0, 0, 0}

Variables

Name	Expression	Unit	Description	Selection
solid.uInitx	0	m	Initial value of displacement, x component	Domains 1–34
solid.uInity	0	m	Initial value of displacement, y component	Domains 1–34
solid.uInitz	0	m	Initial value of displacement, z component	Domains 1–34
solid.utInitx	0	m/s	Initial value of structural velocity, x component	Domains 1–34
solid.utInity	0	m/s	Initial value of structural velocity, y component	Domains 1–34
solid.utInitz	0	m/s	Initial value of structural velocity, z component	Domains 1–34

Roller 1



Roller 1

Selection

Geometric entity level	Boundary
Selection	Boundaries 1–2, 4–5, 7–8, 11–13, 275–277

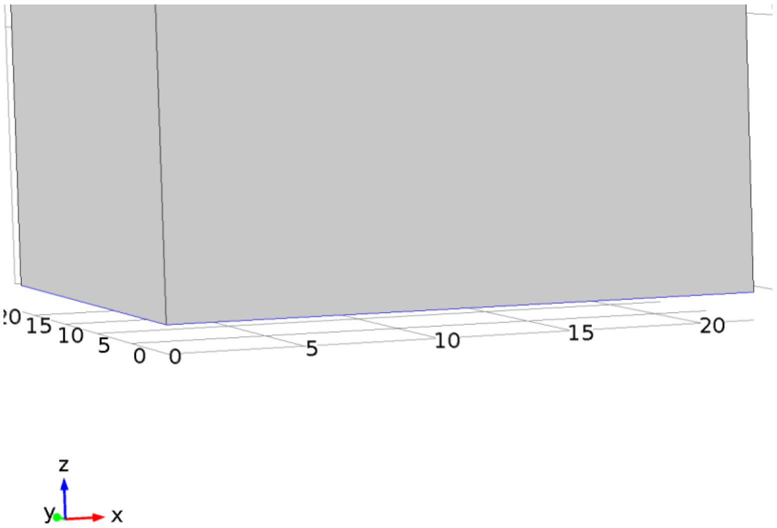
Settings

Description	Value
Apply reaction terms on	All physics (symmetric)
Use weak constraints	Off
Constraint method	Elemental

Shape functions

Constraint	Constraint force	Shape function	Selection
-solid.nX*u-solid.nY*v-solid.nZ*w	test(-solid.nX*u-solid.nY*v-solid.nZ*w)	Lagrange (Quadratic)	Boundaries 1–2, 4–5, 7–8, 11–13, 275–277

Fixed Constraint 1



Fixed Constraint 1

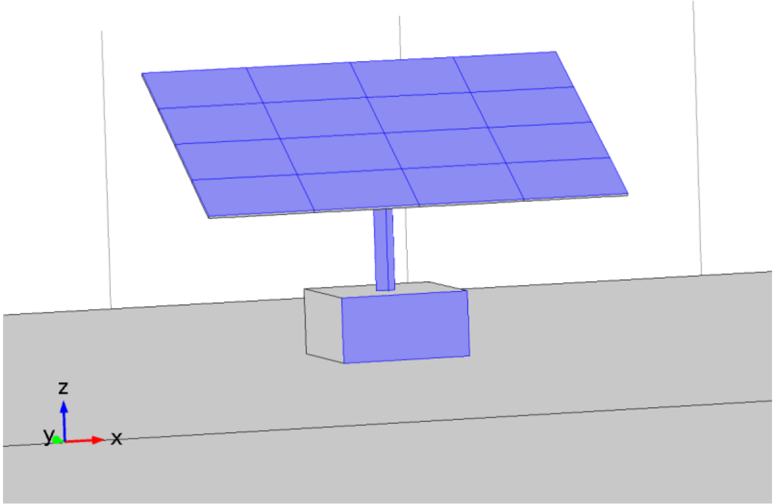
Selection

Geometric entity level	Boundary
Selection	Boundary 3

Shape functions

Constraint	Constraint force	Shape function	Selection
-u	test(-u)	Lagrange (Quadratic)	Boundary 3
-v	test(-v)	Lagrange (Quadratic)	Boundary 3
-w	test(-w)	Lagrange (Quadratic)	Boundary 3

Boundary Load 1



Boundary Load 1

Selection

Geometric entity level	Boundary
Selection	Boundaries 16, 20, 24, 28, 74, 78, 82, 86, 108, 144, 156, 160, 164, 167, 172, 219, 223, 227, 231

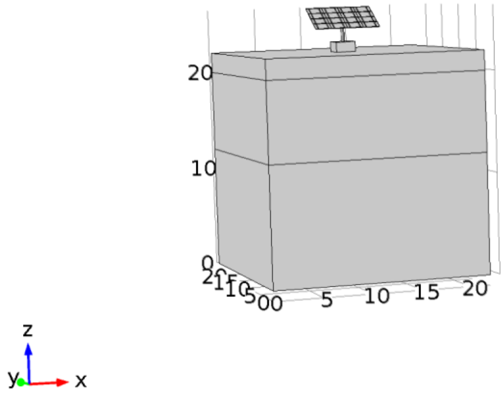
Settings

Description	Value
Load type	Load defined as force per unit area
Load	User defined
Load	{0, 614, 0}

Mesh 1

Mesh statistics

Property	Value
Minimum element quality	0.0
Average element quality	0.0



Mesh 1

Size (size)

Settings

Name	Value
Maximum element size	2.11
Minimum element size	0.264
Curvature factor	0.5
Resolution of narrow regions	0.6
Maximum element growth rate	1.45
Predefined size	Fine

Free Tetrahedral 1 (ftet1)

Selection

Geometric entity level	Remaining

Study 1

Parametric Sweep

Parameter name	Parameter value list
theta	range(0,15,75)

Stationary

Study settings

Property	Value
Include geometric nonlinearity	Off

Physics and variables selection

Physics interface	Discretization
Solid Mechanics (solid)	physics
Heat Transfer in Solids (ht)	physics

Mesh selection

Geometry	Mesh
Geometry 1 (geom1)	mesh1

Solver Configurations

Solution 1

Compile Equations: Stationary (st1)

Study and step

Name	Value
Use study	Study 1
Use study step	Stationary

Dependent Variables 1 (v1)

General

Name	Value
Defined by study step	Stationary

Initial values of variables solved for

Name	Value
Solution	Zero

Values of variables not solved for

Name	Value
Solution	Zero

Displacement field (Material) (comp1.u) (comp1_u)

General

Name	Value
Field components	{comp1.u, comp1.v, comp1.w}

Stationary Solver 1 (s1)

General

Name	Value
Defined by study step	Stationary

Results while solving

Name	Value
Probes	None

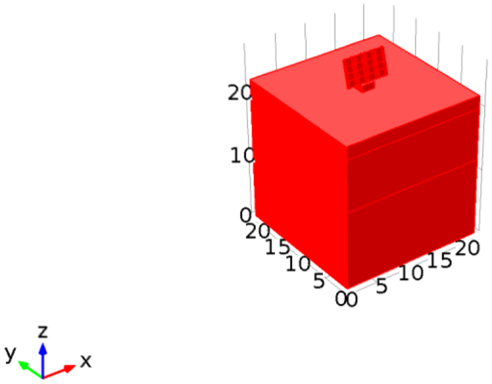
Results

Data Sets

Study 1/Solution 1

Solution

Name	Value
Solution	Solution 1
Component	Save Point Geometry 1

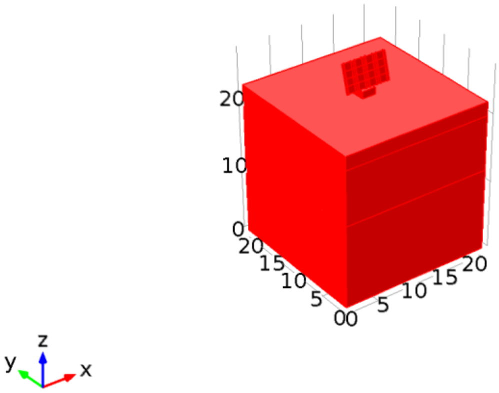


Data set: Study 1/Solution 1

Study 1/Parametric Solutions 1

Solution

Name	Value
Solution	Parametric Solutions 1
Component	Save Point Geometry 1



Data set: Study 1/Parametric Solutions 1

Derived Values

Surface Maximum 1

Selection

Geometric entity level	Boundary
Selection	Boundary 10

Data

Name	Value
Data set	Study 1/Parametric Solutions 1

Expression

Name	Value
Expression	solid.mises
Unit	kPa
Description	von Mises stress