QATAR UNIVERSITY

COLLEGE OF ENGINEERING

TECHNO-ECONOMIC ANALYSIS OF USING SOLAR PV SYSTEM FOR AUXILIARY POWER IN A POWER PLANT

BY

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ABSTRACT

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Title: Techno-Economic Analysis of Using Solar PV System for Auxiliary Power in a Power Plant

Supervisor of Project: Prof. Shaligram Pokharel.

Qatar considered among the countries with the largest per capita electricity consumption. Most of the electricity in Qatar generated in power plants, which use natural gas as the fuel. Qatar has initiated plans to utilize renewable energies to produce 20% of electricity needs by 2030.

In this study, the feasibility of using electricity generated by a solar PV system in a power plant is studied through technical and economic analysis. The solar PV system is designed to produce about 15 MW of electricity to feed the power plant auxiliary systems.

In this study, a collection of data on power consumption, gas consumption, irradiation and area available for installing solar PV was used to size the maximum capacity of the solar system. Then the cost of installing and utilizing the solar PV system is analyzed. This cost analysis was carried out by first calculating the investment cost of the proposed design and the net present value (NPV). The net present value calculations were done for different scenarios. The first scenario is increasing power plant power capacity. The second scenario is KAHARAMAA to invest 15%, and the third scenario is KAHRAMAA to introduce support initiatives by increasing the cost of electricity by 15 %. The fourth scenario is selling the gas surplus globally. The net present value of all scenarios was found as -$32,717,799, -$23,100,399, -$26,797,148, and $1,353,192 respectively. The study concludes that a solar PV system in Qatar is technically feasible, but a support initiative should be considered. This is due to the low current prices of natural gas and electricity tariffs.

This project recommends increasing electricity prices to reflect its actual economic cost. Moreover, the government, along with the power plants, shall invest in utilizing a solar PV system in power plants to reduce gas consumption. So that the saved gas can be exported for income. Those recommendations are proposed to make renewable energy technology adoption in Qatar more feasible.

DEDICATION

I dedicate this project to my wife and my two kids. Whom without their support, patience and understanding, the completion of this work would not been possible.

ACKNOWLEDGMENTS

I want to express my gratitude to my supervisor Prof. Shaligram Pokharel for his guidance, encouragement, and support. He contributed a great deal of time to the development of this project; his knowledge and advice have helped me develop both academically and as an individual.

I want to express my respect and appreciation to the instructors and staff of Qatar University for all their hard work and dedication, providing me with the means to complete my degree. I would also like to thank my friends and colleagues for their assistance and significant support.

I am grateful to my family for unlimited support. None of this would have been possible without the loving support, inspiration, and motivation of my lovely wife.

Finally, I acknowledge that this work was solely done by myself, although some of the data used in the project based on the company where I work.

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Chapter 1: Introduction

1.1. Background

Qatar heavily depends on natural gas for energy. Most of the power produced in Qatar is coming from gas-operated power plants. In 2016, natural gas consumption reached 348,174 Tons, growing 85% from the 2012 level. The current power plant capacity is 11,000 MW. The electricity generation and consumption in 2017 reached about 46,000 GWh and 43,000 GWh, respectively. Figures 1.1 and 1.2 show the electricity generation and consumption from 2013 to 2017 (KAHRAMAA, 2017).

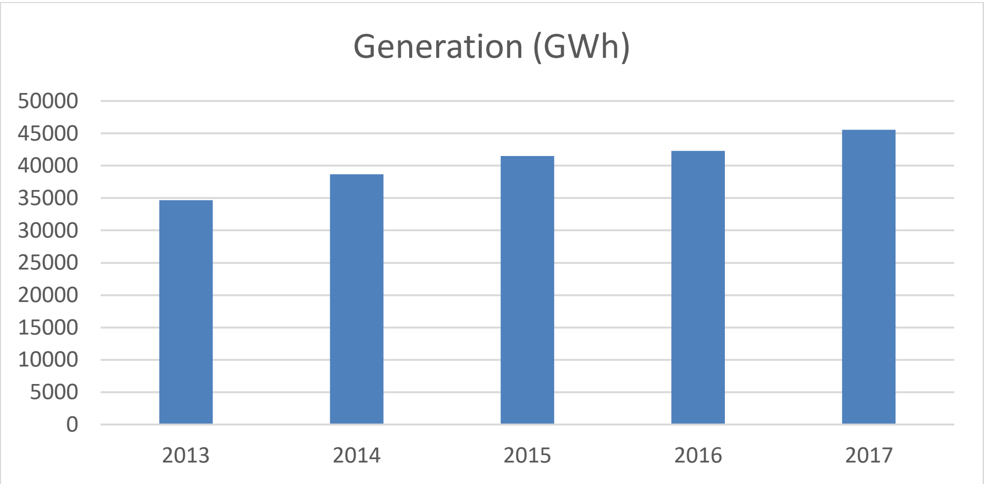

Figure 1.1: Electricity generation in Qatar.

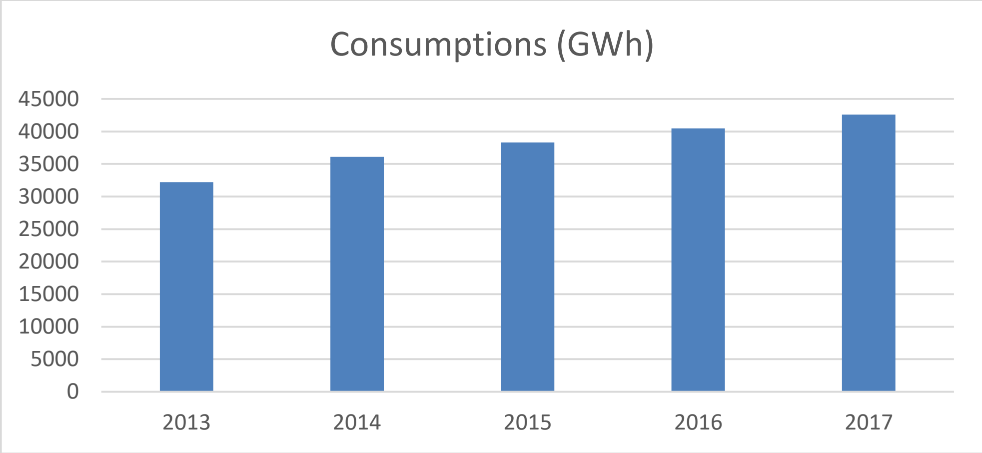

Figure 1.2: Electricity consumption in Qatar.

Electricity consumption in Qatar has grown recently, but this has also resulted in releasing higher pollution (Gastli et al., 2013). Therefore, the utilization of renewable sources in the production of power will be useful in that it will reduce natural sources consumption and reducing CO_2 emissions. In December 2013, it was announced that Qatar would generate 2% of the total energy from renewable energy by 2020. This announcement comes under the Qatar National Vision (QNV 2030), which indicates to increase the investments in the human, social, environment, and economic development and reduce the dependencies on hydrocarbon energy.

1.2. Objectives and scope

The objective of this project is to study the utilization solar photovoltaic PV system in a power plant to provide power for the auxiliary system. Therefore, the main objectives of the project are:

1. To understand the level of electricity use for auxiliary power in the power plan and the possibility of replacing the auxiliary power by the solar PV

based power for daylight consumption.

2. To study the technical feasibility and cost of using solar energy in an electricity generation plant, and;
3. To recommend measures for promoting the installation of solar energy in Qatar.

1.3. Methodology

The following steps are used to complete the project:

- Analyzing power consumption for the auxiliary system.
- Analyzing natural gas consumption used to power the auxiliary system.
- Carry out a technical analysis to size the solar PV system.
- Providing cost analysis for the solar system that includes the costs of installation and operation and maintenance activities.
- Carry out an economic and environmental analysis to study the possible benefits of utilizing a solar PV system.

1.4. Project Outline

In the first chapter, the project is introduced, and objectives are highlighted. In Chapter 2, a literature review is provided. In Chapter 3, the analysis methodology is given, and the data needed are identified. In Chapter 4, the case study is described, and the analysis of the collected data is presented. The technical and economic analysis of the solar system is given in Chapter 5. The conclusions and recommendations are given in the final chapter.

Chapter 2: Literature Review

A literature review is conducted in this study by obtaining the published resources from the university library database. One of the methods for obtaining the literature for the focus of the study is to use content analysis, as suggested in Rebeeh et al. (2019), Caunhye et al. (2012), Pokharel and Mutha (2019). The keyword search is used in ScienceDirect, EmeraldInsight, Wiley and Taylor and Francis journal databases, and the relevant literatures were extracted. The keywords used for the extraction were solar energy, PV system, economic analysis, technical analysis, solar grid system, and solar system. The resulting literatures have been grouped and discussed in the following sections.

2.1. Solar PV System

Photovoltaic (PV) systems are power systems devices made to convert sunlight to electricity without any needs of machines or moving parts. These systems generate clean, reliable energy without the need for fossil fuel, which has the advantage of increasing the income and improving environmental conditions. Solar PV is used in many applications such as powering remote areas, communications, space systems, and as a power plant for regular grid connection.

Generally, solar PV systems can be differentiated under three categories: on-grid system, off-grid system, and hybrid system.

2.1.1. On-grid System

In an On-grid PV system, or grid-connected PV, electricity generated by the solar system is relayed to the grid system for transmission to the utility. In some of these systems, the owner consumes a small part or most of the energy and relays the excess electricity onto the utility grid instead of sorting it with batteries.

In such a system, batteries and other stand-alone equipment are not required, which decreases the cost of purchasing such equipment as well as their maintenance and makes on-grid cheaper and simpler to install.

The components of on-grid systems are limited to Grid-Tie Inverter (GTI) or Micro invertors, and power meter (Kumar and Moses, 2018)

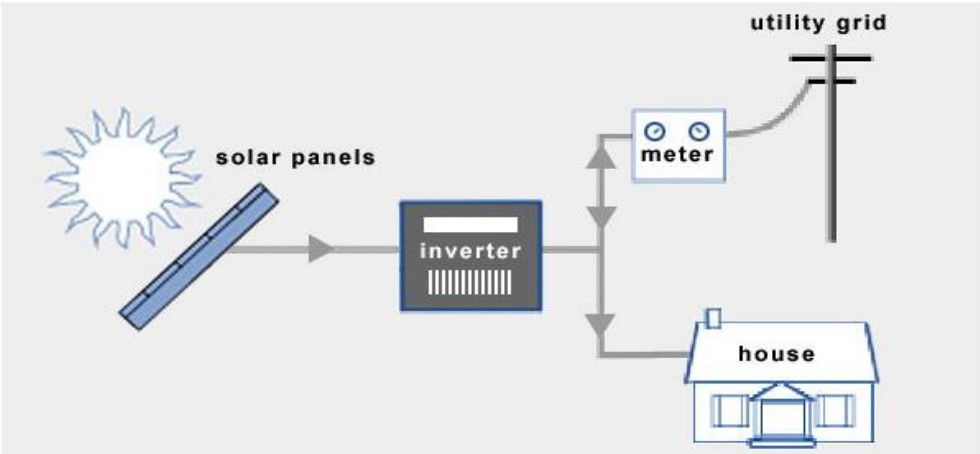

Figure 2.1: On grid solar PV system.

2.1.2. Off grid System

Off-grid PV system is the entirely a substitute for utility grid, in rural areas, highly priced power grids or even when the user has no access to the utility grid for one reason or another.

Despite of its advantages of the elimination of utility grid, securing an access to electricity at all times requires a battery bank for energy storage, which typically needs to be replaced after a period of time, as well as the necessary maintenance for the whole system, for batteries are complicated, expensive and decrease the overall system efficiency.

Typical off-grid PV system requires a group of equipment; solar charge controller, batter bank, DC Disconnect and off-grid inverter (Alkhalidi, 2018).

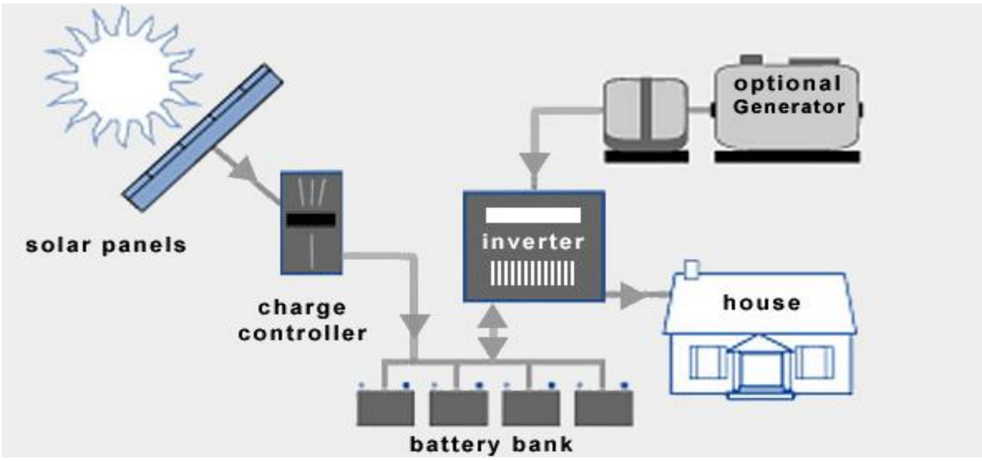

Figure 2.2: Off grid solar PV system.

2.1.3. Hybrid PV System

Hybrid PV system combines the best from on-grid & off-grid systems, it allows storing solar electric power in a battery bank system for using in the case of losing the utility grid service. Hybrid PV system can either be described as off-grid PV with utility backup power, on-grid PV with extra batter storage. Besides being considered as smart a promising system, hybrid system is less expensive than off-grid solar systems (Energy informative, 2012)

The main equipment needed to function such a system are; charge controller, battery bank, DC disconnector, battery-based grid-tie inverter, and power meter.

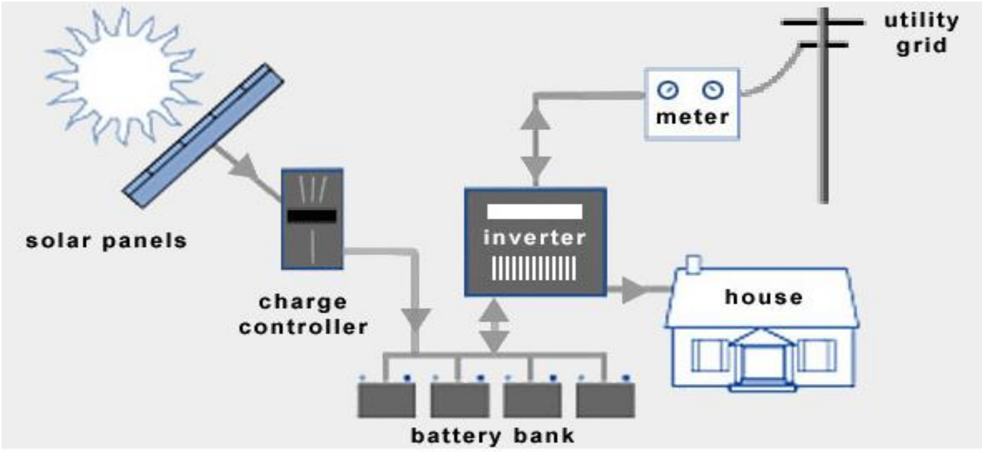

Figure 2.3: Hybrid solar PV system.

2.2. PV System Components

2.2.1. Modules

Solar PV module consists of various interconnected solar cells (Alkhalidi, 2018). As modules are installed as a system of an exact layout, and this layout is called an array. Arrays are in turn can be connected parallel or series such as modules and cells.

For PV modules characteristics Standard Test Conditions (STC) values are considered, which are considered in terms of 1000 W/m^2. For the test condition, a temperature of 25^{0}C is considered.

2.2.1.1 Irradiance:

Power is calculated as the product of voltage (V) and current (I). The IV curve of PV modules for different conditions of irradiance is given in Figure 2.4. Higher irradiance can boost voltage, which can take place when there is clear sky with lighter air mass for direct sunlight, and PV surrounding bodies reflect solar light rather than absorbing it.

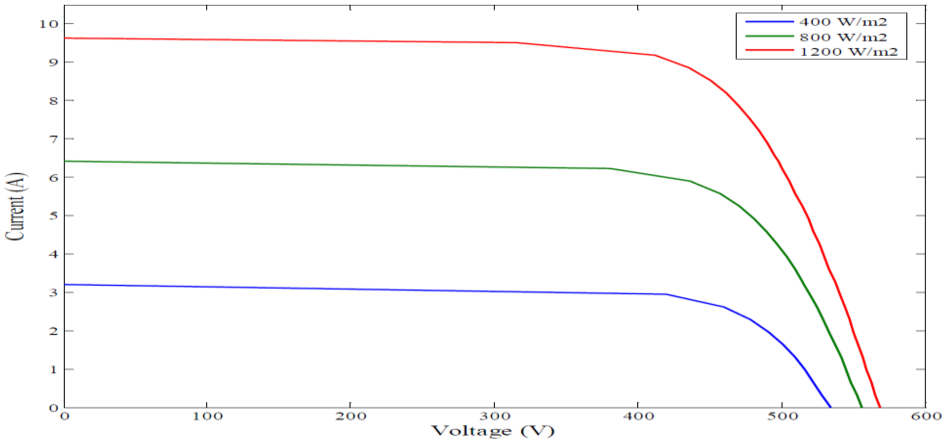

Figure 2.4: The effect of varying solar radiation on voltage and current. (Darwish, 2014)

2.2.1.2 Cell Temperature:

The effect of temperature refers to the inherent characteristics of the material that PV modules are manufactured from, i.e., crystalline silicon cells. According to its physical characteristics, a silicon cell tends to function more efficiently, i.e. produce higher voltage at low temperature degrees, and vice versa.

Charge controllers and on-grid inverters, for example, as well as all other related PV system components must be designed and their sizes calculated to have adjustments necessary to deal with such temperature effects, and to handle possible current spikes from the PV array under the effect of irradiance and temperature effects. (Store, 2010).

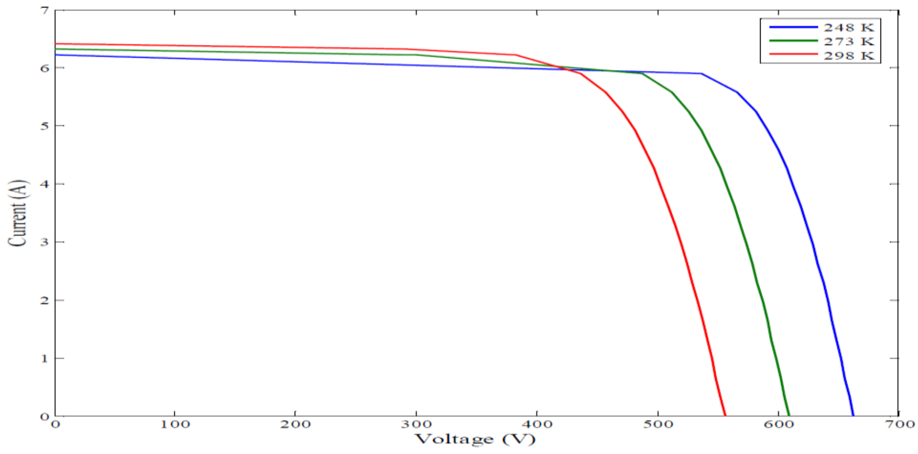

Figure 2.5: The effect of varying temperature on voltage and current. (Darwish, 2014)

There are several other factors that effects the behaviour of solar module such as air mass, air pollutants, and nearby water availability, but shall not be discussed as it is beyond project scope. The factors irradiance and cell temperature shall be considered as both are the main factors that affect solar module behaviour.

2.2.2. Inverters

The role that inverter plays is to convert the variable direct current DC output of a photovoltaic solar system into utility alternating current AC, where AC current is the standard used by all kinds of commercial and residential demands (Kumar and Moses, 2018).

There are two main types of inverters string and central inverters. String inverters can be used to combine solar panels with much ease by using connective strings (Trina Solar, 2018).

Central inverters can handle many panels of strings and are integrated together for DC to AC conversion. They require fewer component connections than string inverters, however, they require a pad and combiner box. (Zipp, 2016)

Most of the inverters nowadays have a high efficiency regardless of the type, however, some differences are there when device functionality and installation is important. Central inverters have advantage when there are large number of strings in the system as several strings can be attached to one central inverter rather than each string connected to single inverter, this will reduce the number of inverters in the system. Moreover, when it comes to large solar PV systems (MW), central inverters are frequently used for its capability to handle the system (Armbruster et al., 2010). On the other hand, string inverters are more suitable for small to medium solar PV system as the number of strings are low. When it comes to the cost, purchase / installation cost is high for central inverters and low for string inverters but, for components connection, central inverters tend to have fewer connection so lower cost and string inverters tend to have more connection so higher cost.

Table 2.1: Comparsion between central and string inverters. (The Solar Report, 2014).

Parameter	Type	Advantages	Disadvantages
Cost	**Central**	- Lower DC watt unit cost - Fewer component connections.	- Higher installation cost. - Higher DC wiring and combiner costs. - Larger inverter Pad footprint.
	String	- Lower system costs. - Lower ongoing maintenance costs. - Simpler design for limited inverter pad spaces.	- Higher DC watt unit cost. - More component connections. - More distributed space for mounting inverters.
Efficiency	**Central**	- More suitable for large system with constant production across arrays. - Proven field reliability.	- Less suitable for systems with different array angles and/or orientations.
	String	- Better modularity with different array angles and/or orientations. - Fewer arrays are affected with one inverter failure.	- Newer and less field-tested product.

2.2.3. Transformers

Transformer is a static device, transforming power from one source to another without changing frequency. Large plants are connected with step-up transformers in order to transmit power to the transmission system, therefore, sizing based on peak of PV plant becomes important (Testa et al., 2013).

Although step-up transformers in general conditions are used for medium voltage (Zhao et al., 2010) for power plants, they are integral and important part in the solar based systems (Testa et al., 2013). In general, there are different types of solar transformers including distribution, station, sub-station, pad mounted and grounding, where all types have specialized need affecting the cost.

2.2.4. Mounting System

Solar PV systems are usually installed on rooftops, which is considered appropriate option allowing PV arrays to receive sufficient solar rays without be troubled with any kind or barriers, as well as not to consume required areas for the purpose of installing relatively large solar PV arrays. Mounting systems should comply with engineering and technical specifications, so they meet two basic criteria:

1- To ensure the stability and strength of the placement of different components of PV System.

2- To ensure avoiding any damage of any of the PV system's components as a result of poor handling during the installation process.

Rooftop mounting systems are not the only type of mounting used, according to several circumstances, PV systems may be mounted on ground, for the purpose of the installation of utility PV plant, for example. It is necessary to determine the best choice regarding the mounting type according to the available needs and circumstances.

2.3. PV Cell Materials

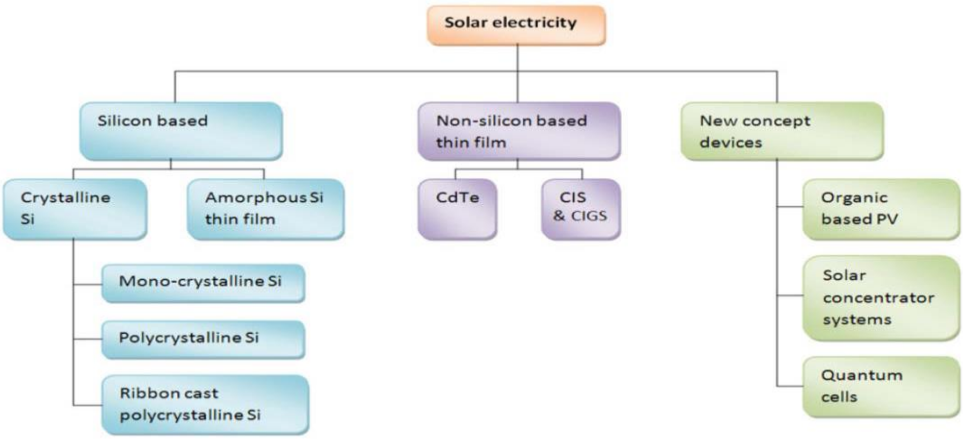

Figure 2.6: Solar PV cell materials type. (Jelle, Breivik, & Røkenes, 2012)

2.3.1. Mono crystalline solar cells

Mono crystalline solar cells called also Si-mono provide the best performance under the STC conditions. However, high temperature levels decrease Si-mono cells efficiency (Bhubaneswari and Iniyan, 2011). The efficiency for this type of PV is between 13% and 17%. While the expected lifespan is 25-30 years, the efficiency degrades over the years (Čotar, 2012).

2.3.2. Poly crystalline solar cells

Poly crystalline solar cells called also Si-poly, consisted of small crystals of the shape of a crystal grain, known as crystallites. Si-poly are produced by sawing a square cast block of silicon into bars firstly, and wafers finally. Like Si-mono cells, Si-poly cells' best performance takes place at the STC, and its efficiency decreases in the case of high temperature. The efficiency for this type of PV ranges between 10% and 14%. While the expected lifespan is 20-25 years, degrading over the years (Čotar, 2012).

2.3.3. Thin Film

This type of cells is manufactured by "piling extremely thin layers of photosensitive materials on a cheap substrate such as glass, stainless steel or plastic". Crystalline silicon cell is more intense and efficient; however, thin-film technology has been developed in order to reduce costs of PV system manufacturing compared with crystalline silicon technology. However, this leads to a sacrifice in efficiency, which is generally between 5% and 13%. While the expected lifespan is 15-20 years, the efficiency degrades over the years (Čotar, 2012).

2.4. Solar PV System Cost Trends

Figure 2.7 shows the percentage of each parameter from the total cost in a solar PV installation. The modules have the highest value that counts about 50% of the total cost, then comes the costs of installation, and the inverters.

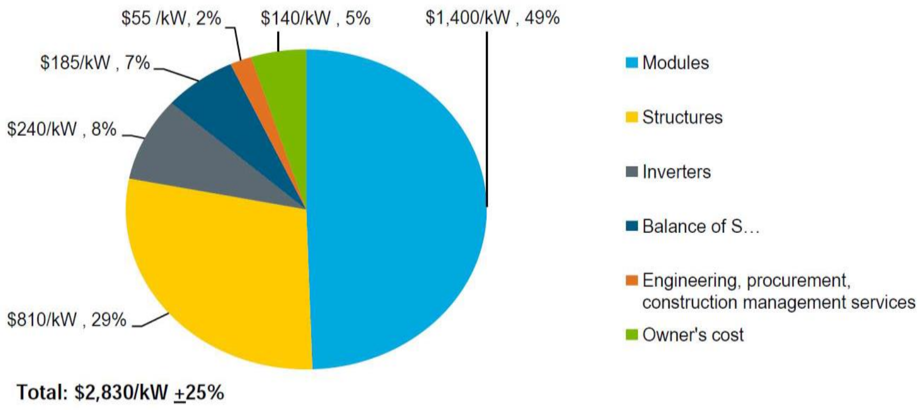

Figure 2.7: The cost percentage of solar PV system parameters. (Veatch, 2012)

The solar PV efficiency has improved a lot over the years, and this has been able to reduce the cost of the PV system (EPIA et al, 2010). The cost of the solar PV system is improving by time, and the manufacturing of PV cells is increasing, whereas their price is decreasing. Therefore, the number of solar PV system utilization has an increasing trend.

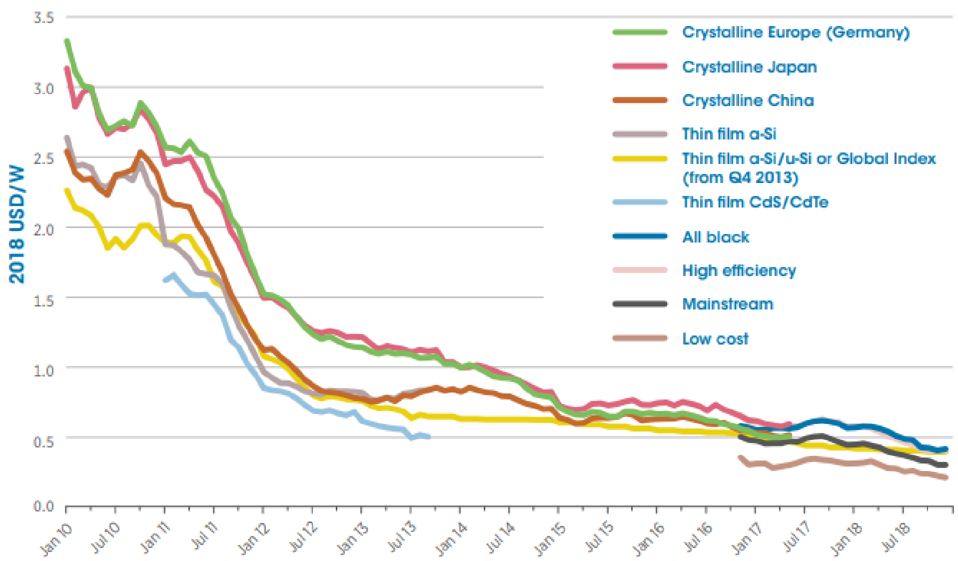

Figure 2.8: Solar PV modules prices per watt peak (IRENA, 2018)

2.5. Recent Projects

A study conducted by (Al Omari and Ayadi, 2017) that aims to integrate a solar PV system with a conventional power plant. The proposed plan was that during solar radiation availability, the in-house requirements would be powered by the solar PV system, and if no solar radiation is available, the in-house loads will be powered by the conventional system. The study showed that the investment in a solar PV system is more attractive to power producers to install the system in a hybrid configuration rather than a stand-alone grid-connected system. The authors recommend using the net present value and internal rate of return to evaluate the economic cost of installing a solar PV system. In their work, the authors find the system to have a net present value (NPV) of $16,842,521, the internal rate of return (IRR) 13.2%, and the payback period of 7 years. The avoided cost for fuel and transmission lines is $2,095,000 and $781,248 per year, respectively.

Another study by (Hammad and Ebaid, 2015) propose a 20 MW system with a grid connection. In this work, the authors conducted both technical and economic analysis. Economic analysis focused on life cycle cost (LCC). The authors report that total LC cost for the system is $124,070,000 ($6.2 /W), and the net present value (NPV) of the overall system was found as $147,387,557 ($7.4 /W). The total CO_2 reduction is about 541,798 tons of CO_2. The study concluded that with the current prices of electricity generation in gas-powered power plants and PV power plants, the cost of PV power plants is not cost-effective.

A study is conducted by (Chandel et al., 2013) for 2.5 MW solar plant to electrify a village. Technical and economic analysis was done for the on-site (with battery) and off-site (without battery) conditions. The result concluded that for 25 years with a 10% discount rate, the off-site is more promises than the on-site condition that has better NPV, IRR, and payback period.

Research by (Abbood et al., 2018) to design a 1MW solar PV system in Iraq. Technical, economic, and environment analysis was done with a total life cycle cost of $1,170,568 and energy production about 40,445 MWh. The system saved about 27,794 tons of CO_2 emission during the whole lifetime. Moreover, the work was analyzed with different electricity prices. The study proved that as the electricity prices increase, the solar PV system is getting more attractive based on the cost.

2.6. Solar System in Qatar

Qatar introduced its vision in attempts to increase the dependency of the economy from an oil based-economy to a knowledge-based economy, which in turn can help diversify the economy (MPDS, 2018). One of Qatar's national strategy for 2018 – 2020 plan is to manage the natural resource by calling for the increase of renewable energy use. By 2020, Qatar plans to install 200 MW to 500 MW of solar PV based generation capability (MPDS, 2018). In this respect, KAHARAMAA has asked bidders for prequalification for a 500 MW PV generation (Teanova, 2018). The expected operation date for this project is by the end of 2020 (IRENA, RENEWABLE ENERGY MARKET ANALYSIS: GCC 2019, 2019).

Currently, solar PV projects in Qatar are minimal. The first installed commercial PV project of 3MW was in Qatar Foundation. The total capacity of electricity that is generated by renewable energies is about 43 MW in Qatar that include the technology of PV solar system and waste-to-energy system (IRENA, RENEWABLE ENERGY MARKET ANALYSIS: GCC 2019, 2019).

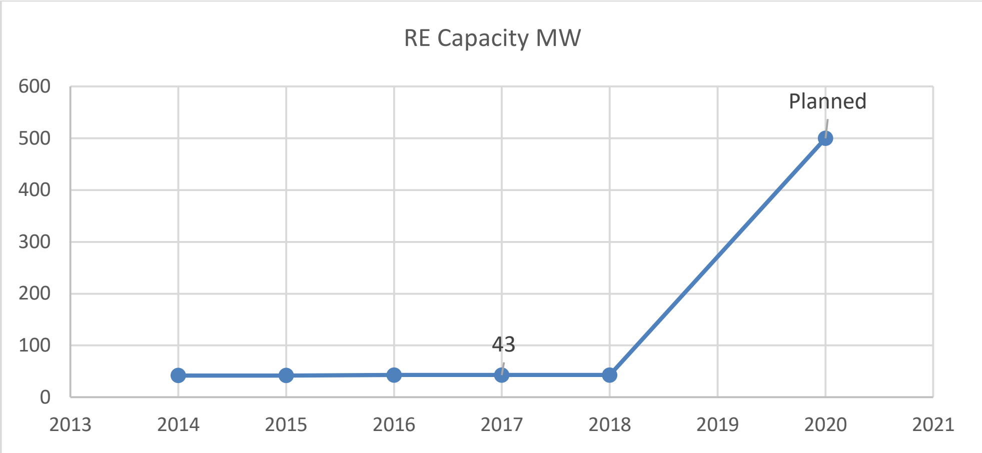

Figure 2.9: Capacity of electricity generation by renewable energy.

Table 2.2: Current and planned statistics of renewable energies.

Installed Renewables-based Capacity (2017)	43 MW
Share in Total Installed Power Generation (2017)	0.4 %
Project Planned (2020)	500 MW

2.7. Qatar Power Generation Structure

There are three key players in Qatar energy sector, Qatar Petroleum (QP), Qatar Electricity and Water Company (QEWC), and Qatar General Electricity and Water Corporation (KAHRAMAA or KM).

- Qatar Petroleum: The supplier of the natural gas to the power plants.

- Qatar Electricity and Water Company (QEWC): The company is responsible for the power generation and water production. This company manages most of the power plants in Qatar. The power plants buy the gas from Qatar Petroleum.

- Qatar General Electricity and Water Corporation (KAHRAMAA or KM): This corporation is responsible for the transmission and distribution of electricity and water to the customers. KAHRAMAA buys the electricity and water form power plants.

QEWC has all the responsibilities for power generation and water production. It owns several power plants and is also in partnership with private companies (locally and abroad). Figure 14 explains the relationship between main stakeholders.

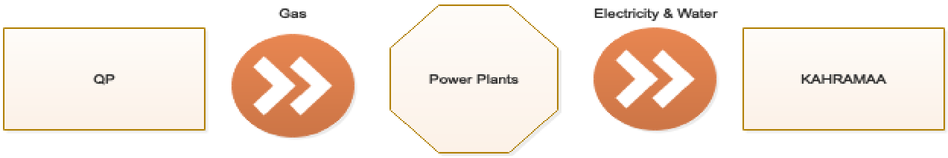

Figure 2.10: Electricity key players relationship.

Power plants purchase natural gas from QP to power their gas turbines and generate electricity. Then power plants sell their production to KAHRAMAA, which in turn, they transmit and distribute the power to the customers.

Now a day, with high electricity demand around the world, natural gas will play an important role in Qatar's economy. Moreover, the prices of natural gas are expected to increase due to the high demand. Figure 16 shows the prices of natural gas worldwide. As shown, the lowest price is about 4 $ / MMBtu and the highest price is about 10 $ / MMBtu with an average value of 7 $ / MMBtu.

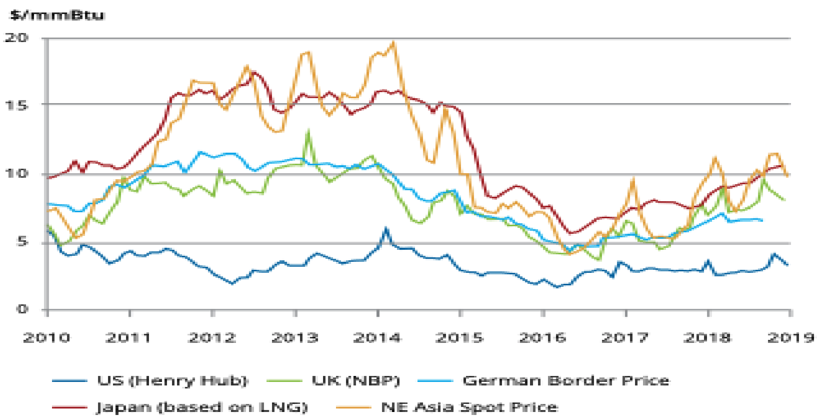

Figure 2.11: Average gas prices from different regional. (EIA, 2019)

According to (Darwish, Abdulrahim, & Hassan, Realistic power and desalted water production costs in Qatar, 2014), the price of natural gas in Qatar 4 $ / MMBtu and comparing to worldwide price is considered the lowest within them. Locally, power plants purchase the gas from Qatar petroleum at the cost of 0.0374 $ / kWh. Then power plants sell their electricity to KAHRAMAA at a rate of 0.0583 $ / kWh, then KAHRAMAA distribute the electricity to the users at different tariff. Usually, in Qatar, the price of electricity is low and is free for Qatari citizen.

2.8. Literature review summary

Solar PV technology, as other types of renewable energies, generates clean, reliable energy without the need for fossil fuel, which has an advance in increasing the income and improving environmental conditions. Qatar announced in 2018- 2022 strategy plan to increase the utilization of solar technology by 2% to achieve 2030 goal that state 20% of energy used shall be from solar technology.

After reviewing the literature, it has been found that there are different options for solar technology that can be used. The system can be either designed as a grid-connected solar PV power plant that generates electricity and directly connected to the national grid. In Qatar, a limited number of solar PV system is installed. Based on the literature, Qatar has a significant opportunity for using solar PV technology, especially for reducing the dependency on fossil fuel. The review shows the technical and economical methods to evaluate the solar PV system.

Based on these findings, system type and the components required are going to be described first in the next section, followed by the technical and economic analysis.

Chapter 3: Analysis methodology

From the literature, there are three main types of analysis used to study the technical and economic impacts from utilizing of renewable energies. The types include mathematical analysis and modeling, field experiments, and computer modeling (Abu Hijleh, 2016). The authors of (Khatri, 2016) used mathematical analysis to design a solar PV plant for a university girls' hostel. He used the same analysis to assess the plant based on the life cycle, greenhouse gas emission reduction, and financial assessment of the plant. The authors of (Abu Hijleh, 2016) used computer modeling to simulate the use of hybrid PV and wind turbine grid-connected systems in a local home in the UAE. HOMER software was used in the analysis, which only needs local solar radiation and wind data as an input to the software to work out technical and economic analysis. Field experiment analysis mostly used on already installed systems such as (Allouhi et al., 2018), where extensive energy, economic, and environmental analysis of 2 kW for three types of modules was carried out. The mathematical analysis was selected as an analysis method for the project. This decision was made because the field experiment analysis requires installing of PV system, which is out of the project scope. Moreover, computer modeling software was expensive to purchase and needs time to learn how to use it.

This project is about the integration of a PV power plant into an existing power plant that is powered by natural gas. The aim is to study the technical and economic benefits of such integration. Figure 3.1 summarizes the steps done in the project to achieve the goal.

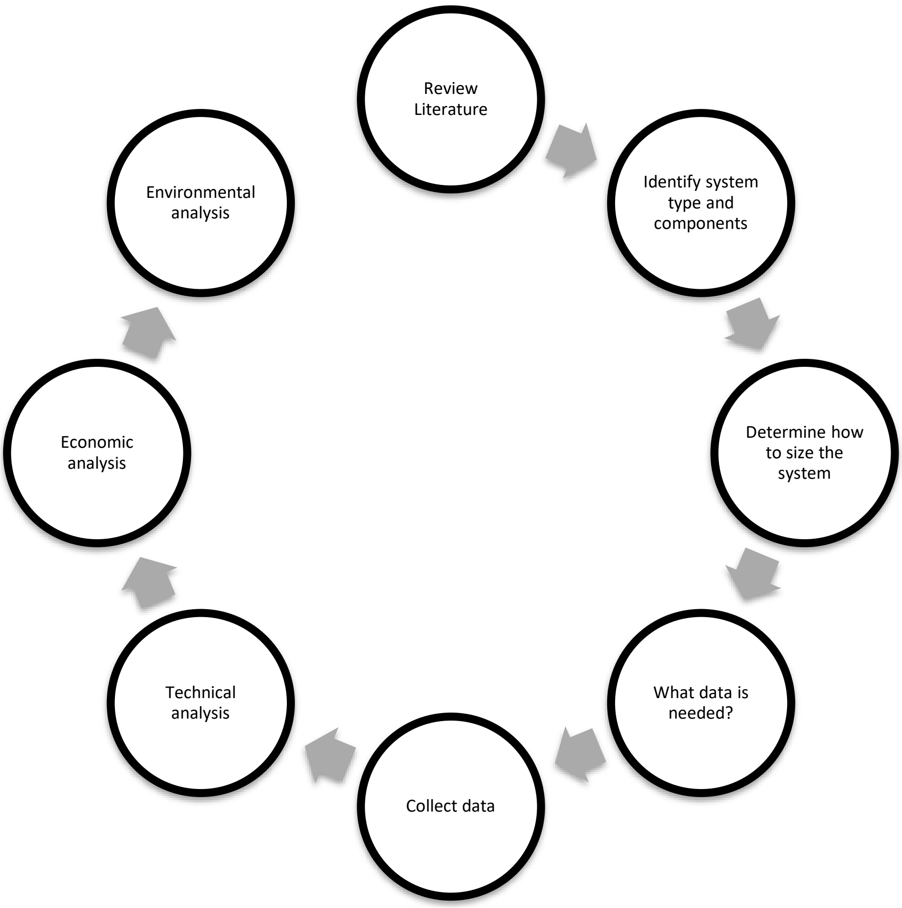

Figure 3.1: Solar PV project workflow

The first step is to review literature reviews that have the same concept as the project to understand the requirements for the integration of a solar PV system. The second step is to identify system type, wither to be on-grid or off-grid configuration. Moreover, the components of the system can be identified when deciding the system type. The third step is to figure out how to size the system, or in other words, how to quantify the components in the system. The fourth step is to search for and locate the data needed. The fifth step is to size the system by using suitable equations and data. After that, the next step is doing a cost analysis in which the initial investment cost will be calculated that includes to costs of components, installation, and engineering design.

For the next step, an economic analysis, to check if the project is cost-effective or not, will be done that includes calculating the present value of cost outflows during project lifespans, such as operation and maintenance cost and replacement cost. With that, an economic analysis will be done for four different scenarios:

1- Increasing power plant power capacity: the power plant current capacity is 2520 MW. So, by utilizing a solar PV system with a capacity of 15 MW, the new capacity is 2535 MW, which will lead to selling more electricity.
2- KAHRAMAA to invest 15% for the installation of 15 MW solar plant as subsidizing incentives. This scenario is coupled with the first scenario.
3- KAHRAMAA to provide some incentives for utilizing renewable energy: the assumption here is that KAHRAMAA is to pay 15% of energy cost to the utility for replacing the grid electricity by solar PV. Although, it sounds hypothetical, this will motivate more off-grid generation and use through renewable energy.
4- Selling surplus gas globally. The analysis will be done assuming that the fuel gas which was saved in the power plant will be available globally. This scenario was used because selling gas globally is more beneficial than considering only reducing the cost of gas purchased to power the gas turbines.

The final step will be to do environment analysis to study the benefit of utilizing of the solar PV system in the environment.

Chapter 4: Case Study

The power plant facility where solar energy is being considered consists of Water Plant, Power Plant, and associated systems. The Power plant configuration comprise of two combined cycle power blocks. Each block consists of three gas turbines and generators (GTGs), three heat recovery steam generators (HRSGs), and two steam turbine and generator (STG). The water plant consists of five Multistage Flash Desalination Plant (MSF Plant), Reverse Osmosis Desalination Plant (RO Plant), Potabilization Plant, and auxiliary systems. The plant capable of generating 2520 MW of power and producing 136.5 MIGD of water.

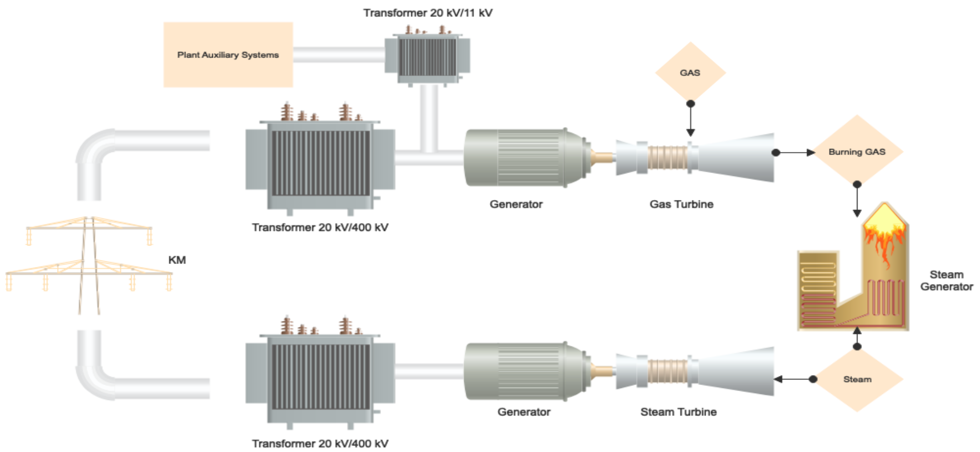

Figure 4.1: Power plant configuration.

Each gas turbine generating unit is coupled with one number of an auxiliary transformer to supply power to the unit and common auxiliaries to provide auxiliary power to the entire power plant. The LV terminals of the unit auxiliary transformer (UAT) are connected to the 11kV switchgear of GTG, and HV terminals of UAT are connected between generator and generator step-up transformer.

The overall single line diagram below shows the configuration of the power plant. The gas turbine generates a voltage of 20 kV, which then is transferred to the gas insulation switchgear by a step-up transformer (from 20 kV to 400 kV). The 20 kV line is also connected to the auxiliary system by a step-down transformer (from 20 kV to 11 kV) to power the auxiliary equipment. The auxiliary single line diagram below shows how the auxiliary systems are connected. The unit auxiliary transformer (UAT) is connected to the GT unit switchgear that power the gas turbine auxiliary system. The unit switchgear then is connected to the common switchgear that powers most of the plant. The load of each switchgear is shown in Appendix A.

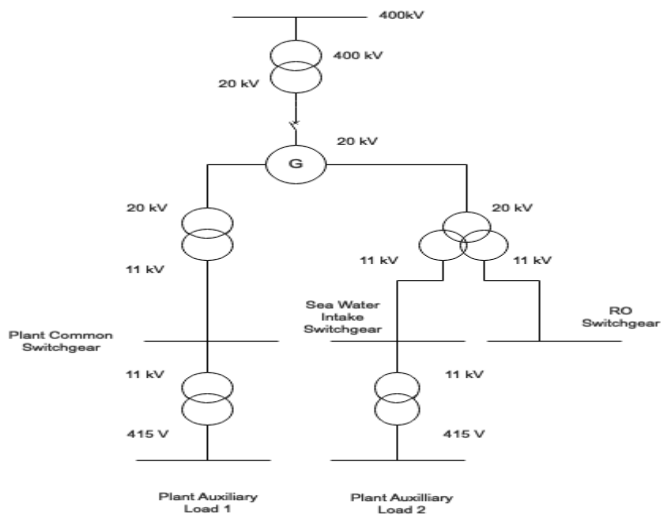

Figure 4.2: Power plant single line diagram.

About 6 % of the power generated (MW) is used to power GT, ST auxiliaries, and power plant standard services. Examples of auxiliary loads are motors, emergency power, monitoring and controlling systems, lighting, heaters, battery chargers, HVAC, cranes, and UPS. The plant is consuming gas fuel for each MW generated, therefore, reducing the usage of power (reduce the 6 % in our case) will reduce the consumption of gas fuel, which will lead to lowering the cost for the company budget.

The system type is a grid-connected system where the planned solar PV system will be connected to the power plant switchgear. The component of a grid-connected system includes solar modules, inverters, and transformers with no requirement of battery storage. Therefore, the number of modules, inverters, and transformers shall be identified. For the power plant, load consumption, fuel consumption, and the load profile will be determined. Also, meteorology data, such as the temperature and solar irradiance, will be identified. For system sizing, peak energy demand and losses factors for both solar PV and the overall system will be identified and discussed. Finally, selection analysis for the PV module, inverter, and transformers shall be done.

4.1. Load consumption

The first data to be collected is to know how much power the plant generates. Figure 4.3 shows the average monthly power generated in 2018. The maximum daily average power generated was in July 2018, about 1266 MW, and the minimum daily average power generated was in February 2019, about 855 MW. The average daily power generation is about 1062 MW. Appendix A

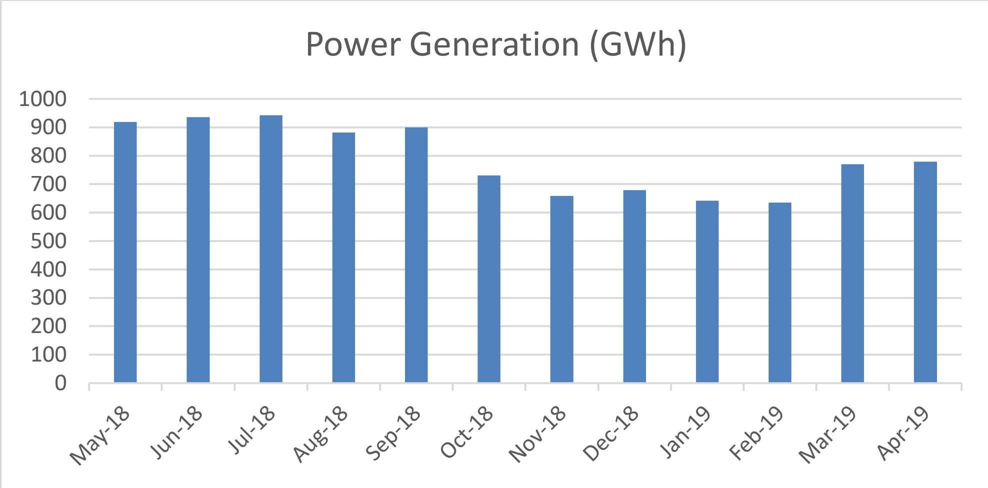

Figure 4.3: Monthly power generation from the power plant.

Figure 4.4 shows the average monthly power consumption for the power plant auxiliary system for the same period. The maximum daily average power was in July 2018, about 145 MW, and the minimum daily average power was in February 2019 about 123 MW. The average daily auxiliary load power in the power plant is about 132 MW. This amount counts about 12% (132/1062) of the average power generation. For the load list with their power rating, please see Appendix A.

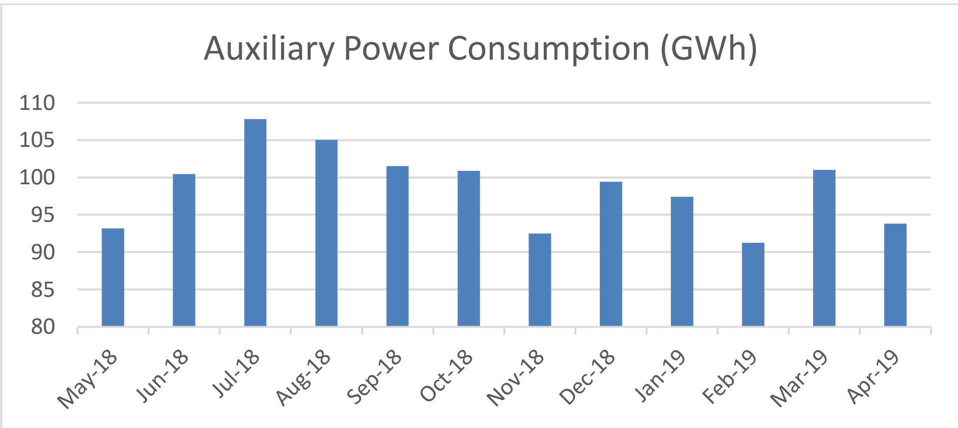

Figure 4.4: Monthly average auxiliary load power.

The proposed solar system is aimed to meet a maximum of 11.3% (15/132) of power consumed for the auxiliary systems, which is about 15 MW. This was decided due to the area size limitation. Average monthly auxiliary power consumption is about 98.7 GWh, and the daily auxiliary power consumption is 3183.8 MWh. This daily consumption is being consumed for 24 hours; however, the solar PV system is only generating during the daytime. So, for 11.3%, the daily required power generation from PV system shall be (0.113*(3183.8/24) *h), where h is the number of hours when the solar PV system generates electricity.

4.2. Natural Gas consumption

The average gas consumption for the proposed power plant is 6,657,228 MMBtu per month. Figure 4.6 shows monthly gas consumption for the year 2018.

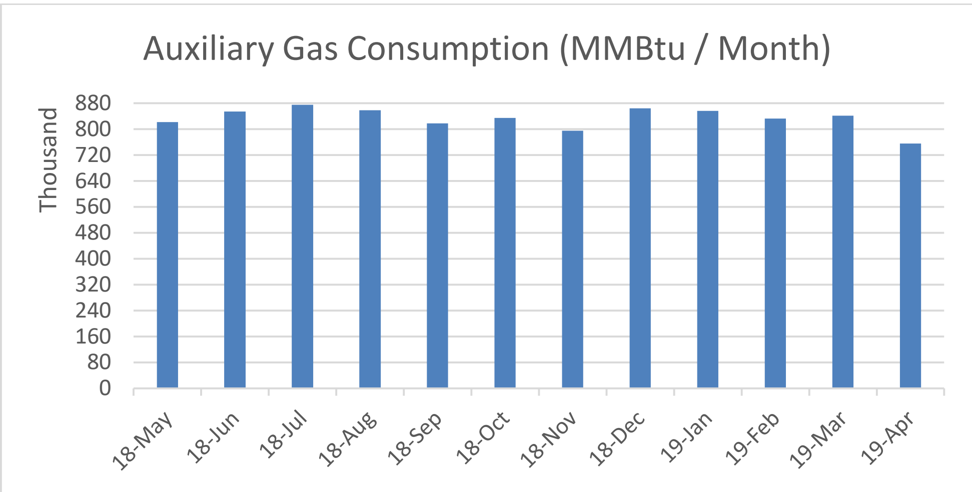

Figure 4.5: Gas consumption for auxiliary power.

The average natural gas needed for 1 MWh of power is 8.456 MMBtu therefore, for 15 MW, we need to multiply 15 MW by total time of consumption to find power consumption and then multiply that by 8.456 which will give the total MMBtu of natural gas required which in our case is the amount of natural gas saved from utilizing of solar PV system. This gas used to generate MWh can be assumed as income for the company for scenario analysis.

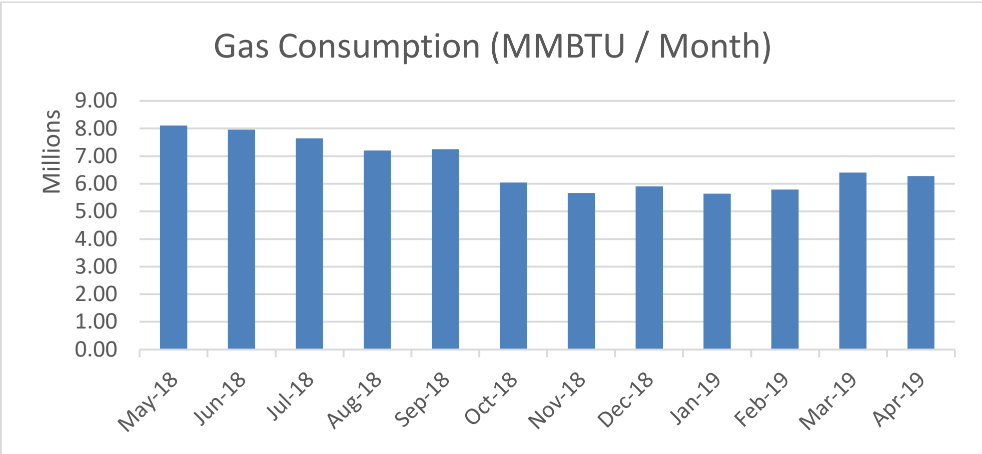

Figure 4.6: Monthly gas consumption in the power plant.

Most of the gas is consumed within the gas turbines, and some are consumed for other processes such as supplementary firing for the heat recovery steam generator (HRSG) systems and brine heaters for the desalination process. For this study, it is assumed that gas turbines consume 100% of gas fuel.

4.3. Loss factors

For ideal behavior, the maximum energy generated by the solar system is maintained (the solar system will be 100% efficient). However, in the real world, there is no system such as an ideal one, there are some factors that make systems not behaving correctly. Such factors could be internal factors that are within the system itself or could be external such as environmental or even human error. The following table summarizes the losses and its percentage based on recent papers (INDIA, 2016), (Benjamin and Dichson, 2017), and (Abbood et al., 2018).

Table 4.1: Internal and external losses for the system.

Losses	
Internal	**%**
Connection	2
External	**%**
Temperature	3
Mismatch	1
Dirt	3
Aging	1

Those factors shall be used for the sizing of the system to quantify both solar PV modules and the overall system. Therefore, the losses in the system are assumed to be 10%. These losses are for the PV system to the inverter input. Inverter losses shall be discussed in section 4.7. Transformers and cables (HV) losses are not considered in the project.

4.4. Selection of solar PV cell

As discussed in Chapter 2, there are different types of PV cell. Each has its uniqueness and benefits, so one shall select the one that will suit the purpose of his work. The below table shows the main parameters of each type. The selection method will be based on a technique called factor rating method. Each parameter will be graded based on their uniqueness in each kind, the parameters will be weighted based on the priorities.

Table 4.2: PV cell type selection using factor rating method.

Parameters	Weight (0 to 1)	Grades (0 to 100)		
		Monocrystalline	Polycrystalline	Thin film
Efficiency	0.2	90	70	60
Temperature	0.2	80	70	90
Shade	0.05	50	50	90
Power Output	0.1	90	80	70
Environment	0.05	80	80	40
Cost	0.3	40	80	50
Area for 1kW	0.1	80	70	50

$$WV_{MONO} = (90 \times 0.2) + (80 \times 0.2) + (50 \times 0.05) + (90 \times 0.1) + (80 \times 0.05) + (40 \times 0.3) + (80 \times 0.1) = 69.5$$
$$WV_{POLY} = (70 \times 0.2) + (70 \times 0.2) + (50 \times 0.05) + (80 \times 0.1) + (80 \times 0.05) + (80 \times 0.3) + (70 \times 0.1) = 73.5$$
$$WV_{Thin} = (60 \times 0.2) + (90 \times 0.2) + (90 \times 0.05) + (70 \times 0.1) + (40 \times 0.05) + (50 \times 0.3) + (50 \times 0.1) = 63.5$$

So based on the assessment, polycrystalline solar PV type is selected. Several manufacturers are available in the market, so one should choose the well-known one, especially for Qatar's climate condition. Table 4.3 shows the specification of the selected solar PV panel.

Table 4.3: Solar PV module characteristics. Appendix C.

Characteristics	Value
Maximum Power (P_{max})	350
Optimum Operating Voltage	39.2
Optimum Operating Current	8.93
Open Circuit Voltage (V_{oc})	46.6
Short Circuit Current (I_{sc})	9.52
Module Efficiency	17.7
Temperature Coefficient of P_{max}	-0.38
Temperature Coefficient of V_{oc}	-0.33

4.5. Selection of Inverter and transformer

As discussed in Chapter 2, two main types of inverters were introduced central and string inverters. Although the efficiency of both systems is the same, however, central inverters are frequently used for large solar PV systems (Abella, 2004); therefore, a central inverter is selected for the proposed project.

Regarding the transformer, the selection is based on the same transformers in the power plant. As the voltage output from the PV system is considered as a low voltage; therefore, the transformer shall step-up the low voltage to higher voltage. The plant has three voltage levels, 400 kV, 11 kV, and 415 V. Therefore, the input voltage to the transformer shall be between 415 V to 800 V, and the output voltage shall be 11 kV. Table 4.4 summarize the characteristics of the selected transformer.

Table 4.4: Transformer characteristics.

Rating (kVA)	2000
Frequency (HZ)	50
Primary Voltage	0.433 kV
Secondary Voltage	11 kV
Connections	Ydn11
Efficiency	95%
Cooling System	ONAN

4.6. Qatar climate

Qatar Climate is desert, very hot during summer and sunny, mild winter with few rainfall and clouds. The summer season is from July to September, and the winter season is from December to March. The sky is almost clear during the year except for some days during the winter season. Figure 4.7 shows the mean temperature of about

$\mathbf{43}^{\circ}$ during July, and Figure 4.8 shows the mean of minimum as $\mathbf{14}^{\circ}$ during January (Authority, 2019). The highest temperature recorded in Qatar was in 2010 of about 50 ℃ (Authority, 2019)

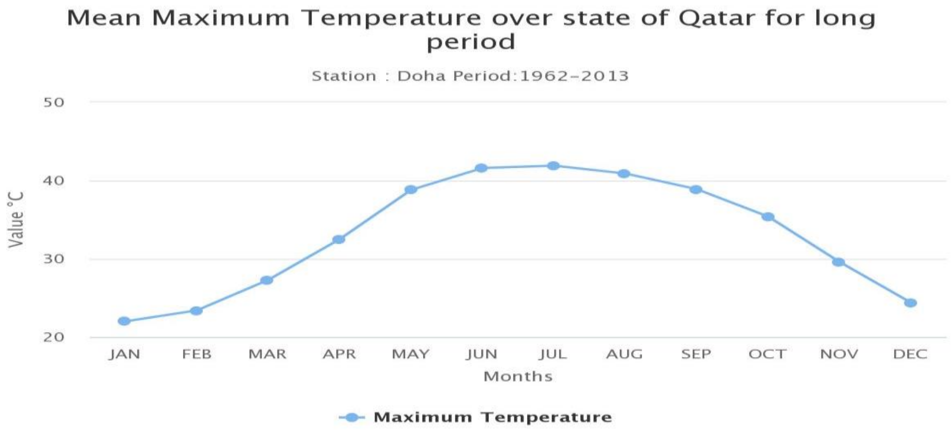

Figure 4.7: Monthly average maximum temperature.

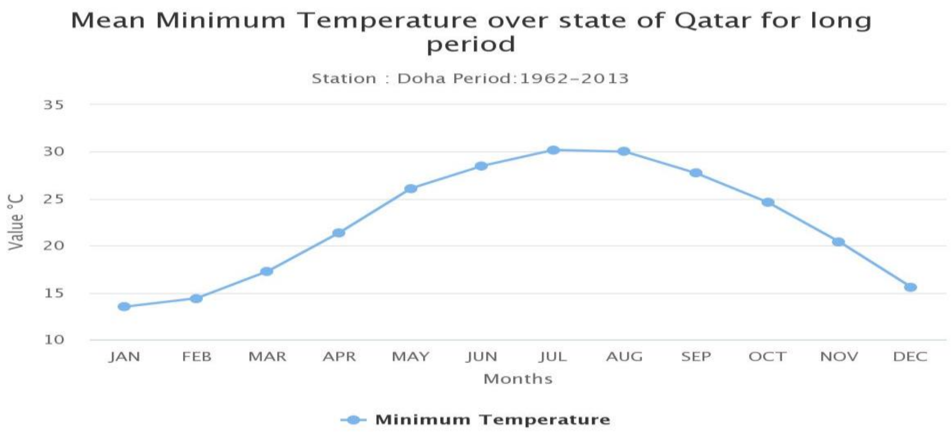

Figure 4.8: Monthly average minimum temperature.

However, one of the main important factors that effects solar cell efficiency is the solar radiation quantity. Qatar location is excellent, where solar radiation is high. Figure 4.9 shows irradiation values within Qatar with an average value of 2125 $\frac{kWh}{m^2}/year$.

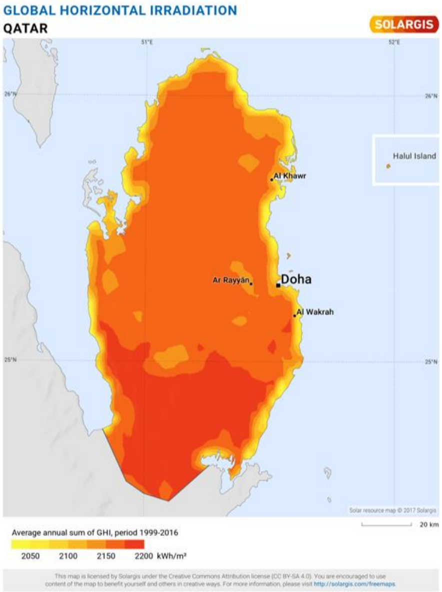

Figure 4.9: Average solar irradiation in Qatar (Solargis, 2016).

The standard test condition (STC) for a solar module is defined as a standard lab condition where the solar irradiance value is $1000\ W/m^2$. Therefore, the annual rate of solar radiation is about $\frac{2125}{9.5\times360}\times1000=621\ W/m^2$. The performance of a PV cell depends on the intensity of the sun. Furthermore, not only the intensity, but also depends on the duration of sun radiation. For PV cells, peak sun hours are used to define when the sun is highest in the sky or in another word when the sun radiation is in the highest level. Figure 4.10 shows the average monthly daylight hours and peak sun hours in Doha (Darwish et al., 2015) and (Atlas, 2019).

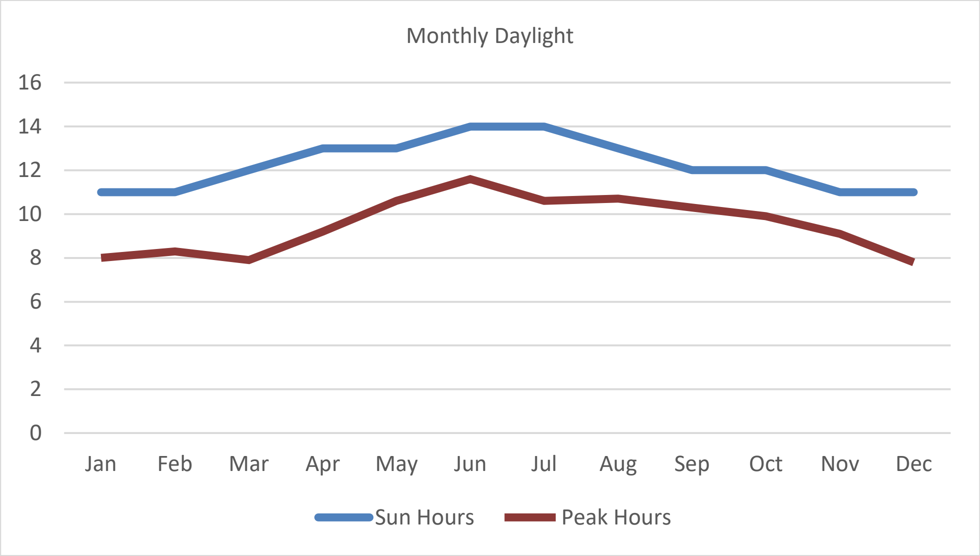

Figure 4.10: Monthly daylight hours and peak sun hours in Qatar.

The average annual peak sun hour is 9.5 hours, and this shall be used in system sizing calculations. Therefore, the daily required peak power generation from the solar PV system is (0.113*(3183.8/24) *9.5) = 142.41 MWh.

4.7. System Sizing

For the system, the number of each component required to design the system is to be calculated. The following equations will be used to calculate the number of each component.

1- Power Generation Factor (PGF): is obtained by taking into consideration the correction factor for a solar PV module (Chandel et al., 2013).

$$PGF = \frac{Solar\ Irradiance\ \times Peak\ Sun\ Hours}{STC\ Irradiance} \quad (1)$$

2- Energy required from PV modules is obtained from Eq. (2) by considering the peak energy available and energy losses (Chandel et al., 2013).

$$Energy\ Required\ From\ PV = Peak\ Energy\ Requirement \frac{kWh}{day} \times\ Energy\ lost\ in\ PV\ system \qquad (2)$$

3- The peak watt rating for PV modules is calculated in Eq. (3) by using energy required (Eq. (2)) and the panel generation factor (Eq. (1)). (Benjamin and Dichson, 2017), (Chandel et al., 2013).

$$Total\ peak\ Watt\ rating\ for\ PV\ modules = Energy\ required\ from\ PV\ modules \div\ PGF \qquad (3)$$

4- Number of PV modules required depends on the peak power and rated power output from the PV module as given in Eq. (4) (Benjamin and Dichson, 2017), (Chandel et al., 2013).

$$Number\ of\ PV\ modules\ required = Total\ Watt\ peak\ rating \div\ PV\ module\ peak\ rated\ output \qquad (4)$$

5- Inverter sizing: based on Qazi (2017), inverter size is assumed as 30% larger than the required capacity, as shown in Eq. (5). (Benjamin and Dichson, 2017), (Chandel et al., 2013).

$$Inverter\ Size = Total\ Watt\ required\ W \times\ 130\% \qquad (5)$$

$$Number\ of\ inverters\ required = inverter\ size \div\ rating\ of\ an\ inverter \qquad (6)$$

6- Number of modules in series per string (a string is consisting of modules connected in series that is within an array that consists of strings connected in series and parallel): The modules number attached to a string is based on input voltage to the inverter. They are usually based on the lowest temperature during the day. The different operating can be calculated (Abbood et al., 2018) as:

$$V(t) = V_{25^\circ} \times \left(1 + \alpha(T_x - T_{STC})\right) \tag{7}$$

Here $V(t)$ is the module voltage at temperature T_x; α is the temperature Coefficient, T_x is the temperature on PV, and T_{STC} is the STC temperature. The calculation basically will be to identify the highest module voltage for minimum and highest possible cell temperature (Abbood et al., 2018).

$$Maximum\ number\ of\ modules\ per\ string = \frac{V(inverter)_{max}}{V_{OC_{Min^\circ}}} \tag{8}$$

$$Minimum\ number\ of\ modules\ per\ string = \frac{V(mpp)_{inv_{min}}}{V_{mpp_{Max^\circ}}} \tag{9}$$

Eq. (8) will calculate the maximum number of modules per string at the minimum cell temperature that can be measured with the open-circuit voltage. Eq. (9) will calculate the minimum number of modules per string at the maximum cell temperature, which can be measured with the nominal voltage.

$$Array\ Voltage\ = Result\ of\ (8)\ or\ (9) \times V_{mpp} \tag{10}$$

The condition for the array voltage that it should be in the range of inverter maximum and minimum allowed voltages. Moreover, the array voltage must be below the module maximum system voltage. Therefore, the number of modules in series per string is selected, whether from Eq. (8) or Eq. (9), which one of them satisfy the conditions.

7- Required number of strings in parallel is based on the power generated in MW and is obtained by using the following equations (Abbood et al., 2018).

$$Number\ of\ strings\ in\ parallel = \frac{P_{out} \div \eta_{inverter_{max}}}{Number\ of\ modules\ in\ series \times P_{module_{max}}} \quad (11)$$

$$Number\ of\ strings\ in\ parallel\ per\ array = \frac{Number\ of\ strings\ in\ parallel}{Number\ of\ inverters\ required} \quad (12)$$

To calculate the values required from the above equations, the following data need to be identified:

- The total power that we need to generate from the system. Power consumption data of the proposed power plant shall be collected, and from there, the total power will be identified.
- Solar irradiance data in the proposed site.
- Total correction factor on the solar panel.
- Peak energy requirement kWh/day.
- Energy loss in a PV system (%)
- Selection of PV panel.
- Selection of the inverter(s).
- Selection of transformer(s).
- Selection of other electrical equipment's (Balance of the system)
- Meteorology data such as max/min temperature and peak sun hours.

After collecting the data, the next step is to size the system. Sizing the system means to find out the number required for each component, such as the number of solar panels needed, how many inverters to be used, and so on. Based on the result, an overall system could be designed, and the interconnections between system components shall be identified.

4.8. Area calculation

In this part, the required area for utilizing the solar PV system shall be calculated. This calculation could be done after sizing the system when the dimension of the solar PV module is known plus the configuration of series and parallel connection in the system. However, there shall be a spacing between strings to eliminate any shading that could happened if the spacing is not sufficient. Therefore, the spacing value (Space Y in Figure 4.11) between each string shall be identified.

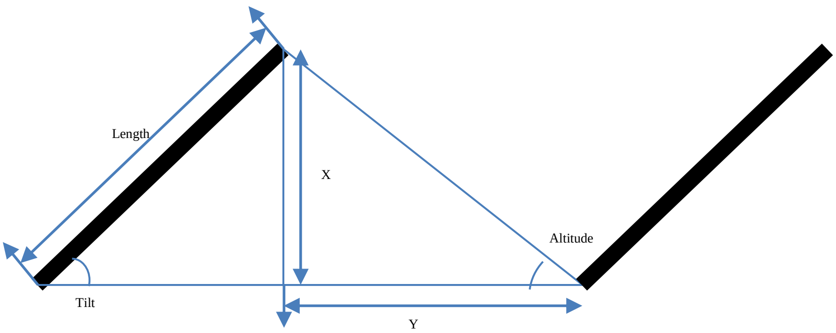

Figure 4.11: Spacing between modules.

$$The\ height\ X = Length\ \times \sin\beta \qquad (13)$$

Where β, is the tilt angel.

$$The\ minimum\ spacing\ Y = (X)\frac{\cos(azimuth\ angle)}{\tan(altitude\ angle)} \qquad (14)$$

Where the azimuth angle is the angle where the module is facing, and the altitude angle is the angle that corresponds to the minimum spacing Y.

$$The\ length\ of\ each\ array = Parallel\ strings\ per\ array\ \times\ Y \quad (15)$$

$$The\ length\ of\ overall\ system = The\ length\ of\ each\ array\ \times\ Number\ of\ arrays \quad (16)$$

$$The\ width\ of\ overall\ system = Number\ of\ series\ modules\ \times\ Width\ of\ PV\ module \quad (17)$$

$$The\ area\ needed = The\ length\ of\ overall\ system\ \times\ The\ width\ of\ overall\ system \quad (18)$$

4.9. Economic analysis

Solar power plants need high initial investment to utilize. This high investment cost could be one of the reasons why these systems still not utilized well. For any investment, a benefit analysis shall be done to check whether the project is beneficial or not. Solar power plants are, in general, capital intensive, but the cost of fuel is almost zero. Theretofore, an analysis of cost-benefit shall be done by identifying the following parameters:

1- Net present value (NPV): is a method used to determine whether a project is worth doing by calculating the cash inflows and outflows over some time and convert it to the present time. It is used for capital budgeting and investment planning to analyze the profitability of a project. A positive NPV indicates the project is feasible, and a negative NPV suggests the project is not viable. This method is also can be used to compare different investment alternatives that are similar. In our case, NPV will be used to compare different profit scenarios and decide which scenario is better.

$$NPV = \sum_{n=0}^{N} \frac{CF_n}{(1+r)^n} - INV \quad (19)$$

Where CF_n is the net cash flow in n year, r is the discount rate, and INV is the project investment cost. The discount rate in Qatar is taken as 5%, which is closest to the current discount rate offered by Qatar Central Bank (Bank, 2019).

- Investment cost: includes the cost of the equipment, installation/construction, engineering/management, and the land.

- Operation and maintenance cost: The cost of O&M is over the project lifetime. Usually, this cost is represented as a percentage of the total cost of the project or as a cost per kW peak. As the cost of this component paid yearly, therefore it is essential to convert the cost to present value.

$$O\&M\ Present\ Value = Cost\ per\ year\ \times \frac{(1+i)^n - 1}{i(1+i)^n} \tag{20}$$

- Replacement cost: Any equipment that has a lifetime lowest than the lifetime of the project. As the cost of this component will be paid in the future, therefore it is vital to convert the cost to the present value.

$$Replacement\ Present\ Value = \frac{Future\ Value}{(1+r)^n} \tag{21}$$

By which all future value can be converted to the present value

2- Internal rate of return (IRR) is obtained as a nominate rate when NPV=0 and is obtained as:

$$NPV = \sum_{n=0}^{N} \frac{CF_n}{(1 + IRR)^n} = 0 \quad (22)$$

If IRR is more than the discount rate, the project is considered desirable, but if IRR is less than the discount rate, then the project is considered not feasible. A positive IRR indicates the project is expected to return some profit, and a negative IRR indicates the project is expected to have more cost than profit.

3- The payback period (PBP): is an approach that defines how many years it is needed to recover an investment. Two types of payback period are available, the simple payback (SPB) and the dynamic or discounted payback (DPB). The first is calculated without considering the discounted rate, and the second is calculated considering the discounted rate.

$$PBP = \frac{Total\ System\ Cost}{Annual\ Production\ kWh \times Cost\ per\ Energy} \quad (23)$$

4.10. Avoided emissions

Solar PV, when installed and used, would offset the environmental emissions generated through natural gas. Although natural gas is classified as the cleanest fuel, it still emits about 430 $kg\ CO_2/MWh$ compared to 1000 $kg\ CO_2/MWh$ generated from coal power plants (Energy, 2016). The average saving amount of greenhouse gas is summarized in table 4. The values were taken from a different number of research papers (Li et al., 2018), (Qiu et al., 2019), and (Tarigan et al., 2015).

Table 4.5: Emission factor and the corresbonding saving amount.

Emission Factor	Saving
CO_2	0.7
SO_2	0.02
NO_x	0.033

4.11. Cost data

The cost of the proposed project is based on the cost figures in the literature. Table 4.5 shows the approximate initial cost of each unit of work based on recent papers (Oko et al., 2012), (Abbood et al., 2018), (Chandel et al., 2013), (Kumi and Hammond, 2013), and (Mandal, 2016).

Table 4.6: Solar PV system initial cost.

Description	Cost Approximation ($/W)
Solar PV Modules	2.4
Inverter	0.424
Connection equipment	0.155
Transformer	0.387
Mounting	0.2184
Contingency	0.44
Engineering/Installation	0.25
Land	0
Total Initial Cost	4.2744

Authors (Abbood et al., 2018) and (Baras, 2012) has assumed the cost of the O&M is $0.0227 / W and $0.012 / W per year, respectively. This includes the cost of normal maintenance and operation routine and also spare parts. Therefore, the O&M is assumed to be $0.017 / W per year.

The average lifetime of solar PV is assumed to be 25 years. Within this period, equipment like inverters, or electronics would have to be replaced for continuity of solar PV generation. As per inverter datasheet, inverter lifetime is between 13 to 15 years. Therefore, to be on the conservative side, the replacement time for the inverter is assumed to be 13 years. So that only one replacement of inverter would have to be done within the lifetime of solar PV.

4.12. Proposed location for equipment installation

The power plant is located in the west south of Doha. Figure 4.12 shows the location where the PV system shall be installed. The proposed location has four big water tanks where PV modules could be installed on the top of them. Each water tank has an area of 14400 m^2 (Green circle), and the total area is 57600 m^2. This area is the maximum area for the tanks; therefore, a suitable area for PV installation will be less than the total area. The maximum appropriate area is donated with a red circle with an area of 11400 m^2, and the total area for the four tanks is 65600 m^2. The area next to the tanks (Yellow line) is also available for PV system installation. The total area is about 92700 m^2. Therefore, the total area for PV modules and connection equipment to be installed is 158300 m^2. The blue lines are where electrical equipment shall be installed; such equipment includes inverters and transformers. The two locations have an area of 2700 m^2 and 1200 m^2.

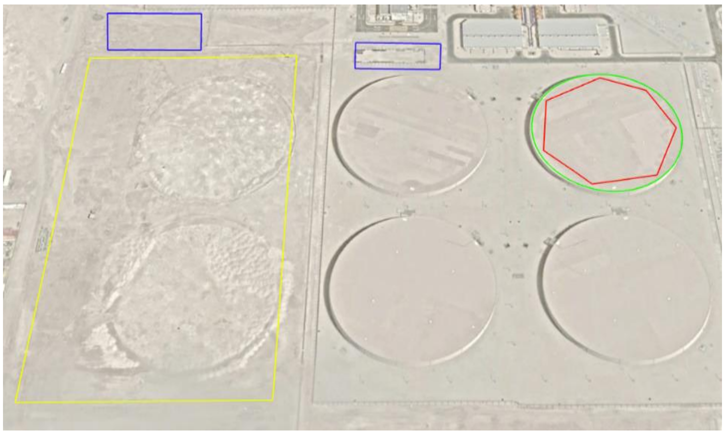

Figure 4.12: Locations where the PV system shall be installed.

Chapter 5: Results and discussion

5.1. Solar system sizing

Table 5.1: System sizing result summary.

Description	Result
Power Generation Factor	5.8995
Energy Required from PV (MWh)	156.65
Total Peak Watt Rating for PV Modules (MW)	26.55
Number of PV modules	75914
Inverter Size (MW)	19.5
Number of Inverters	13
Module Voltage at Temperature (T_{xmin}) (V)	49.67
Module Voltage at Temperature (T_{xmax}) (V)	34.67
Maximum Number of Modules Per String	20
Minimum Number of Modules Per String	17
Number of Strings in Parallel	4511
Number of Modules in Parallel Per String	347

The energy required from PV was calculated by using Eq. (2), multiplying the energy required per day (142.41 MWh) by the losses factors in the system (10%) so to handle any possible losses during the operation.

$$Energy\ Required\ From\ PV = 142.41\ \times\ 1.1 = 156.65\ MWh$$

Then total peak watt rating is found by using Eq. (3) dividing the energy required from PV by the power generation factor that was calculated using Eq. (1) (621*9.5 / 1000=5.8995). Power generation factor is a factor that take into account the variation in the solar irradiance and also to consider peak time the system can work. For example, in our case, the peak sun hour was 9.5 hours. However, in other locations, this value could be lower; therefore, the power generation factor will be reduced. This means more energy is required from the system to accomplish load requirements by adding more solar modules.

$$Total\ peak\ Watt\ rating\ for\ PV\ modules = 156.65\ MWh \div 5.8995 = 26.55\ MW$$

The total number of PV modules in the system is calculated using Eq. (4), dividing the total peak watt rating by the power rating, which is 350 W, of the selected module type.

$$Number\ of\ PV\ modules\ required = 26.55\ MW \div 350 = 75914$$

The total number of inverters is found by dividing the inverter size by inverter rating. The selected inverter is rated at 1500 kW and is capable of handling up to 2500 kW for any up normal activities; therefore, the total number of inverters is 10.

$$Inverter\ Size = 15\ MW \times\ 130\% = 19.5\ MW$$

$$Number\ of\ inverters\ required = 19.5 \div\ 1.5 = 13$$

However, as discussed in chapter 2 about the effect of high and low temperature, an analysis for maximum and minimum possible temperature was done to find the highest DC voltage (Eq. (7)) that the system can generate that will be used to decide how many modules are connected in series. The highest temperature was chosen as 60 °C, and the lowest temperature was selected as 5 °C, and therefore, the highest DC voltage was found to be 49.67 V.

$$V(t) = V_{25^\circ} \times \left(1 + \alpha(T_x - T_{STC})\right)$$

Table 5.2: Maximum DC voltage at lowest and highest tempreature.

V_{25} Data Sheet	$\propto$ Data Sheet	T_x $5^{\circ} or\ 60^{\circ}$	T_{STC} 25	$V(t)$
39.2	-0.0033	5	25	41.78
46.6	-0.0033	5	25	**49.67**
39.2	-0.0033	60	25	**34.67**
46.6	-0.0033	60	25	41.21

The next step was to calculate the number of modules connected in series per string by using Eqs. (8 and 9). The calculation was done in two conditions a) highest inverter voltage (1100 V), b) lowest inverter voltage (580 V), and using the DC voltage calculated from the previous part (49.67 V). To note, for nominal inverter operation, the voltage range into the inverter is between 580 V to 850 V. Therefore, the voltage generated for the series connection shall be within this limit. Moreover, the voltage should be lower than the maximum module DC voltage (1000 V as per the data sheet).

$$Maximum\ number\ of\ modules\ per\ string = \frac{1000}{49.67} \approx 20$$

$$Minimum\ number\ of\ modules\ per\ string = \frac{580}{34.67} \approx 17$$

From the calculations for both conditions, the number of modules for the highest voltage is 20 and for the lowest voltage is 17. Using module open-circuit voltage (39.2 V), for 20 modules the voltage is about 784 V, and for 17 modules the voltage is about 666 V. The 17 modules configuration was selected to be in safe side, and the voltage is close to the transformer primary voltage (433 V) which means less conversion process.

Using the inverter efficiency (99%), the number of strings connected in parallel was identified by using Eq. (10). The number of stings is 4511 in total, and the number of strings per array is 347, which was calculated by Eq. (11). See Appendix B for array configuration.

$$Number\ of\ strings\ in\ parallel = \frac{26.55\ MW \div 0.99}{17 \times 350} \approx 4511$$

$$Number\ of\ strings\ in\ parallel\ per\ array = \frac{4511}{13} \approx 347$$

The total number of modules per array (one array for each inverter) is 17 * 347 = 5899; the power generated from one array is 5899 * 350 = 2,064,650 W, which is fed to the inverter. The inverter has a conversion ratio (DC to AC conversion ratio) up to 1.3. Therefore, the power coming from the inverter is equal 2,064,650 / 1.3 = 1,588,192 W which is as per design requirement.

The main findings are that the system is configured with 13 arrays of solar modules, 13 inverters, and 7 transformers. However, the decision of how the system shall be connected with the power plant must be clear and reasonable. From a maintenance point of view, the effect of components availability should be considered. That means any fail in any equipment should not compromise the system. Therefore, the concept of redundant system is very critical and should be considered. As discussed in chapter 4, the power plant has two main switchgear for the auxiliary systems, plant common switchgear, and seawater intake switchgear. Both have their own systems, which means any fault in one of them; its loads can't be powered by the other switchgear. Therefore, the decision is to split the power generated from the solar PV system into two sections. So, 9 MW shall be connected to plant common switchgear, and 6 MW shall be connected to the seawater intake switchgear, as shown in Figure 5.1.

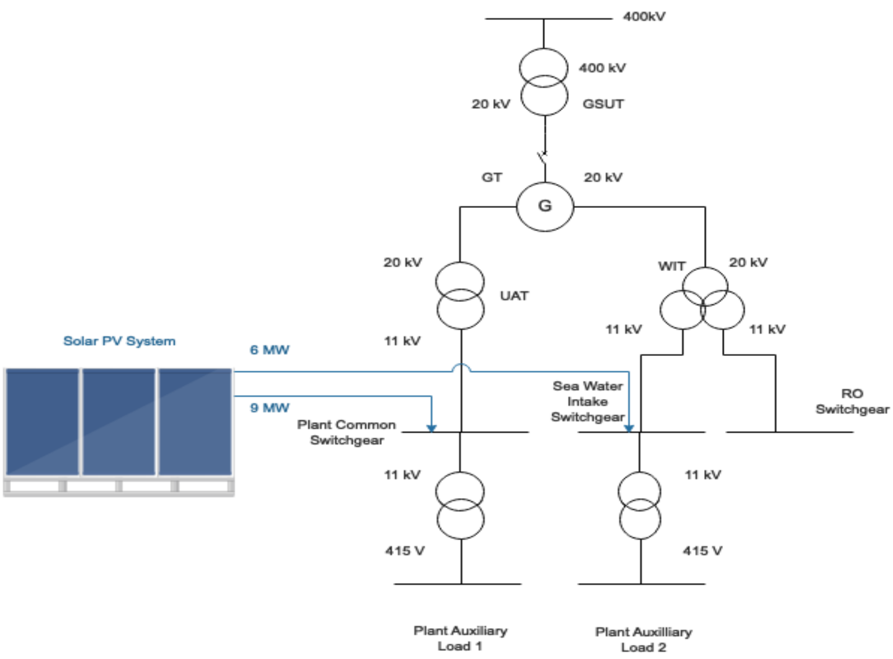

Figure 5.1: Location where solar PV system shall be connected in the power plant.

The configuration of the solar PV system is shown in Figure 5.2. As both redundancy and availability have been considered, 13 inverters and 7 transformers have been selected to increase the efficiency of the system. The system can be configured as 13 inverters connected to one switchgear and then using one transformer to step-up the voltage. But what if the transformer has a fault and needs repairing, or even replacing, this will affect the availability of the system.

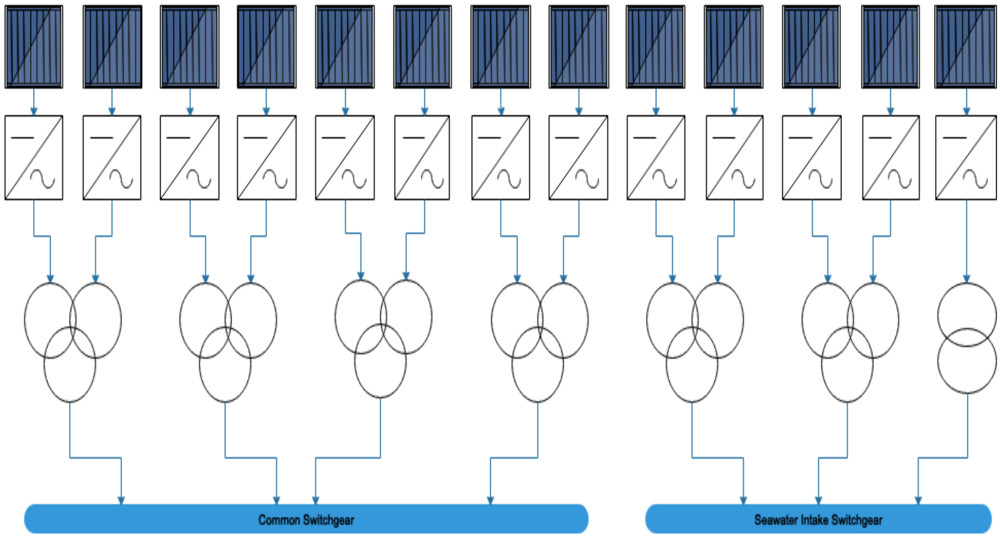

Figure 5.2: Solar PV system configuration.

For the design, the following assumption was considered:

1. The system will behave as designed, internal, and external losses already considered.
2. The inverter has a voltage regulator that produces fixed voltage to the transformers.
3. Balance of system components such as switches, fuses, circuit breakers, earthing, and disconnectors are available and considered under connection equipment.
4. The transformers are synchronized with the switchgear based on voltage, phase, and frequency.
5. The switchgear already has incomer circuit breakers.
6. No modification needed for switchgear buildings only to connect the cables.
7. Protection and monitoring system are available and considered under connection equipment.

5.2. Identify the components

The following table summarize the main project components that were identified in the previous part. The summary includes the type or made of each equipment and their dimensions.

Table 5.3: Solar PV system main components.

Item	Type	Quantity	Rating	Dimension (mm)	Space Required
PV Module	SunTech	75914	350 W	1988 * 992 * 40	1.972 m2 each
Inverter	SunGrow	13	1500 kVA	2150*2120*850	4.558 m2 each
Transformer	Hyundai	7	2000*2 kVA	2800*1900*580	5.32 m2 each
Cables	XLPE MV	3280 m	8 - 17.5 kV	150 mm2	
Cables	XLPE LV	5735 m	0.6 - 1.2 kV	120 mm2	

5.3. Area calculation

The height X of the PV module was found to be 0.994 m, and the minimum spacing Y is calculated and shown in table 5.4. As the PV module facing south, the azimuth angle is equal 0. The minimum spacing Y was calculated with different altitude angles ranging from 10° to 80°. The average value of minimum spacing Y was selected for the next calculations.

Table 5.4: Minimum spacing between modules with different altitude angle.

Altitude angle	Minimum spacing
10	5.64
20	2.73
30	1.72
40	1.18
50	0.83
60	0.57
70	0.36
80	0.18
Average Spacing	**1.65**

Therefore, by using the minimum spacing Y, one can calculate the area required from the proposed system based on the info found during the sizing of the system.

Table 5.5: Area needed for solar PV system.

Spacing Per String (m)	572.55
Length of overall system (m)	7443.15
Width of overall system (m)	16.86
Area required (m^2)	125491.5
Estimated (add 25%) (m^2)	156864.4

The minimum area required was found as 125491.5 m^2. However, a 25% to 30% increase is proposed due to site condition. For example, lighting and cleaning services need to be considered, which needs some more space to utilize. Therefore, the estimated area required is about 156864.4 m^2.

5.4. Economic analysis

5.4.1. Investment cost

As stated, the investment cost is the initial project cost that corresponds to the cost of the life cycle cost of the project. That includes the cost of the equipment, installation/construction, engineering/management, and the land. The following table summarizes the cost of each item.

Table 5.6: Total investment cost for solar PV system parameters.

Description	Cost Approximation ($/W)	Total Cost (Million $)
Solar PV Modules	2.4	36
Inverter	0.424	6.36
Connection equipment	0.155	2.325
Transformer	0.387	5.805
Mounting	0.2184	3.276
Contingency	0.44	6.6
Engineering/Installation	0.25	3.75
Land	0	0
Total Cost	**4.2744**	**64.116**

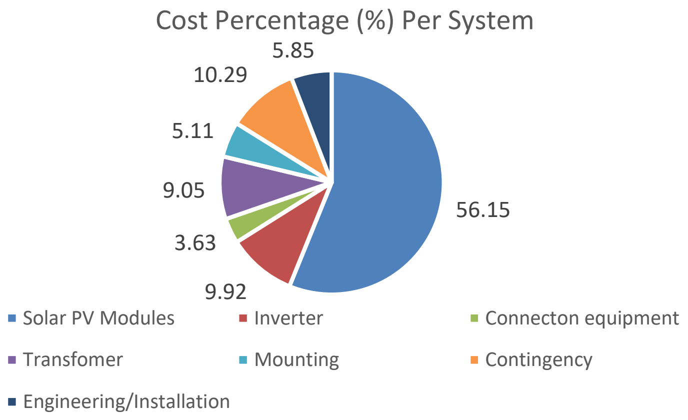

Figure 5.3: Cost breakdown (%) for the system.

5.4.2. Operation and Maintenance (O&M) cost

Table 5.7: Cost breakdown for O&M activities (Abbood et al., 2018) and (Baras, 2012).

Parameter	Value
System Lifetime	25 years
O&M Cost	0.017 per Wp per year
Discount Rate	5% per year

Operation and maintenance costs represent the cost of normal routine maintenance work that includes cleaning of PV modules and also the cost of labors who are in duty for the operation and maintenance activities. The cost of O&M is $ 0.017 per peak power for one year.

$$O\&M\ cost\ per\ year = 0.017 \times 19616099.1 = 333473.68\ \$\ per\ year$$

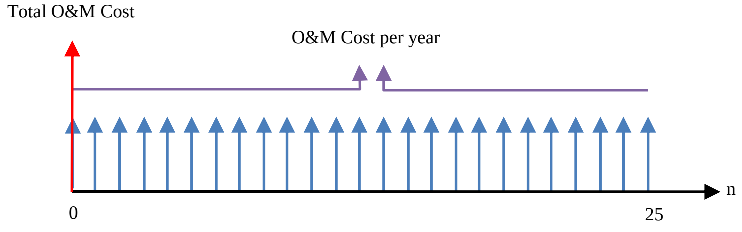

Figure 5.4: Cash flow diagram for O&M activities.

The total cost of O&M activities is the sum of all costs in 25 years, taking into account the discount rate, which is assumed to be 5%. Therefore, the total O&M cost is as following:

$$PV_{O\&M} = cost\ per\ year \times \frac{(1+i)^n - 1}{i(1+i)^n}$$

$$PV_{O\&M} = 333473.68 \times \frac{(1+0.05)^{25} - 1}{0.05(1+0.05)^{25}}$$

$$PV_{O\&M} = 4.7\ Million\ \$$$

5.4.3. Replacement cost

The replacement cost represents the cost of replacing the inverters as the lifetime is 13 years, which is lowest than the system lifetime. The assumption here is that the replacement will happen only for one time.

Table 5.8: Cost breakdown for replacement activities.

Parameter	Value
Inverter Lifetime	13 years
Replacement Cost	6.36 Million $
Discount Rate	5% per year

$$PV_{InvRep} = \frac{Future\ Value}{(1+i)^n}$$

$$PV_{InvRep} = \frac{6360000}{(1+0.05)^{13}}$$

$$PV_{InvRep} = 3.37\ Million\ \$$$

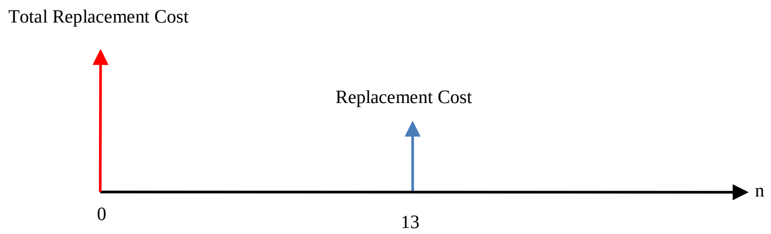

Figure 5.5: Replacment cash flow diagram.

Therefore, the total life cycle cost of the proposed project, including the operation and maintenance cost and replacement cost, is summarized in the below table.

Table 5.9: Total life cycle cost for solar PV system.

Parameter	Cost per watt peak $/W	Net Present Value (Million $)
Investment	4.2744	64.116
O&M	0.313	4.7
Replacement	0.225	3.37
Total	4.812	72.186

5.4.4. Net present value analysis

As stated, the net present value method is used to determine whether the project is feasible or not by analyzing the cash outflow and inflows. In this analysis, the project shall be investigated for different alternatives benefit scenarios. The scenarios are summarized below:

1- Increasing power plant power capacity.

2- KAHRAMAA to invest 15% for the installation of 15 MW solar plant.

3- KAHRAMAA to provide some incentives for utilizing of renewable energy

4- Selling surplus gas globally.

Before doing the analysis, energy production per year shall be identified. The system rating is 15 MW per hour per day. The peak sun hours were identified as 9.5 hours per day. Which, when the system is assumed to generate 15 MW during a day (30 days is assumed). Another critical factor is the degradation value (D), based on the datasheet for the selected solar module, will have a degradation value of 0.7% every year to system lifetime (25 years). Therefore, for each year, the generated energy is:

$$Energy\ Generated\ (kWh) = 15000\ kW \times Peak\ Sun\ Hours \times 30 \times 12 \times D$$

$$Energy\ Generated\ (kWh) = 15000 \times 9.5 \times 30 \times 12 \times 1 = 51300000\ kWh$$

There is no degradation for the first year but increases by 0.7% every year starting from year two. The annual energy generation for the 25 years is summarized in the table below.

Table 5.10: Annual energy generation for project lifetime.

Year	Energy Production (MWh)
1	51300
2	50941
3	50584
4	50230
5	49879
6	49530
7	49183
8	48838
9	48500
10	48157
11	47820
12	47485
13	47153
14	46823
15	46500
16	46170
17	45846
18	45525
19	45207
20	44890
21	44576
22	44264
23	43954
24	43646
25	43341

The value of energy production in real-time could be different due to different reasons such as cloudy day, dust, or even a malfunction in the system. However, for the analysis, it is assumed that the numbers in the table above are correct.

1- Increasing power plant power capacity.

The idea here that the power plant capacity is now 2535MW, adding the 15 MW generated from the solar PV system. Therefore, there shall be an increase in electricity generation due to the use of a solar PV system. As stated in Chapter 3, the electricity cost is about $0.0582 / kWh. By using the electricity cost, one can identify the cost-benefit from utilizing a 15 MW solar PV system. Table 5.11 shows the net present value for the system. A point to be clear, the electricity prices is assumed to be fixed for the 25 years, but in reality, the cost could decrease or even increase depending on the demand.

Table 5.11: Economic analysis for scenario 1.

SPB	Never
DPB	Never
IRR	-1.304%
NPV	($32,717,799)

For this scenario, both the net present value and the internal rate of return are negative which indicates the project is not cost-effective with such scenario. The internal rate of return indicates even if the discount rate was selected as zero instead of 5% the project will still not cost-effective.

2- KAHARAMAA to invest 15%.

KAHRAMAA is raising awareness in the rational use of electricity and water. One way to raise awareness is to provide support for the installation of solar systems. In this scenario, it is assumed that KAHRAMAA will invest 15% for the installation of a solar PV system. Table 5.12 shows the net present value for the system. It also shows that there is a small change in the IRR and NPV values, but it is still negative. It is indicating that such incentives may not be enough to promote solar energy.

Table 5.12: Economic analysis for scenario 2.

SPB	Never
DPB	Never
IRR	-0.056%
NPV	(23,100,399)

For this scenario, both the net present value and the internal rate of return are negative which indicates the project is not cost-effective with such scenario. The internal rate of return indicates even if the discount rate was selected as zero instead of 5% the project will still not cost-effective. Further analysis to scenario 2 shows that the breakeven point requires about 55% as an investment subsidized by KAHRAMAA instead of 15%.

3- KAHRAMAA to provide some initiatives for utilizing renewable energy.

KAHRAMAA can provide financial support by reducing prices on consumers or increasing the purchase price of electricity from the power plants. As stated in

Chapter 3, KAHRAMAA is buying the electricity from the power plants at a rate of $0.0583 / kWh. Although at present, grid connectivity of renewable system like this still in infancy, we can assume that technically it is feasible to feed back some electricity to the grid. However, in this case, we assume that KAHRAMAA will provide 15% of the electricity cost (that utility self generated and used) to the utility instead of providing a 15% investment in the cost of the solar plant, then the revenues related to electricity generated by solar plant becomes 0.0583*1.15= $0.067 / kWh.

Table 5.13: Economic analysis for scenario 3.

SPB	24.87
DPB	Never
IRR	0.04%
NPV	($26,797,148)

For this scenario, the net present value is negative which indicates the project is not cost-effective with such scenario. However, the internal rate of return indicates if the discount rate was selected as zero instead of 5% the project will be cost-effective with a net present value of $322,739 and a discounted payback of 25 years. Further analysis for the third scenario, the breakeven point requires approximately 85% provided by KAHRAMAA as an increase in power price for solar-generated power instead of 15%.

4- Selling gas surplus globally.

In this scenario, it is assumed that the power plant capacity will remain 2520 MW that include the 15 MW generated for the solar PV system. Therefore, there will be a saving in gas consumption, which is assumed to be as a surplus. This surplus could be sold globally, or it could be sent to other factories within the county. If it assumed that the excess would be sold globally and the income is provided to the power plant, then the proposed project becomes viable. As stated in Chapter 3, that Qatar is selling their natural gas at an average price of $4 / MMBtu (Darwish et al., 2014). And as discussed in Chapter 4 that:

$$1\ MWh = 8.456\ MMBtu$$

$$1\ MMBtu = 0.11826\ MWh$$

Based on the above calculation, 1 MMBtu is equivalent to 0.11826 MWh of energy produced; therefore, using this value, one can calculate how much is the financial profit when selling the surplus globally.

Table 5.14: Gas (MMBtu) cost per energy produced (MWh).

Cost ($/MMBtu)	$4.00
1 MMBtu	0.11826
Cost ($/MWh)	$33.824

Table 5.15: Economic analysis when selling gas surplus.

SPB	14.12
DPB	23.96
IRR	5.22%
NPV	$1,353,192

For this condition, the project is more feasible as the net present value is about $1.3 Million with a discounted payback of about 24 years. The internal rate of return is 5.22%, which means the discount rate could be raised to this value, and still, the project is feasible. Therefore, it is necessary to provide the right incentives for solar energy to be used in Qatar.

5.5. Environment analysis

Gas emissions is depending on how much energy is generated from the power plant. The saving quantity of gas emissions is equal to the energy generated multiplied by the saving factor, which was introduced in Chapter 3. The estimated emissions saving by integrating the solar PV system in the power plant is summarized in Table 5.18.

Table 5.16: Emission reduction quantities.

Emission Factor	CO_2	SO_2	NO_x
Total in Tons	711979	20342	33564

Chapter 6: Conclusion and Recommendations

6.1. Conclusion

Electricity consumption in Qatar is very high compared per capita. Most power plants in Qatar rely on natural gas to produce electricity, and with the continued high consumption of electricity, the demand for natural gas will increase. Therefore, increasing dependence on clean energy will help to reduce the use of natural gas in the power plants, which will increase the sustainability and income of the state.

Solar energy is one of the types of clean energy that can be used in Qatar when the country has all the factors to utilize solar energy successfully. Solar energy is a clean and continuously available energy that does not require any fuel to be used as well as can help to reduce the emissions that affect the environment.

In this project, a technical, economic, and environmental analysis was carried out to study the feasibility of utilizing a solar power station in a natural gas power plant to provide a capacity of 15 MW to power the auxiliary loads of the plant. These auxiliary loads are used either to operate machinery that generates/production electricity and water or to operate the auxiliary loads in the plant, such as lighting and air conditioning.

The analysis presented in this project shows that technically, the system has a capacity of 15 MW of power distributed between 13 inverters that has a rating of 1500 kVA each. For each inverter, there are 17 modules connected in series and 347 modules connected in parallel with a total of 5899 modules. Then 7 transformers rated 2000 kVA each used to step up the voltage to 11 kV. Four transformers were connected to the common switchgear with a power of 9 MW, and three transformers were connected to the seawater intake switchgear with a power of 6 MW.

Economically, the total investment cost was calculated as $64.116 Million, and the total life cost for 25 years was computed as $72.186 Million. The net present value (NPV) was calculated for different scenarios, as summarized below:

Table 6.1: Economic analysis summary of all scenarios.

	NPV	IRR	SPB	DPB
Scenario 1	($32,717,799)	-1.304%	Never	Never
Scenario 2	($23,100,399)	-0.056%	Never	Never
Scenario 3	($26,797,148)	0.04%	24.87	Never
Scenario 4	$1,353,192	5.22%	14.12	23.96

Environmentally, the reduction of emission gases was calculated for different emission factors such as $\boldsymbol{CO_2}$, $\boldsymbol{SO_2}$, and $\boldsymbol{NO_x}$. The system was capable of reducing almost 2% of emission due to the offsetting of auxiliary power during project lifetime.

Both technical and environmental factors are feasible for the project. It is to note that the system is to be used only during the sunlight hours. Thus, it does not require a battery backup, which reduces the cost of the system.

However, from an economic perspective, it was found that if the project to be feasible economically, financial support shall be considered. From the power plant’s management, both scenarios 1 and 2 will not be cost-effective as no profit is generated from utilizing the solar PV system. Moreover, for scenario 3, even if KAHARAMAA did increase the price as an incentive for utilizing the solar PV system, it is still not cost-effective.

Moreover, if the surplus of gas that was avoided due to utilizing of the solar PV system to be sold in the global market, the project was more cost-effective, and the discounted payback period was almost 24, with a profit of about $1.3 Million.

Therefore, to conclude, Qatari institutions, whether governmental or private, shall think about investing in such projects. As, without their support, this kind of project could not be utilized because of their high cost. This was said due to the current electricity prices, which are subsidized.

6.2. Recommendation

Implementation of renewable energy needs government support as there can be many hurdles that need to be cleared to adopt renewable energy in a country (Pokharel, 2003) and including that of the environmental concerns (Pokharel, 2007). Therefore, the following recommendations are proposed to make renewable energy technology adoption in Qatar more feasible:

1- An increase in electricity prices to reflect its actual economic cost. Although this analysis is not done in this paper, the true cost will help to understand the feasibility of solar energy on a comparative basis.

2- The government, along with the power plants, shall invest in utilizing a solar PV system in power plants to reduce gas consumption so that the saved gas can be exported for income.

6.3. Limitations

The following points summarize the project limitations:

1- The effect of air mass on solar PV modules was not discussed in this work. This may affect the results of solar PV power generation.

2- The costs of system components were selected based on the literature. This may affect the economic analysis calculations.
3- Limited information about solar PV system are available in Qatar.
4- The real natural gas prices in Qatar are not published. The price was selected from the literature.
5- Power plant load data was collected for one year only. More data can raise the accuracy of the calculations.
6- The irradiance value was selected as an average value per year. This may affect the accuracy of the calculations.
7- The peak sun hour was selected as an average value per year. This may affect the calculations of power generation as the peak sun hour may differ from day to day.

6.4. Contribution

There are some limitations in the literature about the solar PV system in Qatar:

1. There is a limited number of studies about a solar PV system in Qatar.
2. There is a limited number of studies about the technical and economic analysis of solar PV systems.
3. Most studies discuss the impact of installing a solar system on the residential level, but few consider the impact of this system on the industrial level.

This work is different from other studies on:

1. Detailed technical and economic analysis is introduced.
2. Study the possible integration of Solar PV system in a power plant and investigate the possible economic benefits.

3. Real data for load demand and natural gas demand is used. Although, solar PV system costs and other costs are based on the literature.
4. The study contributes to the growing literature on the solar system but also spread the literature toward a more wide-ranging view of the solar PV system, especially in Qatar.

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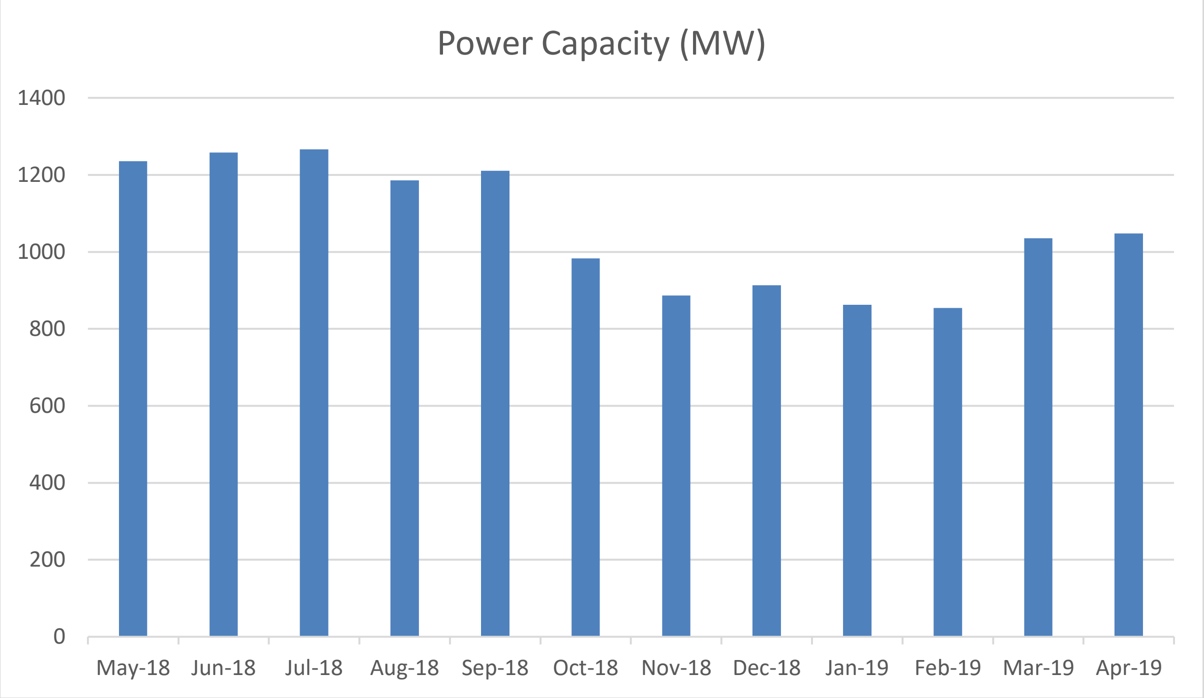
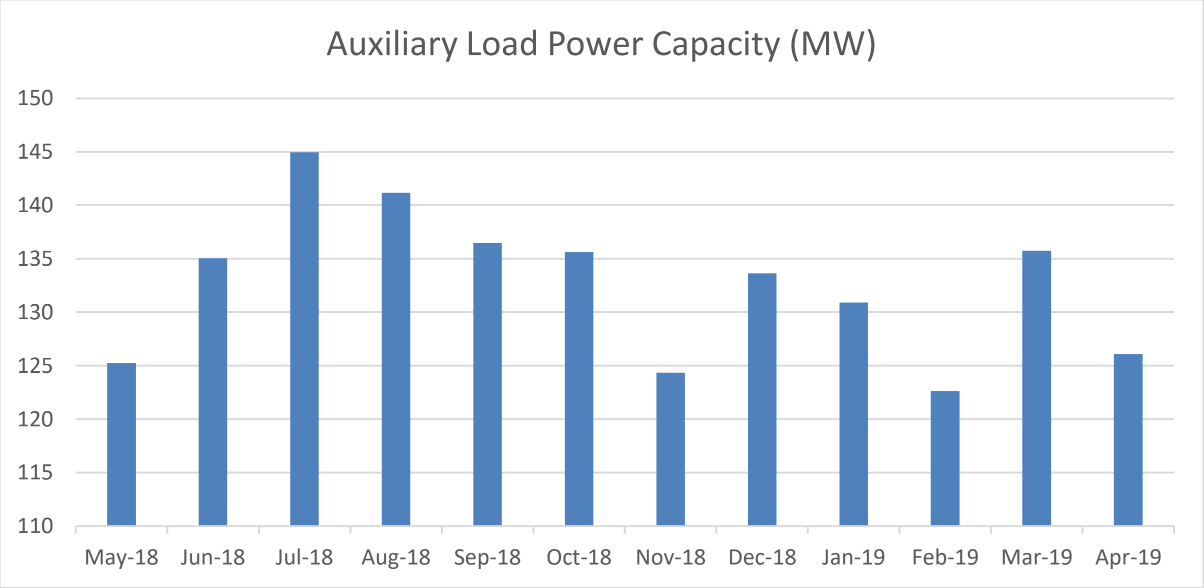
APPENDIX A: POWER PLANT DATA

The table below shows the switchgear of the power plant with their corresponding auxiliary loads. The total auxiliary load is about 146 MW. The solar PV system is to be connected to both plant common switchgear (≅ 19 MW) and seawater switchgear (≅ 29 MW).

Plant Main Switchgear Loads		
Location	Voltage Level	Power (MW)
unit switchgear 13	11KV	20.11
unit switchgear 14	11KV	22.98
unit switchgear 15	11KV	9.38
Plant Common Switchgear 1	11KV	10.07
Plant Common Switchgear 2	11KV	8.39
Sea Water Switchgear 1	11kV	15.51
Sea Water Switchgear 2	11kV	13.60
unit switchgear 23	11kV	10.22
unit switchgear 24	11kV	21.76
unit switchgear 25	11kV	9.80
Plant Common Service Switchgear 1	415 V	1.22
Plant Common Service Switchgear 2	415 V	0.73
Intake Facility Switchgear 1	415 V	1.15
Intake Facility Switchgear 2	415 V	1.08
Total		**145.99**

Total power generated and auxiliary loads consumption in the power plant is shown next page. Average power generation is 1061 MW, and average load consumption is 132 MW. The next page shows the gas consumption in the power plant in a year. The average gas consumption per day is 8724 MMBtu.


Power Capacity (MW)
1400
1200
1000
800
600
400
200
0
May-18
Jun-18
Jul-18
Aug-18
Sep-18
Oct-18
Nov-18
Dec-18
Jan-19
Feb-19
Mar-19
Apr-19

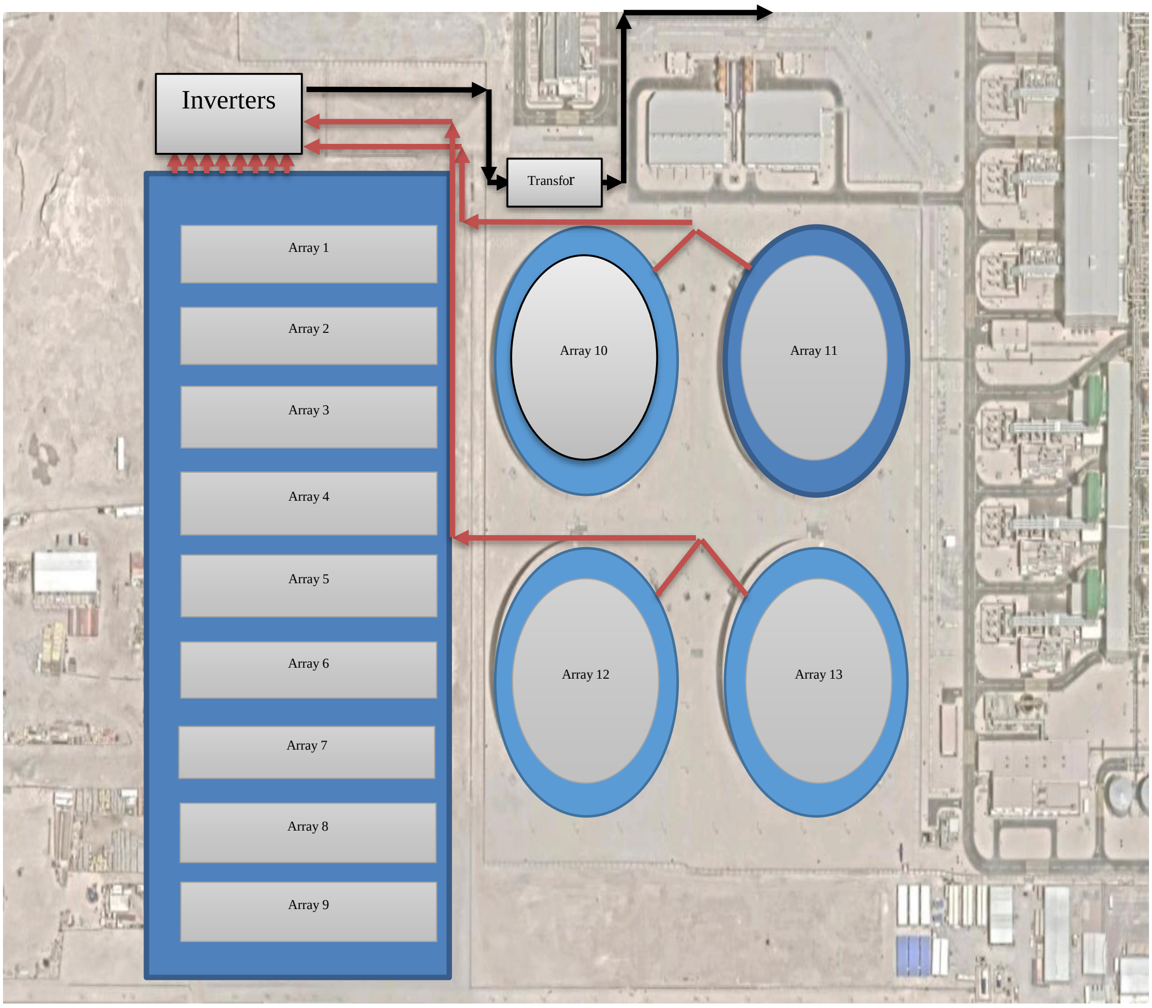

Auxiliary Load Power Capacity (MW)
150
145
140
135
130
125
120
115
110
May-18
Jun-18
Jul-18
Aug-18
Sep-18
Oct-18
Nov-18
Dec-18
Jan-19
Feb-19
Mar-19
Apr-19

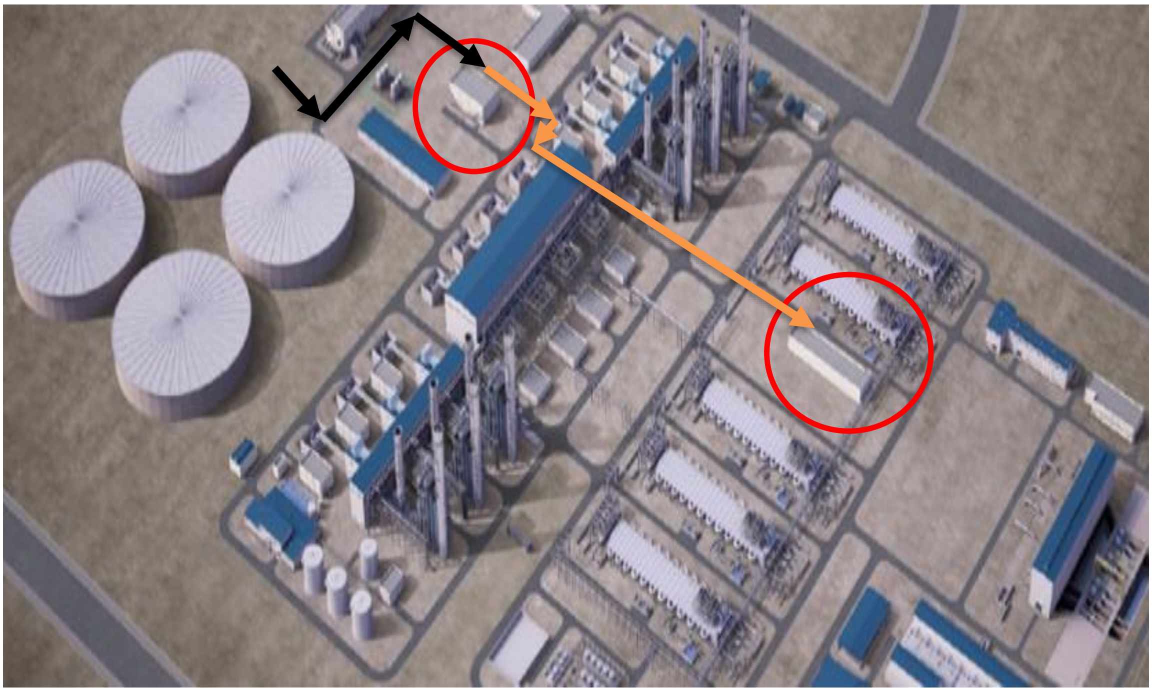
Month	May-18		Jun-18		Jul-18		Aug-18		Sep-18		Oct-18		Nov-18		Dec-18		Jan-19		Feb-19		Mar-19		Apr-19	
Day	Total Load	Aux Load	Total Load	Aux Load	Total Load	Aux Load	Total Load	Aux Load	Total Load	Aux Load	Total Load	Aux Load	Total Load	Aux Load	Total Load	Aux Load	Total Load	Aux Load	Total Load	Aux Load	Total Load	Aux Load	Total Load	Aux Load
1	27270	2813	33607	3202	30898	3607	26028	3469	31493	3337	26513	3241	22589	3181	22312	3135	21194	3106	20324	3337	25170	3379	26286	3239
2	28748	3009	34692	3131	30600	3334	25872	3439	31407	3435	26244	3270	21413	3143	22605	3313	21505	3028	21655	3338	24758	3275	26234	3197
3	28551	2823	31737	3593	33063	3315	25659	3441	29836	3514	25655	3376	22877	3126	22745	3322	22228	3041	20900	3162	24414	3364	27518	3310
4	28350	2495	31637	3249	34517	3608	26522	3541	30046	3442	25971	3307	23202	3228	23026	3318	20585	2987	24969	3181	25080	3428	27683	3329
5	29481	2639	33336	3143	34780	3538	25999	3446	29848	3347	25194	3200	23209	3252	22780	3314	21025	2979	24408	3152	25707	3219	27582	3288
6	29324	2811	32818	3084	33697	3387	28448	3556	29900	3332	25493	3202	23130	3254	24508	3339	20501	2988	24786	3182	26101	3226	26752	3267
7	27604	2807	34073	3513	34440	3417	29615	3521	29235	3305	25643	3240	22829	3112	22694	3432	20559	3233	21250	3185	24844	3261	27405	3149
8	24545	2704	32940	3476	32532	3427	29456	3321	29350	3381	24871	3304	23653	3021	21775	3389	20615	3246	20973	3390	23943	3204	26108	3146
9	20071	2502	33124	3580	32350	3528	29346	3621	30226	3416	25372	3454	23057	3030	22024	3355	21516	3277	21486	3396	27614	3431	25430	3130
10	24326	2625	31522	3069	32807	3523	29474	3587	29785	3352	25743	3518	21435	2904	22210	3013	19126	3180	22490	3372	25702	3419	25634	3148
11	22632	2741	31156	3086	32719	3501	28460	3415	30740	3560	25666	3390	21568	3104	22514	3271	19274	3133	23291	3277	24760	3413	26180	3179
12	26646	2775	31919	3152	33238	3498	28104	3377	29900	3459	24147	3331	21192	2994	21849	3246	20215	3178	20567	3167	25205	2865	27527	3185
13	26913	2748	32315	3324	30399	3493	28995	3402	30217	3327	25619	3400	21170	2856	21839	3212	18881	3167	23819	2969	24823	3411	25391	3201
14	28996	2753	32707	3559	32022	3444	28302	3398	29671	3342	25594	3377	21397	3022	21584	3168	21211	3187	24990	3386	24557	3384	24642	3168
15	32390	3113	32316	3722	33414	3525	27476	3371	30246	3351	23681	3366	21990	3023	21957	3126	21668	3183	21978	3279	24687	3335	25850	3138
16	34375	3361	31002	3657	32705	3652	27495	3375	29947	3358	25447	3573	22377	3050	21767	3164	21983	3182	22196	3310	26661	3317	26661	3174
17	32669	3679	30438	3402	32840	3656	29864	3375	30288	3439	24544	3524	22592	3073	21141	3183	21711	3197	22142	3275	26107	3256	25454	3189
18	26533	3087	28461	2866	31080	3547	31217	3407	30258	3449	24813	3500	21695	3136	20799	3083	19651	3103	21466	3283	22764	3278	25944	3268
19	25213	2973	29582	3040	28690	3480	29254	3290	31232	3508	23918	3298	21761	3128	21639	3112	19098	3134	21469	3305	22579	3293	26783	3257
20	25470	2859	32744	3542	30261	3582	28587	3279	30909	3398	21588	3177	20279	2996	22055	3139	20034	2993	22365	3282	21910	3288	27186	3248
21	27261	3305	31587	3580	30115	3529	27552	3254	30569	3319	20662	3049	21353	3059	21416	3104	19653	2999	23138	3325	21837	3239	27633	3211
22	32811	3380	26938	3210	28036	3480	25883	3217	28996	3252	20734	3029	21502	3063	21598	3091	19893	3025	22265	3360	22627	3094	25725	3219
23	32970	3359	27993	3460	26652	3424	26132	3228	29198	3304	21515	3043	20446	2967	21536	3195	20336	3060	22253	3368	23436	3005	24217	3001
24	33271	3148	30188	3119	26388	3375	29404	3274	30537	3449	21773	3223	22307	3043	20980	3215	21161	3073	24533	3218	26391	3137	24975	2913
25	34298	2921	30021	3239	26419	3439	30254	3266	30061	3468	21729	3212	22718	3207	21702	3181	21695	3280	23977	3196	25932	3111	25457	3009
26	34883	3577	29751	3615	26228	3394	30122	3293	28592	3379	21314	3035	21508	3166	23368	3291	21617	3303	24173	3207	25875	3249	25075	2962
27	34545	3179	29740	3615	25857	3357	30758	3413	27672	3375	21013	3083	21731	3132	21462	3090	21258	3166	23013	3204	25023	3220	25247	2939
28	35275	3226	28305	3578	26731	3444	29666	3345	28531	3326	20345	3187	21124	2948	20252	3120	21206	3246	24652	3137	25612	3288	24432	2884
29	35084	3235	27980	3363	26541	3451	29303	3489	34688	3275	20215	2963	21564	3169	21220	3182	21480	3151	0	0	24919	3130	23958	2822
30	34160	3240	31288	3291	26103	3479	29666	3345	27035	3349	20142	2994	21702	3122	20616	3164	20451	3266	0	0	24843	3257	24800	2633
31	34400	3303	0	0	26128	3410	29023	3292	0	0	20098	3020	0	0	21369	3161	20316	3313	0	0	26238	3233	0	0
MWH	29647.26	3006.13	30190.87	3240.65	30395.16	3478.84	28449.55	3388.61	29045.58	3275.74	23588.90	3254.39	21270.00	2984.16	21914.26	3207.35	20698.26	3142.06	20500.90	2943.32	24842.55	3258.35	25153.84	3025.90
MW	1235.30	125.26	1257.95	135.03	1266.47	144.95	1185.40	141.19	1210.23	136.49	982.87	135.60	886.25	124.34	913.09	133.64	862.43	130.92	854.20	122.64	1035.11	135.76	1048.08	126.08

Load Production (Month/Day)													
May-18	Jun-18	Jul-18	Aug-18	Sep-18	Oct-18	Nov-18	Dec-18	Jan-19	Feb-19	Mar-19	Apr-19		Average
1235.302	1257.95	1266.47	1185.4	1210.233	982.871	886.25	913.09	862.4274	854.204	1035.106	1048.08		1061.448

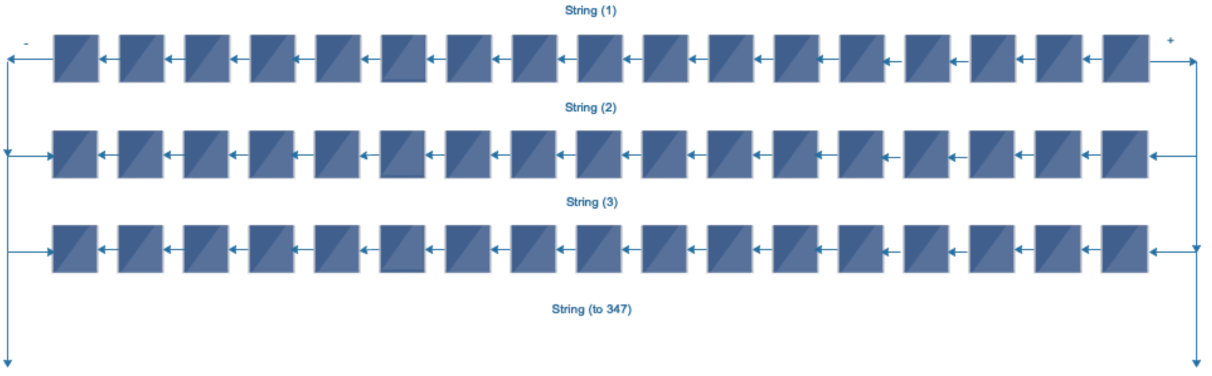
Auxiliary Load Production (Month/Day)													
May-18	Jun-18	Jul-18	Aug-18	Sep-18	Oct-18	Nov-18	Dec-18	Jan-19	Feb-19	Mar-19	Apr-19		Average
125.2554	135.027	144.952	141.192	136.4892	135.599	124.3401	133.64	130.9194	122.638	135.7648	126.079		132.658

Month	5_18	6_18	7_18	8_18	9_18	10_18	11_18	12_18	1_19	2_19	3_19	4_19
Day	MMBTU	MMBTU	MMBTU	MMBTU	MMBTU	MMBTU	MMBTU	MMBTU	MMBTU	MMBTU	MMBTU	MMBTU
1	235,966.00	292,443.00	240,896.00	218,874.00	245,211.00	216,644.00	204,306.00	199,507.00	180,844.00	206,124.00	206,124.00	219,698.00
2	264,326.00	313,978.00	253,147.00	218,124.00	244,637.00	216,037.00	187,336.00	204,680.00	184,163.00	203,835.00	203,835.00	218,421.00
3	253,655.00	285,773.00	261,072.00	216,887.00	235,923.00	212,427.00	197,194.00	197,333.00	188,112.00	208,965.00	208,965.00	227,303.00
4	245,330.00	282,195.00	271,845.00	222,076.00	238,097.00	214,393.00	192,356.00	207,901.00	179,061.00	212,682.00	212,682.00	230,600.00
5	238,649.00	293,694.00	273,933.00	218,435.00	239,746.00	209,193.00	190,463.00	199,101.00	181,608.00	213,311.00	213,311.00	224,173.00
6	241,168.00	255,523.00	264,768.00	244,304.00	238,907.00	212,271.00	191,211.00	207,213.00	187,789.00	215,630.00	215,630.00	214,059.00
7	224,007.00	285,272.00	276,374.00	242,365.00	234,155.00	212,310.00	190,131.00	197,020.00	187,108.00	204,378.00	204,378.00	220,577.00
8	208,250.00	276,167.00	263,679.00	236,806.00	232,751.00	208,231.00	194,501.00	192,763.00	189,881.00	196,554.00	196,554.00	219,433.00
9	162,555.00	279,664.00	260,827.00	236,415.00	237,698.00	210,794.00	192,411.00	195,100.00	194,393.00	225,770.00	225,770.00	208,288.00
10	198,968.00	248,134.00	264,700.00	238,300.00	241,391.00	214,081.00	186,167.00	195,034.00	175,235.00	213,062.00	213,062.00	211,140.00
11	206,905.00	249,205.00	266,520.00	232,368.00	239,067.00	212,807.00	184,240.00	196,936.00	174,723.00	212,441.00	212,441.00	210,294.00
12	248,457.00	252,693.00	270,562.00	230,259.00	233,938.00	203,853.00	181,416.00	193,582.00	181,447.00	213,384.00	213,384.00	215,864.00
13	255,136.00	272,226.00	252,362.00	235,355.00	236,081.00	211,147.00	182,534.00	191,648.00	172,639.00	213,624.00	213,624.00	201,677.00
14	253,373.00	280,799.00	263,033.00	231,459.00	233,015.00	210,794.00	188,356.00	188,640.00	185,266.00	205,617.00	205,617.00	201,175.00
15	266,821.00	288,617.00	272,847.00	226,799.00	242,062.00	200,219.00	185,950.00	195,323.00	184,943.00	204,389.00	204,389.00	206,215.00
16	296,816.00	292,885.00	266,780.00	228,625.00	242,388.00	214,384.00	189,213.00	193,890.00	186,315.00	213,807.00	213,807.00	213,961.00
17	289,330.00	269,640.00	266,277.00	240,604.00	244,020.00	205,447.00	192,353.00	185,177.00	194,260.00	211,644.00	211,644.00	209,659.00
18	266,120.00	263,814.00	252,684.00	252,403.00	242,118.00	210,028.00	185,602.00	182,903.00	175,126.00	192,029.00	192,029.00	219,366.00
19	257,499.00	260,769.00	235,880.00	236,081.00	248,489.00	202,118.00	186,044.00	184,891.00	170,967.00	189,514.00	189,514.00	213,557.00
20	250,107.00	304,243.00	244,584.00	232,253.00	246,450.00	190,312.00	179,720.00	188,778.00	173,558.00	186,189.00	186,189.00	216,296.00
21	261,889.00	281,765.00	238,195.00	226,158.00	243,457.00	185,017.00	186,510.00	181,546.00	171,537.00	185,932.00	185,932.00	220,717.00
22	292,386.00	229,174.00	226,620.00	220,043.00	234,849.00	184,896.00	183,569.00	181,745.00	171,233.00	183,830.00	183,830.00	206,919.00
23	290,638.00	236,575.00	217,596.00	215,198.00	237,267.00	188,808.00	177,637.00	182,202.00	175,643.00	193,398.00	193,398.00	198,323.00
24	288,630.00	239,252.00	214,989.00	239,433.00	254,668.00	188,785.00	190,103.00	179,435.00	178,544.00	217,150.00	217,150.00	198,530.00
25	299,635.00	233,886.00	214,845.00	239,434.00	252,099.00	192,973.00	195,862.00	184,594.00	188,466.00	219,229.00	219,229.00	200,162.00
26	301,209.00	259,021.00	213,511.00	238,809.00	242,776.00	185,284.00	188,426.00	200,080.00	185,127.00	223,049.00	223,049.00	193,882.00
27	300,962.00	233,891.00	211,551.00	241,587.00	227,487.00	185,123.00	191,327.00	178,480.00	189,484.00	214,832.00	214,832.00	193,238.00
28	301,486.00	226,060.00	222,161.00	236,777.00	231,758.00	182,610.00	188,589.00	177,204.00	191,332.00	212,489.00	212,489.00	190,287.00
29	296,391.00	222,488.00	223,794.00	233,551.00	301,887.00	182,465.00	190,073.00	178,697.00	181,894.00	0	200,611.00	188,399.00
30	306,617.00	242,997.00	218,752.00	235,909.00	225,998.00	182,234.00	192,740.00	175,588.00	180,334.00	0	203,690.00	189,113.00
31	299,653.00	0	219,483.00	233,251.00	0	0	0	186,113.00	178,593.00	0	213,268.00	0
Total	8,102,934.00	7,952,843.00	7,644,267.00	7,198,942.00	7,248,390.00	6,045,685.00	5,666,340.00	5,903,104.00	5,639,625.00	5,792,858.00	6,410,427.00	6,281,326.00


Inverters
Transfor
Array 1
Array 2
Array 3
Array 4
Array 5
Array 6
Array 7
Array 8
Array 9
Array 10
Array 11
Array 12
Array 13



The picture below shows the configuration of 1 array.



Cables Measurement	
LV Cables (PV Modules to Inverters)	Value (m)
Array 1	45
Array 2	85
Array 3	125
Array 4	180
Array 5	210
Array 6	250
Array 7	300
Array 8	340
Array 9	380
Array 10	380
Array 11	400
Array 12	505
Array 13	535
LV Cables (Inverters to Transformers)	2000
Total LV Cables	**5735**
HV Cables (Transformers to Switchgears)	
Common Switchgear	1640
Sea Water Intake Switchgear	1640
Total HV Cables	**3280**

APPENDIX B: NPV CALCULATIONS

For scenario 1:

Year	Energy Production (kWh)	Elec Cost ($/kWh)	Cost Saving (M$)
1	51300000	$0.0583	$2.9908
2	50940900	$0.0583	$2.9699
3	50584313.7	$0.0583	$2.9491
4	50230223.5	$0.0583	$2.9284
5	49878611.94	$0.0583	$2.9079
6	49529461.66	$0.0583	$2.8876
7	49182755.42	$0.0583	$2.8674
8	48838476.14	$0.0583	$2.8473
9	48496606.8	$0.0583	$2.8274
10	48157130.56	$0.0583	$2.8076
11	47820030.64	$0.0583	$2.7879
12	47485290.43	$0.0583	$2.7684
13	47152893.39	$0.0583	$2.7490
14	46822823.14	$0.0583	$2.7298
15	46495063.38	$0.0583	$2.7107
16	46169597.94	$0.0583	$2.6917
17	45846410.75	$0.0583	$2.6728
18	45525485.87	$0.0583	$2.6541
19	45206807.47	$0.0583	$2.6356
20	44890359.82	$0.0583	$2.6171
21	44576127.3	$0.0583	$2.5988
22	44264094.41	$0.0583	$2.5806
23	43954245.75	$0.0583	$2.5625
24	43646566.03	$0.0583	$2.5446
25	43341040.07	$0.0583	$2.5268

	INV	O&M	REP	Net Value	Cost Saving	Cash Flow
0	($64,116,000.00)	$0.00	$0.00	($64,116,000.00)	$0.00	($64,116,000.00)
1	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,990,790.00	$2,657,316.32
2	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,969,854.47	$2,636,380.79
3	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,949,065.49	$2,615,591.81
4	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,928,422.03	$2,594,948.35
5	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,907,923.08	$2,574,449.40
6	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,887,567.61	$2,554,093.93
7	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,867,354.64	$2,533,880.96
8	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,847,283.16	$2,513,809.48
9	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,827,352.18	$2,493,878.50
10	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,807,560.71	$2,474,087.03
11	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,787,907.79	$2,454,434.11
12	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,768,392.43	$2,434,918.75
13	$0.00	($333,473.68)	($6,360,000.00)	($6,693,473.68)	$2,749,013.68	($3,944,460.00)
14	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,729,770.59	$2,396,296.91
15	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,710,662.19	$2,377,188.51
16	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,691,687.56	$2,358,213.88
17	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,672,845.75	$2,339,372.07
18	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,654,135.83	$2,320,662.15
19	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,635,556.88	$2,302,083.20
20	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,617,107.98	$2,283,634.30
21	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,598,788.22	$2,265,314.54
22	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,580,596.70	$2,247,123.02
23	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,562,532.53	$2,229,058.85
24	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,544,594.80	$2,211,121.12
25	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,526,782.64	$2,193,308.96
					NPV	($32,717,799.04)

For Scenario 2:

Year	Energy Production (kWh)	Elec Cost ($/kWh)	Cost Saving (M$)
1	51300000	$0.0583	$2.9908
2	50940900	$0.0583	$2.9699
3	50584313.7	$0.0583	$2.9491
4	50230223.5	$0.0583	$2.9284
5	49878611.94	$0.0583	$2.9079
6	49529461.66	$0.0583	$2.8876
7	49182755.42	$0.0583	$2.8674
8	48838476.14	$0.0583	$2.8473
9	48496606.8	$0.0583	$2.8274
10	48157130.56	$0.0583	$2.8076
11	47820030.64	$0.0583	$2.7879
12	47485290.43	$0.0583	$2.7684
13	47152893.39	$0.0583	$2.7490
14	46822823.14	$0.0583	$2.7298
15	46495063.38	$0.0583	$2.7107
16	46169597.94	$0.0583	$2.6917
17	45846410.75	$0.0583	$2.6728
18	45525485.87	$0.0583	$2.6541
19	45206807.47	$0.0583	$2.6356
20	44890359.82	$0.0583	$2.6171
21	44576127.3	$0.0583	$2.5988
22	44264094.41	$0.0583	$2.5806
23	43954245.75	$0.0583	$2.5625
24	43646566.03	$0.0583	$2.5446
25	43341040.07	$0.0583	$2.5268

	INV	O&M	REP	Net Value	Cost Saving	Cash Flow
0	($54,498,600.00)	$0.00	$0.00	($54,498,600.00)	$0.00	($54,498,600.00)
1	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,990,790.00	$2,657,316.32
2	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,969,854.47	$2,636,380.79
3	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,949,065.49	$2,615,591.81
4	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,928,422.03	$2,594,948.35
5	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,907,923.08	$2,574,449.40
6	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,887,567.61	$2,554,093.93
7	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,867,354.64	$2,533,880.96
8	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,847,283.16	$2,513,809.48
9	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,827,352.18	$2,493,878.50
10	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,807,560.71	$2,474,087.03
11	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,787,907.79	$2,454,434.11
12	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,768,392.43	$2,434,918.75
13	$0.00	($333,473.68)	($6,360,000.00)	($6,693,473.68)	$2,749,013.68	($3,944,460.00)
14	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,729,770.59	$2,396,296.91
15	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,710,662.19	$2,377,188.51
16	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,691,687.56	$2,358,213.88
17	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,672,845.75	$2,339,372.07
18	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,654,135.83	$2,320,662.15
19	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,635,556.88	$2,302,083.20
20	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,617,107.98	$2,283,634.30
21	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,598,788.22	$2,265,314.54
22	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,580,596.70	$2,247,123.02
23	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,562,532.53	$2,229,058.85
24	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,544,594.80	$2,211,121.12
25	$0.00	($333,473.68)	$0.00	($333,473.68)	$2,526,782.64	$2,193,308.96
					NPV	($23,100,399.04)

15%	$54,498,600.00	($54,498,600.00)	($23,100,399.04)	Our Scenario
20%	$51,292,800.00	($51,292,800.00)	($19,894,599.04)	
25%	$48,087,000.00	($48,087,000.00)	($16,688,799.04)	
30%	$44,881,200.00	($44,881,200.00)	($13,482,999.04)	
35%	$41,675,400.00	($41,675,400.00)	($10,277,199.04)	
40%	$38,469,600.00	($38,469,600.00)	($7,071,399.04)	
45%	$35,263,800.00	($35,263,800.00)	($3,865,599.04)	
50%	$32,058,000.00	($32,058,000.00)	($659,799.04)	
55%	$28,852,200.00	($28,852,200.00)	$2,546,000.96	Required
60%	$25,646,400.00	($25,646,400.00)	$5,751,800.96	
65%	$22,440,600.00	($22,440,600.00)	$8,957,600.96	
70%	$19,234,800.00	($19,234,800.00)	$12,163,400.96	
75%	$16,029,000.00	($16,029,000.00)	$15,369,200.96	
80%	$12,823,200.00	($12,823,200.00)	$18,575,000.96	

For Scenario 3:

Year	Energy Production (kWh)	Elec Cost ($/kWh)	Cost Saving (M$)
1	51300000	$0.067045	$3.439409
2	50940900	$0.067045	$3.415333
3	50584313.7	$0.067045	$3.391425
4	50230223.5	$0.067045	$3.367685
5	49878611.94	$0.067045	$3.344112
6	49529461.66	$0.067045	$3.320703
7	49182755.42	$0.067045	$3.297458
8	48838476.14	$0.067045	$3.274376
9	48496606.8	$0.067045	$3.251455
10	48157130.56	$0.067045	$3.228695
11	47820030.64	$0.067045	$3.206094
12	47485290.43	$0.067045	$3.183651
13	47152893.39	$0.067045	$3.161366
14	46822823.14	$0.067045	$3.139236
15	46495063.38	$0.067045	$3.117262
16	46169597.94	$0.067045	$3.095441
17	45846410.75	$0.067045	$3.073773
18	45525485.87	$0.067045	$3.052256
19	45206807.47	$0.067045	$3.030890
20	44890359.82	$0.067045	$3.009674
21	44576127.3	$0.067045	$2.988606
22	44264094.41	$0.067045	$2.967686
23	43954245.75	$0.067045	$2.946912
24	43646566.03	$0.067045	$2.926284
25	43341040.07	$0.067045	$2.905800

	INV	O&M	REP	Net Value	Cost Saving	Cash Flow
0	($64,116,000)	$0	$0	($64,116,000)	$0	($64,116,000)
1	$0	($333,474)	$0	($333,474)	$3,439,409	$3,105,935
2	$0	($333,474)	$0	($333,474)	$3,415,333	$3,081,859
3	$0	($333,474)	$0	($333,474)	$3,391,425	$3,057,952
4	$0	($333,474)	$0	($333,474)	$3,367,685	$3,034,212
5	$0	($333,474)	$0	($333,474)	$3,344,112	$3,010,638
6	$0	($333,474)	$0	($333,474)	$3,320,703	$2,987,229
7	$0	($333,474)	$0	($333,474)	$3,297,458	$2,963,984
8	$0	($333,474)	$0	($333,474)	$3,274,376	$2,940,902
9	$0	($333,474)	$0	($333,474)	$3,251,455	$2,917,981
10	$0	($333,474)	$0	($333,474)	$3,228,695	$2,895,221
11	$0	($333,474)	$0	($333,474)	$3,206,094	$2,872,620
12	$0	($333,474)	$0	($333,474)	$3,183,651	$2,850,178
13	$0	($333,474)	($6,360,000)	($6,693,474)	$3,161,366	($3,532,108)
14	$0	($333,474)	$0	($333,474)	$3,139,236	$2,805,762
15	$0	($333,474)	$0	($333,474)	$3,117,262	$2,783,788
16	$0	($333,474)	$0	($333,474)	$3,095,441	$2,761,967
17	$0	($333,474)	$0	($333,474)	$3,073,773	$2,740,299
18	$0	($333,474)	$0	($333,474)	$3,052,256	$2,718,783
19	$0	($333,474)	$0	($333,474)	$3,030,890	$2,697,417
20	$0	($333,474)	$0	($333,474)	$3,009,674	$2,676,200
21	$0	($333,474)	$0	($333,474)	$2,988,606	$2,655,133
22	$0	($333,474)	$0	($333,474)	$2,967,686	$2,634,213
23	$0	($333,474)	$0	($333,474)	$2,946,912	$2,613,439
24	$0	($333,474)	$0	($333,474)	$2,926,284	$2,592,810
25	$0	($333,474)	$0	($333,474)	$2,905,800	$2,572,326
					NPV	($26,797,148)

	Ele Cost + %	NPV	
15%	0.067045	($26,797,148.40)	Our Scenario
20%	0.06996	($24,796,516.87)	
30%	0.07579	($20,869,727.42)	
40%	0.08162	($16,942,937.97)	
50%	0.08745	($12,948,445.26)	
60%	0.09328	($9,021,655.80)	
70%	0.09911	($5,094,866.35)	
80%	0.10494	($1,168,076.90)	
85%	0.107855	$863,021.09	Required
90%	0.11077	$2,826,415.81	

For scenario 4:

Year	Energy Production (kWh)	Fuel Cost ($/kWh)	Cost Saving (M$)	Fuel Price ($/kWh) Based on 4$/MMBtu	Extra Saving ($/kWh)	Extra Cost Saving
1	51300000	0.0374	1918620	0.033824	0.071224	3653791.2
2	50940900	0.0374	1905189.66	0.033824	0.071224	3628214.662
3	50584313.7	0.0374	1891853.332	0.033824	0.071224	3602817.159
4	50230223.5	0.0374	1878610.359	0.033824	0.071224	3577597.439
5	49878611.94	0.0374	1865460.087	0.033824	0.071224	3552554.257
6	49529461.66	0.0374	1852401.866	0.033824	0.071224	3527686.377
7	49182755.42	0.0374	1839435.053	0.033824	0.071224	3502992.572
8	48838476.14	0.0374	1826559.008	0.033824	0.071224	3478471.624
9	48496606.8	0.0374	1813773.094	0.033824	0.071224	3454122.323
10	48157130.56	0.0374	1801076.683	0.033824	0.071224	3429943.467
11	47820030.64	0.0374	1788469.146	0.033824	0.071224	3405933.862
12	47485290.43	0.0374	1775949.862	0.033824	0.071224	3382092.325
13	47152893.39	0.0374	1763518.213	0.033824	0.071224	3358417.679
14	46822823.14	0.0374	1751173.585	0.033824	0.071224	3334908.755
15	46495063.38	0.0374	1738915.37	0.033824	0.071224	3311564.394
16	46169597.94	0.0374	1726742.963	0.033824	0.071224	3288383.443
17	45846410.75	0.0374	1714655.762	0.033824	0.071224	3265364.759
18	45525485.87	0.0374	1702653.172	0.033824	0.071224	3242507.206
19	45206807.47	0.0374	1690734.599	0.033824	0.071224	3219809.655
20	44890359.82	0.0374	1678899.457	0.033824	0.071224	3197270.988
21	44576127.3	0.0374	1667147.161	0.033824	0.071224	3174890.091
22	44264094.41	0.0374	1655477.131	0.033824	0.071224	3152665.86
23	43954245.75	0.0374	1643888.791	0.033824	0.071224	3130597.199
24	43646566.03	0.0374	1632381.57	0.033824	0.071224	3108683.019
25	43341040.07	0.0374	1620954.899	0.033824	0.071224	3086922.238

	INV	O&M	REP	Net Value	Cash Flow +
0	($64,116,000.00)	$0.00	$0.00	($64,116,000.00)	($64,116,000.00)
1	$0.00	($333,473.68)	$0.00	($333,473.68)	$5,238,937.52
2	$0.00	($333,473.68)	$0.00	($333,473.68)	$5,199,930.64
3	$0.00	($333,473.68)	$0.00	($333,473.68)	$5,161,196.81
4	$0.00	($333,473.68)	$0.00	($333,473.68)	$5,122,734.12
5	$0.00	($333,473.68)	$0.00	($333,473.68)	$5,084,540.66
6	$0.00	($333,473.68)	$0.00	($333,473.68)	$5,046,614.56
7	$0.00	($333,473.68)	$0.00	($333,473.68)	$5,008,953.95
8	$0.00	($333,473.68)	$0.00	($333,473.68)	$4,971,556.95
9	$0.00	($333,473.68)	$0.00	($333,473.68)	$4,934,421.74
10	$0.00	($333,473.68)	$0.00	($333,473.68)	$4,897,546.47
11	$0.00	($333,473.68)	$0.00	($333,473.68)	$4,860,929.33
12	$0.00	($333,473.68)	$0.00	($333,473.68)	$4,824,568.51
13	$0.00	($333,473.68)	($6,360,000.00)	($6,693,473.68)	($1,571,537.79)
14	$0.00	($333,473.68)	$0.00	($333,473.68)	$4,752,608.66
15	$0.00	($333,473.68)	$0.00	($333,473.68)	$4,717,006.08
16	$0.00	($333,473.68)	$0.00	($333,473.68)	$4,681,652.73
17	$0.00	($333,473.68)	$0.00	($333,473.68)	$4,646,546.84
18	$0.00	($333,473.68)	$0.00	($333,473.68)	$4,611,686.70
19	$0.00	($333,473.68)	$0.00	($333,473.68)	$4,577,070.57
20	$0.00	($333,473.68)	$0.00	($333,473.68)	$4,542,696.77
21	$0.00	($333,473.68)	$0.00	($333,473.68)	$4,508,563.57
22	$0.00	($333,473.68)	$0.00	($333,473.68)	$4,474,669.31
23	$0.00	($333,473.68)	$0.00	($333,473.68)	$4,441,012.31
24	$0.00	($333,473.68)	$0.00	($333,473.68)	$4,407,590.91
25	$0.00	($333,473.68)	$0.00	($333,473.68)	$4,374,403.46
				NPV	$1,353,192.74

Environment analysis:

Year	CO_2	SO_2	Nox	Energy Production (kWh)
1	0.7	0.02	0.033	51300000
2	0.7	0.02	0.033	50274000
3	0.7	0.02	0.033	49268520
4	0.7	0.02	0.033	48283149.6
5	0.7	0.02	0.033	47317486.61
6	0.7	0.02	0.033	46371136.88
7	0.7	0.02	0.033	45443714.14
8	0.7	0.02	0.033	44534839.86
9	0.7	0.02	0.033	43644143.06
10	0.7	0.02	0.033	42771260.2
11	0.7	0.02	0.033	41915834.99
12	0.7	0.02	0.033	41077518.29
13	0.7	0.02	0.033	40255967.93
14	0.7	0.02	0.033	39450848.57
15	0.7	0.02	0.033	38661831.6
16	0.7	0.02	0.033	37888594.97
17	0.7	0.02	0.033	37130823.07
18	0.7	0.02	0.033	36388206.61
19	0.7	0.02	0.033	35660442.47
20	0.7	0.02	0.033	34947233.62
21	0.7	0.02	0.033	34248288.95
22	0.7	0.02	0.033	33563323.17
23	0.7	0.02	0.033	32892056.71
24	0.7	0.02	0.033	32234215.57
25	0.7	0.02	0.033	31589531.26

Year	CO_2	SO_2	Nox
1	35910000	1026000	1692900
2	35191800	1005480	1659042
3	34487964	985370.4	1625861.16
4	33798204.7	965662.992	1593343.94
5	33122240.6	946349.732	1561477.06
6	32459795.8	927422.738	1530247.52
7	31810599.9	908874.283	1499642.57
8	31174387.9	890696.797	1469649.72
9	30550900.1	872882.861	1440256.72
10	29939882.1	855425.204	1411451.59
11	29341084.5	838316.7	1383222.55
12	28754262.8	821550.366	1355558.1
13	28179177.5	805119.359	1328446.94
14	27615594	789016.971	1301878
15	27063282.1	773236.632	1275840.44

16	26522016.5	757771.899	1250323.63
17	25991576.1	742616.461	1225317.16
18	25471744.6	727764.132	1200810.82
19	24962309.7	713208.849	1176794.6
20	24463063.5	698944.672	1153258.71
21	23973802.3	684965.779	1130193.54
22	23494326.2	671266.463	1107589.66
23	23024439.7	657841.134	1085437.87
24	22563950.9	644684.311	1063729.11
25	22112671.9	631790.625	1042454.53
Total in Tons	711979.08	20342.26	33564.73

APPENDIX C: COMPONENTS DATA SHEETS

SG1250UD/SG1500UD

SUNGROW
Clean power for all

Outdoor Inverter for 1000 Vdc System

HIGH YIELD

- Efficient three-level topology, max. efficiency up to 99 %, European efficiency 98.7 %
- Full power operation without derating at 50 ℃
- Long-time overload at 1.1 Pn
- DC/AC ratio up to 1.5

EASY O&M

- Integrated intelligent control unit for fast trouble shooting
- Modular design easy for maintenance
- IP65 protection

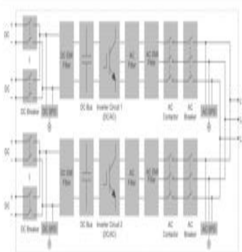
SAVED INVESTMENT

- Can be connected to double-winding transformer, saving transformer costs

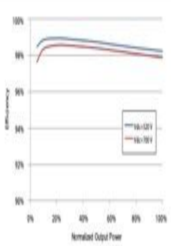
GRID SUPPORT

- Compliance with standards: CE, IEC 62109, IEC61727, IEC62116
- Low/High voltage ride through (L/HVRT)
- Active & reactive power control and power ramp rate control

CIRCUIT DIAGRAM



EFFICIENCY CURVE



Type designation	SG1250UD	SG1500UD
Input (DC)		
Max. PV input voltage	1100 V	
Min. PV input voltage / Startup input voltage	520 V / 540 V	580 V / 600 V
MPP voltage range for nominal power	520 – 850 V	580 – 850 V
No. of independent MPP inputs	2	
No. of DC inputs	12 (Optional: 12 – 18)	14 (Optional: 12 – 18)
Max. PV input current	2 * 1356 A	2 * 1448 A
Max. DC short-circuit current	3200 A	
Output (AC)		
AC output power	1375 kVA @ 45 ˚C / 1250 kVA @ 50 ˚C	1650 kVA @ 45 ˚C / 1500 kVA @ 50 ˚C
Max. AC output current	2222 A	2381 A
Nominal AC voltage	360 V	400 V
AC voltage range	288 – 414 V	320 – 460 V
Nominal grid frequency / Grid frequency range	50 Hz / 45 – 55 Hz, 60 Hz / 55 – 65 Hz	
THD	< 3 % (at nominal power)	
DC current injection	< 0.5 % of nominal output current	
Power factor at nominal power	> 0.99	
Adjustable power factor	0.8 leading – 0.8 lagging	
Feed-in phases / Connection phases	3 / 3	
Efficiency		
Max. efficiency	99.0 %	
Euro. efficiency	98.7 %	
Protection		
DC input protection	Circuit breaker	
AC output protection	Circuit breaker	
Overvoltage protection	DC Type II / AC Type II	
Grid monitoring / Ground fault monitoring	Yes / Yes	
Insulation monitoring	Yes	
Overheat protection	Yes	
Anti-PID function	Yes	
General Data		
Dimensions (W*H*D)	2150 * 2120 * 850 mm	
Weight	1900 kg	
Isolation method	Transformerless	
Degree of protection	IP65	
Auxilury power supply	220 Vac, 2 kVA	
Night power consumption	< 40 W	
Operating ambient temperature range	-35 to 60 ℃ (> 50 ℃ derating)	
Allowable relative humidity range (non-condensing)	0 – 95 %	
Cooling method	Temperature controlled forced air cooling	
Max. operating altitude	4500 m (> 3000 m derating)	
Display	Touch screen	
Communication	RS485, Ethernet	
Compliance	IEC62109-1, IEC62109-2, IEC61727, IEC62116	
Grid support	LVRT, HVRT, active & reactive power control and power ramp rate control	

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Superpoly STP355 - 24/Vfh
STP350 - 24/Vfh
STP345 - 24/Vfh

SUNTECH

355 Watt
POLY HALF CELL SOLAR MODULE

Features

High power output
Compared to normal module, the power output can increase 5W-10W

High PID resistant
Advanced cell technology and qualified materials lead to high resistance to PID

Excellent weak light performance
More power output in weak light condition, such as haze,cloudy ,and morning

lower hot spots
Reduce the hot spots and minimize panel degradation

Extended load tests
Module certified to withstand front side maximum static test load (5400 Pascal) and rear side maximum static test loads (3800 Pascal) *

Withstanding harsh environment
Reliable quality leads to a better sustainability even in harsh environment like desert, farm and coastline

Certifications and standards: IEC 61215, IEC 61730, conformity to CE

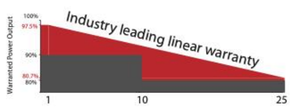
Trust Suntech to Deliver Reliable Performance Over Time

- World-class manufacturer of crystalline silicon photovoltaic modules
- Unrivaled manufacturing capacity and world-class technology
- Rigorous quality control meeting the highest international standards: ISO 9001: 2008, ISO 14001: 2004 and ISO17025: 2005
- Regular independently checked production process from international accredited institute/company
- Tested for harsh environments (salt mist, ammonia corrosion and sand blowing testing: IEC 61701, IEC 62716, DIN EN 60068-2-68)***
- Long-term reliability tests
- 2 x 100% EL inspection ensuring defect-free

Special Cell Design

The unique cell design leads to reduced electrodes resistance and smaller current, thus enables higher fill factor. Meanwhile, it can reduce losses of mismatch and cell wear, and increase total reflection.

Industry-leading Warranty based on nominal power



- 97.5% in the first year, thereafter, for years two (2) through twenty-five (25), 0.7% maximum decrease from MODULE's nominal power output per year, ending with the 80.7% in the 25th year after the defined WARRANTY STARTING DATE.****
- 12-year product warranty
- 25-year linear performance warranty

IP68 Rated Junction Box

IP68

The Suntech IP68 rated junction box ensures an outstanding waterproof level, supports installations in all orientations and reduces stress on the cables. High reliable performance, low resistance connectors ensure maximum output for the highest energy production.

* Please refer to Suntech Standard Module Installation Manual for details. **WEEE only for EU market.
*** Please refer to Suntech Product Near-coast Installation Manual for details. **** Please refer to Suntech Product Warranty for details.

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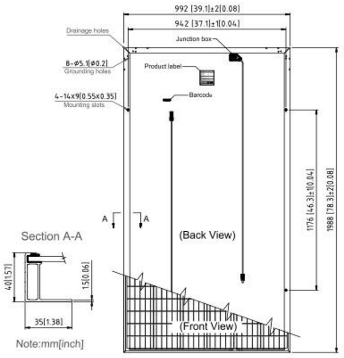
Superpoly STP355 - 24/Vfh STP350 - 24/Vfh STP345 - 24/Vfh

SUNTECH



Electrical Characteristics

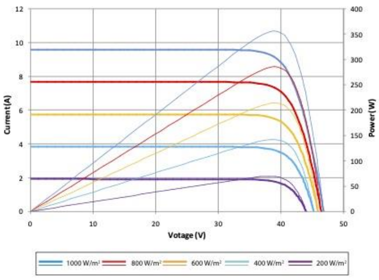
STC	STP355-24/Vfh	STP350-24/Vfh	STP345-24/Vfh
Maximum Power at STC (Pmax)	355 W	350 W	345 W
Optimum Operating Voltage (Vmp)	39.4 V	39.2 V	38.6 V
Optimum Operating Current (Imp)	9.02 A	8.93 A	8.94 A
Open Circuit Voltage (Voc)	46.8 V	46.6 V	46.1 V
Short Circuit Current (Isc)	9.60 A	9.52 A	9.44 A
Module Efficiency	18.0%	17.7%	17.5%
Operating Module Temperature	-40 °C to +85 °C		
Maximum System Voltage	1000/1500 V DC (IEC)		
Maximum Series Fuse Rating	20 A		
Power Tolerance	0/+5 W		

STC: Irradiance 1000 W/m², module temperature 25 °C, AM=1.5;
Tolerances of Pmax, Voc and Isc are all within +/- 5%.

NMOT	STP355-24/Vfh	STP350-24/Vfh	STP345-24/Vfh
Maximum Power at NMOT (Pmax)	265.7 W	263.3 W	259.0 W
Optimum Operating Voltage (Vmp)	36.0 V	36.0 V	35.7 V
Optimum Operating Current (Imp)	7.38 A	7.32 A	7.26 A
Open Circuit Voltage (Voc)	43.5 V	43.6 V	43.1 V
Short Circuit Current (Isc)	7.77 A	7.70 A	7.64 A

NMOT: Irradiance 800 W/m², ambient temperature 20 °C, AM=1.5, wind speed 1 m/s;

Current-Voltage & Power-Voltage Curve (355)



Temperature Characteristics

Nominal Module Operating Temperature (**NMOT**)	42±2°C
Temperature Coefficient of Pmax	-0.38 %/°C
Temperature Coefficient of Voc	-0.33 %/°C
Temperature Coefficient of Isc	0.067 %/°C

Mechanical Characteristics

Solar Cell	Polycrystalline silicon 6 inches
No. of Cells	144 (6 × 24)
Dimensions	1988 × 992 × 40mm (78.3× 39.1 × 1.6 inches)
Weight	22.3 kgs (49.2 lbs.)
Front Glass	3.2 mm (0.13 inches) tempered glass
Frame	Anodized aluminium alloy
Junction Box	IP68 rated (3 bypass diodes)
Output Cables	4.0 mm² (0.006 inches²), symmetrical lengths (-) 1400mm (55.12 inches) and (+) 1400 mm (55.12 inches)
Connectors	MC4 compatible (1000V) MC4 EVO2, Cable01S(1500V)

Dealer information

Packing Configuration

Container	20' GP	40' HC
Pieces per pallet	26	26
Pallets per container	5	22
Pieces per container	130	572

Information on how to install and operate this product is available in the installation instruction. All values indicated in this data sheet are subject to change without prior announcement. The specifications may vary slightly. All specifications are in accordance with standard EN 50380. Color differences of the modules relative to the figures as well as discolorations of/in the modules which do not impair their proper functioning are possible and do not constitute a deviation from the specification.