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Design of a Utility Scale Solar Farm in Saudi Arabia

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Abstract

Saudi Arabia plans to generate 3.45GW of its energy from renewable sources by 2020 and 9.5 GW by 2023. This project addresses the lack of literature on the design and feasibility of large scale solar in Saudi Arabia. This project went through different design steps with proper justification in designing a 50 MW solar farm. Site selection was carried out using Solar GIS to find the optimum location in terms of irradiance, terrain, proximity to roads and air temperature. Then a PV module was selected from a comprehensive list of all available modules in the market by evaluating the modules based on fill factor, efficiency, degradation rate, power density and module price. PVsyst was then used to simulate the project and the results were displayed and discussed. These results include Loss analysis, energy generated analysis and temperature performance. Next, an economic analysis was carried out which showed that the payback period for this project is 6 years, 315.9% return on investment (ROI) and 164 million USD net profit by the end of the project lifetime (25 years). Lastly, CO2 balance analysis was reported which showed that over the project lifetime Saudi Arabia would be able to save more than 1.68 million tons of CO_2 emissions.

Keywords: Fossil fuels; Sustainability; Air temperature; Solar irradiance; Renewable Energy, Co_2 emission

Introduction

Saudi Arabia is planning a grand scheme that would entail a massive shift from the consumption of oil to alternative energy sources, mitigating its dependence on fossil fuels while also working towards fulfilling its commitments to CO_2 reduction. The government has established a program named Saudi Arabia's National renewable energy program (NREP). NREP announced that 3.45GW and 9.5GW of its energy production would be generated by renewable sources by 2020 and 2023 respectively. A memorandum of understanding has been signed by Saudi Arabia and SoftBank Group Corp. to build a 200 billion USD solar project by 2030 [1]. Moreover, according to the World Economic Forum, it is currently investing around £38 billion pounds in solar and wind farms [2]. Such ambitious plans require studies to be produced to address the lack of literature on solar PV power plants in Saudi Arabia.

Examples of current solar PV plants (over 1 megawatt) in Saudi Arabia include a 2MW solar plant location in Thuwal, north of Jeddah [3]. A 10 MW carport system in Dhahran [3] and 300MW plant located in Sakaka and Al-Jouf regions, which was established in February 2018 [4]. The potential for large scale solar PV in Different locations in Saudi Arabia was studied in [5].

Background Information

While Saudi Arabia is a key oil producer and exporter, it is also the largest consumer of energy in the Middle East. By 2032, Saudi Arabia has made plans to increase its electricity generation capacity to 12 Gigawatts in order to fulfill the country's fast-growing electricity demand. According to British Petroleum (BP) Statistical review of World Energy 2014, Saudi Arabia produced 29.2 billion kilowatt-hours of electric energy in 2013 [6].

During the period between 2006 and 2016, Saudi Arabia's electricity consumption increased by 7.5 to 10% annually. This swift increase in electricity demand is driven by growth in population, rapidly growing industrial sector due to the expansion of petrochemical cities, elevated need for air conditioning during summer, and strongly subsidized electricity supply rates [6]. According to the Middle East Economic Survey, Saudi Arabia has the largest expansion plan in the Middle East for energy production from renewable sources. For this purpose, the King Abdullah City for Atomic and Renewable Energy (K.A. CARE) was established in 2010 in order to build a sustainable future for Saudi Arabia through the inclusion of nuclear energy and renewable energy sources within the local energy system. Saudi Arabia plans by 2032 to add 41 GW of solar power, 18 GW of nuclear power, and 4GW from other renewable sources to expand its electricity supply [6]. IEA is the international energy agency made up of more than 30 countries that produces renewable energy studies. According to one of their studies [7] global solar PV capacity is expected to grow to over 1TW by 2023 (Figure 1).

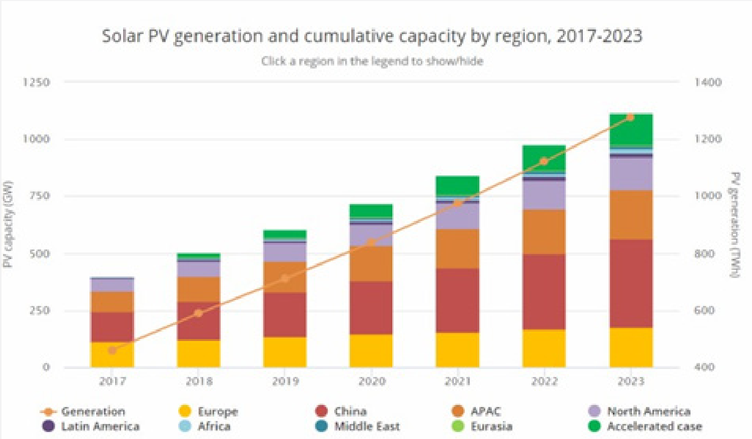

Figure 1: Global Solar PV projections.

Table1: Mena Pv Installed Capacity [8].

Country	PV Capacity (MW)	Year Recorded
Algeria	7.1	2010
Bahrain	5	2011
Egypt	15	2012
Iran	4.3	2010
Iraq	3.5	2009
Kuwait	1.8	2010
Libya	4.8	2012
Oman	0.7	2010
Qatar	1.2	2010
Saudi Arabia	7	2013
Syria	0.84	2010
UAE	1.5	2012
Yemen	1.5	2012
Djibouti	1.4	2010
Israel	269	2012
Jordan	1.6	2012
Lebanon	1	2012
Malta	12	2011
Morocco	15	2012
Palestinian	1	2012
Tunisia	4	2012

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As can be seen in Figure 1, the share of the Middle Eastland North Africa of solar PV production is almost invisible even though the region enjoys high solar resources and high GDP. According to [8], which was published in 2016, the latest installed PV capacities in the Middle Eastland North Africa as of 2016 are listed in Table 1. The International Renewable Energy Agency (IRENA) is an intergovernmental organization supporting countries in their transition to a sustainable energy future. In 2019, it published a report that included the latest figures for renewables in the gulf region (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and United Arab Emirates (UAE)) updated as of the end of 2018 [9].

As can be seen by comparing the two tables; while Bahrain, Oman and Qatar saw a slight increase in their solar capacity, the UAE and Saudi Arabia boomed with over 1000% increase in their PV capacity in the period between 2012 and 2018. This highlights the countries' increased efforts to meet their sustainability targets by subsidizing renewable energy generation to facilitate their penetration. Figure 2 summarizes the sustainability goals of the different gulf countries [9].

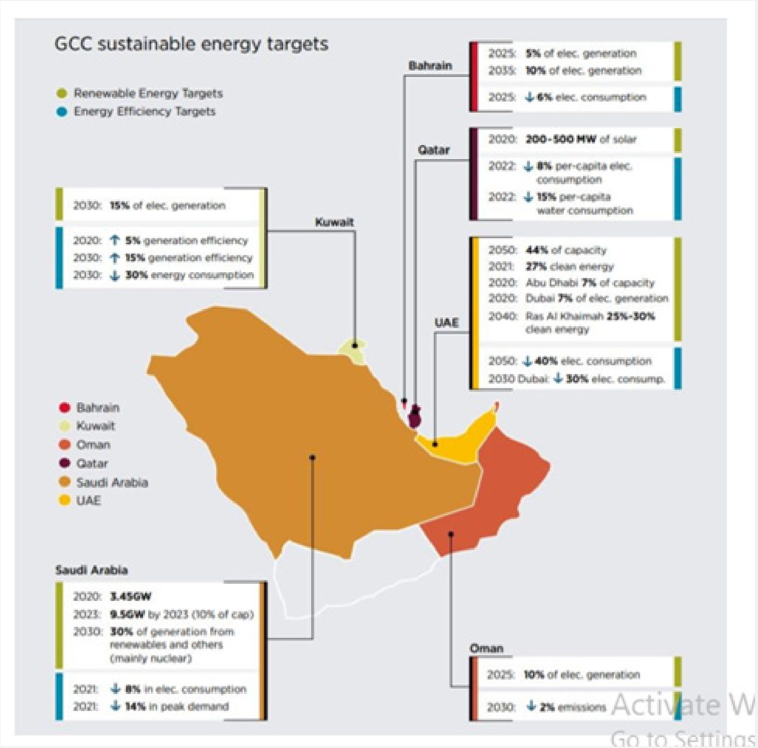

Figure 2: Sustainability goals of the gulf region.

Aims and Objectives

This project will execute the design and examine the feasibility of a 50 MW solar PV farm in Saudi Arabia. The project aims to study and enumerate the various variables that are of significance to Solar PV design through thorough methodology and research. The project will go through the following phases:

a) Site Selection

b) PV module selection and design

c) Inverter selection

d) Losses analysis

Methodology

Site selection

Criteria that determine the optimal site for solar PV farm is obtained from the research paper 'Solar PV power plant site selection using a GIS-AHP based approach with application in Saudi Arabia' by Hassan Z. Al Garni and Anjali Awasthi [5]. The criteria implemented in this project are:

a) Solar irradiance

b) Air temperature

c) Terrain

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d) Road proximity

To analyze the above criteria, Solargis online tool was used. Solargis tool shows the irradiance level at each point. According to the above-mentionedpaper [5], the author states that the optimal location for solar PV in Saudi Arabia is near Tabuk city.Hence,a location with low terrain and high irradiance level near Tabuk city was searched for. It was found that the global horizontal yearly average irradiance level of 2397 KWh/m², which is close to shigry as shown in Figure 3.

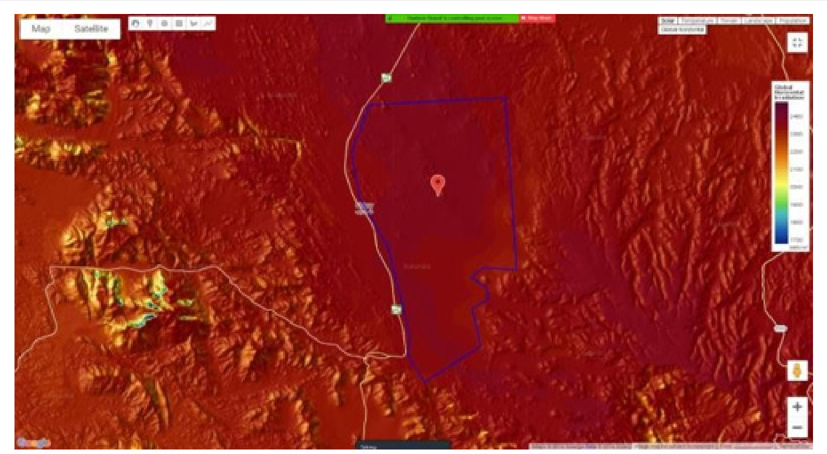

Figure 3: Site selection irradiance.

From Figure 4, the maximum temperature at the costal side of the red sea is around 3°C and falls to 28.5°C near Tabuk city. In the selected region the temperature lies between 16°C and 20°C annual average temperature and since the Standard Test Conditions (STC) temperature for PV panels is 25°C and as the temperature decreases the efficiency increases [10]. It can be expected that the output of the solar farm will increase in winter and decrease slightly in summer due to the increased ambient temperature.

$$V_{oc,\mathrm{mod}} = Temp.coeff.X(TSTC[^{o}C] - T\,\mathrm{mod}[^{o}C]) + V_{oc,rated}[V] \qquad (1)$$

Where

a) $V_{oc,\,mod}$ is the open circuit voltage at current temperature.

b) TSTC[°C] = temperature at standard test conditions ,25°C, 1000 W/m² solar irradiance.

c) Tmod [°C] = module temperature.

d) $V_{oc,\,rated}$ is the open circuit voltage at STC.

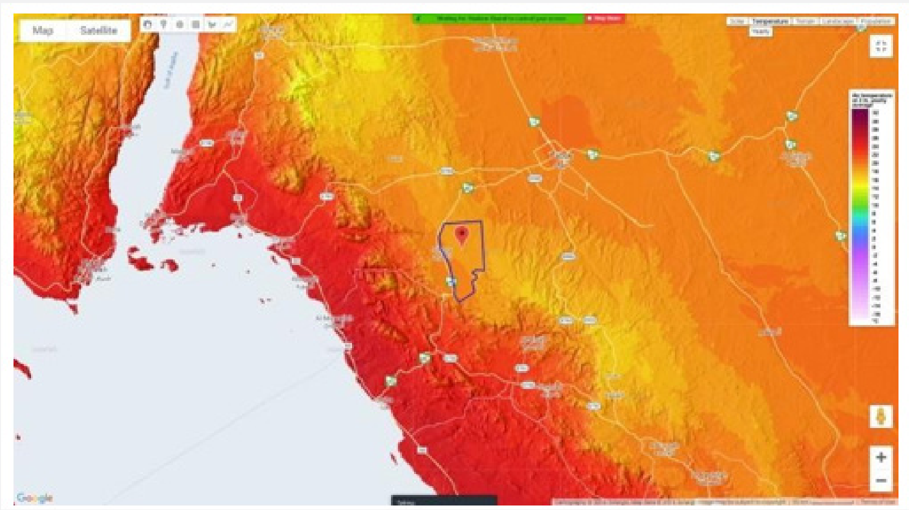

Figure 4: Site selection temperature.

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From this equation, it is evident that as the module temperature decreases below STC levels the open circuit voltage of the module increases. The module temperature is affected by the ambient temperature. As the ambient temperature decreases, it further increases the power curve as can be seen in Figure 5. The reason the average annual temperature is low in this area could be due to the high elevation of the land (1092m) (Table 2).

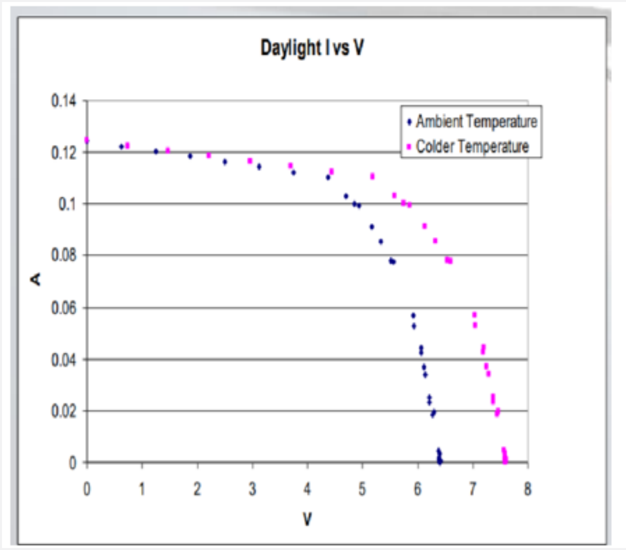

Figure 5: IV power curve of PV cell. Power is greater at lower temperatures.

Table 2: Gulf Region Pv Capacity by the end of 2018 [9].

Country	PV Capacity (MW)
Bahrain	5
Kuwait	19
Oman	8
Qatar	5
Saudi Arabia	89
UnitedArab Emirates	487

For the ease of installation of the large scale, solar, flat terrain that is near to roads is required. As can be seen in Figure 6. The area selected is on a flat area near to the road this minimizes land leveling and transportation costs. The area is sparsely vegetated which means it requires minimum land clearing. The total area of the selected land is 494.8 km^2 it is expected that only a small fraction of this area will be used for the project. The slope of the area is minimal at 0.7° as can be seen in Figure 7. Figure 7 also shows important figures in the right panel under the title “Site info”.

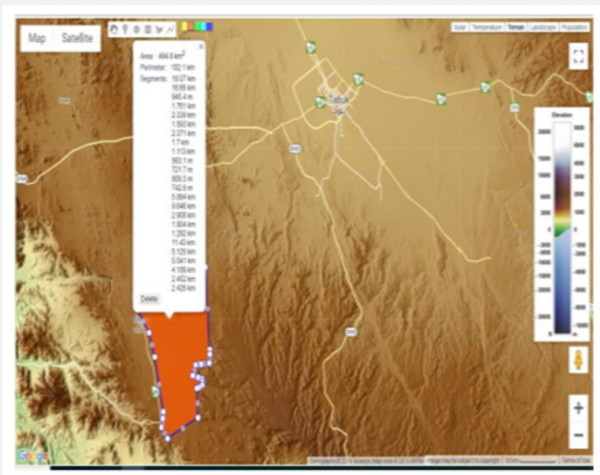

Figure 6: Site selection terrain.

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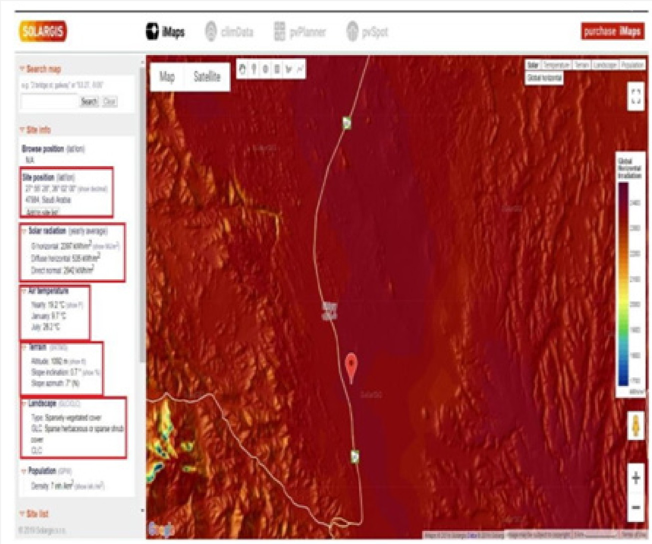

Figure 7: Site selection overall.

PV Module Selection

In order for optimum PV module selection, different selection parameters are covered in this section which include fill factor, efficiency, degradation rate, power density and module price. By studying these parameters, an informed decision can be made on which PV module is optimum for this design.

PV Module Selection Criteria

Fill Factor

According to [11] the fill factor is a measure of the squareness of the I-V characteristics of the solar cell. The factors affecting the fill factors are:

a) The series resistance of the solar cell

b) The parallel resistance of the solar cell

c) The recombination current in the space charge region of the cell

d) The reverse saturation current of the junction

$$FF = \frac{P_m}{(V_{oc} I_{sc})} \quad (2)$$

Where:

P_m is the maximum output power

V_{oc} is the open circuit voltage

I_{sc} is the short circuit current

Ideally, FF = 1, The fill factor decreases as the cell temperature increases. Decreases in fill factor may indicate problems with the cell. A good fill factor based on [11] starts at 0.7.

Efficiency

Efficiency is another measure of PV cell that is sometimes reported. Efficiency is defined as the maximum electrical power output divided by the incident light power. Efficiency is commonly reported for a PV cell temperature of 25°C and incident light at an irradiance of 1000W/m^2 with a spectrum close to that of sunlight at solar noon. An improvement in cell efficiency is directly connected to cost reduction in photovoltaic systems. [11] Maximum efficiency is the ratio between the maximum power and the incident light power, given by:

$$\mu_{max} = \frac{P_{max}}{P_{in}} = \frac{I_{max} V_{max}}{A G_T} \quad (3)$$

Where

a) A = PV cell area (m^2)

b) GT =solar insolation over the cell (Watt/m^2)

Degradation rate

The degradation rate of solar PV is the loss of efficiency every year. Degradation is strongly correlated with weather conditions i.e. panels in harsh (either too hot or too cold) climates suffer higher degradation than panels in moderate climates [12]. According to the national renewable energy laboratory [13], which is a U.S. government associated body that examined the long-term degradation of multiple PV panels. They found that panels made prior to the year 2000 often achieved less than 1% degradation and that modern panels achieve even lower. Old monocrystalline silicon achieves less than 0.5% per year degradation rate and modern less than 0.4%. This means that panels made after the year 2000 should produce 92% of its original power after 20

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years. In [14] the authors examined 11000 degradation rates from 200 studies and analysed them. They found that the median degradation rate for crystalline silicon PV was 0.5-0.6% per year with a mean of 0.8-0.9% per year. Micro silicon and hetero interface PV exhibited a 1%/ year degradation.

Power density

Power density is an important factor to consider since at higher power densities more energy is produced using less area.

$$Power_{density} = \frac{P_{\max}}{Area}\left(\frac{Watt}{m^2}\right) \qquad (4)$$

Analysis

To select the most optimum PV module and manufacturer a list of all available PV modules was obtained from [15]. The excel file contained approximately 22000PV modules updated as of April 2019 and categorized under different performance parameters. Building integrated modules and modules that produce AC power (micro inverter) were omitted.

Initially B_{Voc} was looked at as it is the temperature coefficient. The module, which performs best under hot climate, was found to be REC260TP, which is made by REC Solar with a temperature coefficient of -0.03%/degree C. However, since the temperature in the selected site is very mild (16°C to 20°C annual average temperature) this parameter was disregarded in favor of fill factor and efficiency.

The fill factor was not provided in the file produced by go solar california and had to be manually inputted. The fill factor equation was $\frac{S*R}{Q*P}$

Where S is V_{pmax}, R is I_{pmax} Q is V_{oc} and P is I_{sc}. The best module with the highest fill factor was China Sunergy (Nanjing) CSUN275-60P with a fill factor of 0.97377 however; this specific module was not available on PVSYST.

The next parameter in consideration was efficiency, which also had to be manually added. The equation for which was

$$= \frac{E}{(1000*AG*AF)*100}$$

where E is the P_{max}, AG is the longside and AF is the shortside. The best performing module in terms of efficiency was LG370Q1C-A5, which is manufactured by LG electronics with an efficiency of 22.13437% however; this module was also not available on PVSYST.

Efficiency: PV modules ranging between 19.5 - 22 percent efficiency are considered and sorted out from highest to lowest.

Fill Factor: PV modules ranging between 0.72 – 0.79 are considered and sorted out from highest to lowest after efficiency sorting.

Power Density (Watt/m²): Size of the PV is considered such that it gives out maximum power within that size of the module. Hence, Pmax divided by the area of the panel (short side * long side) is determined. (Equation 4).

Degradation rate: The latest commercial SunPower solar PV panels such as (SPR-X22-360-COM) has a degraded output of 92% and greater after 25 years, LG's latest solar PV panel variants called 'Neon R' gives out 88.4% of the output after 25 years based on the data sheets provided by SunPower and LG [16,17].

The top 5 choices after filtering and sorting were:

a) LG370Q1C-A5

b) SPR-X22-360-COM

c) SPR-X22-359

d) SPR-X22-475-COM

e) LG365Q1C-A5

Prices for the modules were hard to obtain which turned consideration from 5 to 3 options. LG370Q1C-A5 was available at 0.95 USD/Watt, which makes the total panel, cost equal to 47.5 million USD for a 50 MW project (retail price). [18] SPR-X22-360-COM was available at 1.74 USD/Watt which makes the total panel cost equal to 87 million USD for a 50 MW project (retail price) [19]. LG365Q1C-A5 was available at 0.91 USD/Watt which makes the total panel cost equal to 45.5 million USD for a 50 MW project (retail price) [20].

The final comparison between LG and SunPower yielded the following conclusions

a) They are both high in efficiency and fill factor 2- LG is cheaper than SunPower

b) SunPower has a lower degradation rate than LG

c) LG is a more established manufacturer and so more likely to uphold the warranty

Since the project lifetime will be set as 25 years LG is picked as the more favorable manufacturer due to the lower price point of its product. Even though LG365Q1C-A5 will take more area than LG370Q1C-A5 the difference in area is small while there is 2 million USD difference in price and so LG365Q1C-A5 is chosen as the optimum PV module.

The total area that will be occupied by the plant was found to be = 0.23 Km² the equation to find the plant area is:

$$Area\ required = \left(\frac{total\ power}{individual\ cell\ rated\ power}\right) * (cell\ length * cell\ width \qquad (5)$$

The value of the area obtained was later verified through PVsyst. Since the area selected in the previous section was 494.8 km². there is more than enough space to create the project practically. The project will take up 0.046% of the proposed area.

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Supporting structure

For this project, supporting structures provided by Soeasy (Xiamen) Photovoltaic Technology Co., Ltd [21]. The reason this company's product was chosen is because it is reasonably priced, and the company has high reputation on alibaba.com. The total cost of the structure is 4.61 million USD

Inverter selection

A full list of inverters available in the market was obtained from [22]. The list contained a column titled microinverters with values N for No Y for yes and Blank. The list was filtered so that only central inverters that are not micro inverters were shown. Then operating power was filtered so as to minimize the number of inverters used. Inverters with a power of 1.5MW upwards were chosen. Sunny central SC- 2200-Us inverter manufactured by SMA was chosen. It has 2200kw power, 570 minimum voltage, 950 maximum voltage and 665 nominal voltage. Initially Sunny central 3000 kw was chosen, but it generated some errors on PVsyst such as increased overload loss and higher Pnom ratio which, went down as the number of inverters increased. However, another error displayed as "the array Voc at -10 C is greater than the absolute system voltage allowed for this module" persisted even as the number of inverters was increased making this module not compatible with this application.

The price of the inverter was not directly obtainable. So, the per watt cost of a 700kwatt sunny central inverter was found to be 0.18 USD/Watt. A trend can be noted that as the power output of the inverter increases, the per watt cost of the inverter decreases. It could very well be the case that 2200 KWatt inverter is priced lower than 0.18 USD/Watt but since the exact price could not be found, 0.18 USD/Watt is taken as the unit price. For a 44 Mega Watt system the price of the inverters is (44*10^6) *0.18 or 7.92 million USD [23].

Balance of system (BOS) components

a) AC and DC cables

b) Fuses or over current protection units

c) AC and DC switches

d) Array junction box or combiner box

e) Connectors

f) AC and DC surge protection devices

g) Earthing system

h) Lightning protection system (LPS)

i) Special connectors for PV modules, string cables and inverters

j) Supporting structures

k) Land cost

l) Labour cost

Land cost is not included since it is assumed based on the current political situation that the government of Saudi Arabia will carry out this project so no land capital will be allocated. Labour cost is cheap in Saudi Arabia compared to the developed countries and inverter and supporting structure costs have already been included elsewhere. Therefore, the lowest figure for BOS found in a credible source shall be taken. In [24] IRENA states that the lowest cost of BOS is 20% of the total cost. Based on the previous justification this figure shall therefore be used for this project.

PVsyst steps

PVsyst simulation tool was used to design a solar PV farm in the selected location. Meteorological data from meteonorm was used and the respective file was created in PVsyst. By entering the site coordinates, metrological data was obtained with PVsyst and a new location was created since shigri was not one of the locations registered on PVsyst. In PVsyst, under project design a grid-connected system is selected. The project is named Neom; a new site file is created by selecting the site on the interactive map and clicking on import, which provides the details of the site automatically. Then, the meteorological data is imported from meteonorm 7.2 and the file is saved and named shigiri. The project is saved to proceed with the design.

In the orientation tab, orientation of the PV system was determined using the optimization tool within PVsyst. 'Fixed tilted plane', is selected and the plane is tilt of 30° was obtained and kept the orientation of the panels to perfect south (i.e., Azimuth = 0°) since axis tracking would incur additional cost and add complexity beyond the scope of this work. Tilt angle of 30° was chosen based on the angle optimization tool in PVsyst as can be seen in Figure 8. The optimum plane orientation in winter, summer and yearly is 0 degrees and the optimum tilt in winter, summer and yearly is 50,0 and 30 degrees, respectively. Since 30 degrees is the optimum yearly tilt, it was chosen. 0 degree was chosen for the plane orientation. In [25] the authors stated that the optimum tilt angle based on a previous study for panels facing the south was equal to the latitude of the location. This enables the system to achieve at least 98% of its performance. Since the latitude of this project's location is 27.92°N and azimuth angle is 0° (facing south). Choosing 30° as the tilt angle is further justified as a good choice.

Under the system tab, the planned power is initialized to 50,000KWp. The chosen PV module 'LG365Q1C-A5' and the inverter 'SMA SC2200' are selected. Max power at the 25th year was calculated as the efficiency at the 25th year * the max power (50MW). Dc to Ac ratio was calculated with 50MW/Max power at the 25th year and was 1.13. The selections were set in PVsyst and allowed it to size automatically, since some errors with under sizing were found, the number of inverters was increased to 20 and adjusted the number of PV modules in series and parallel

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to 20 and 6800 respectively with total number of PV modules equaling 136000. The results met the desired expectations of DC/AC ratio of 1.13 and with minimum overload loss of 0.5%, with no errors. As can be seen in Table 3.

Table 3: System parameters.

Parameter	Value	Parameter	Value
No. of modules	136000	No. of strings	6800
Module area	234899 m2	Tilt angle	30°
No. of inverters	20	Azimuth angle	0°
Nominal PV power	49640 kW	orientaion	Fixed
Max. PV power	51230 kW	Overload loss	0.50%
Nominal AC power	44000 kW	Pnom ratio	1.13
Modules in series	20	Inverter voltage range	570-950V

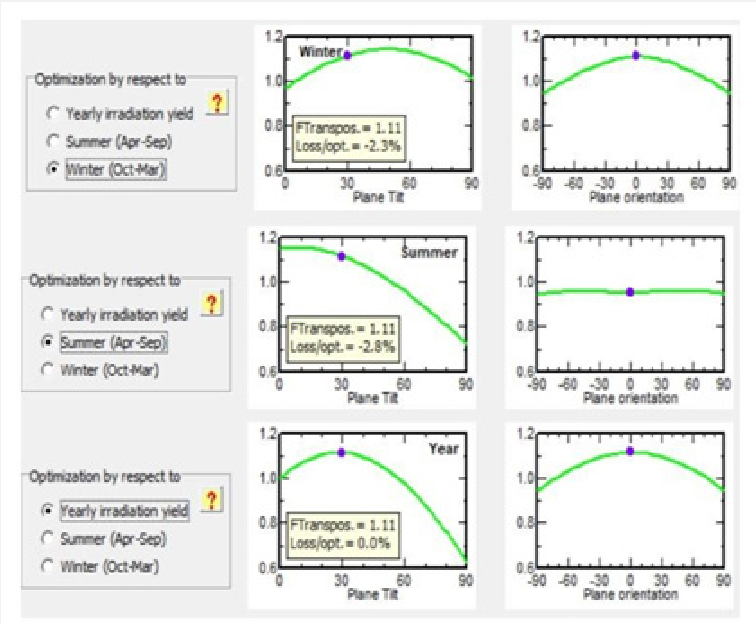

Figure 8: Optimum tilt angle
a) winter (Oct-Mar) optimum angle
b) Summer (Apr-Sept) optimum angle
c) Yearly optimum angle

Results and Discussion

Losses Analysis

Auxiliaries energy losses

In the Loss tab, continuous auxiliary loss for 20 inverters are 162 KW from the datasheet, the threshold inverter output is set to 40 MW. Night standby loss is 6 KW from the datasheet as can be seen in Table 4. Auxillary losses include energy lost in fans, air conditioning, monitoring and other electronics or lighting [26].

Table 4: Auxillaries Energy Losses.

Parameter	Value
Continuous auxiliary losses (fans, etc.)	162 kW
...from inverter output power threshold	40000 kW
Proportional to the inverter output power	0 W/kW
From inverter output power threshold	0 kW
Night axillaries losses	6.0 kW

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Other Losses

Array Thermal losses

The following sections explain how PVsyst calculate thermal losses. The field thermal behavior has a big effect on the electrical performance of the PV cell. It is calculated as the difference between the ambient and cell temperatures. It is given as the following:

$$U.(Tcell - Tamb) = \alpha \times (1-\eta)$$

$$Tcell = Tamb + \frac{1}{U}(\alpha.Ginc.(1-\eta)) \qquad (6)$$

So, where:

a) Tamb is the ambient temperature of the site.

b) Ginc is the irradiance on the module or PV array.

c) Tcell is the cell temperature.

α is the absorption coefficient of solar irradiation (1 - reflection). The usual value of the Absorption coefficient α is 0.9. It is eventually modifiable in the PV module definition dialog. η is the PV efficiency which is calculated according to the operating conditions of the module. Otherwise, it is taken as 10%. The U-valueis the thermal loss factor, which can be split into a constant component Uc, and a factor proportional to the wind velocity U*v*. These U-factors depend on the mounting mode of the modules (sheds, roofing, facade, etc...).

$$U = Uc + Uv \times v \qquad (7)$$

(Ucisin [W/m²·k],Uv is in [W/m²·k / m/s] and v = wind velocity in [m/s]).

Determination of the U-parameters

In the absence of reliable measured data, PVsyst proposes default values without wind dependency (i.e. assuming an average wind velocity). For free-standing systems (with air circulation all around the collectors), according to measurements on several installations: Uc =29 W/m²·k and Uv = 0 W/m²·k/m/s

Therefore, for fully insulated backside (no heat exchange at the backside, only one side contribution to the convection heat exchange), the U value should be divided by 2: Uc= 15 W/m²·k and Uv = 0 W/m²·k/m/s For intermediary cases (semi-integration, air duct below the collectors), the value should be taken between these 2 limits, but preferably lower than 22 W/m²·k as the air heat removing is often not very efficient. The default value proposed by PVsyst for any new project is:Uc= 20 W/m²·kandUv = 0 W/m²·k/m/s.

If reliable wind velocity data is present Pvsyst suggests inserting it. some users have proposed, when using standard meteo values such as those in the US TMY2 data and free- standing system, the following U-values should be used: Uc = 25 W/m²·kand Uv = 1.2 W/m²·k / m/s. Assuming an average wind velocity of 3m/s, this corresponds to U = 28.6 W/m²·k, close to the PVsyst standard value of 29 W/m²·k.

Based on the previous analysis given by Pvsyst and since no accurate wind data was obtained, this project will use Uc =29 W/m²·k and Uv = 0W/m²·k / m/ssince this design involves a free standing system with full air circulation on both sides of the module. Upon switching the Uc value from 20 to 29 W/m²·k. a system error showed up saying the inverters were undersized. By increasing the number of inverters from 20 to 21 the output energy increased from 107723 MWh to 108138 MWh by increasing the number of inverters further to 22 the output energy became 108280 MWh. To evaluate the efficacy of this increase; the average energy generated by an inverter that is part of the first 20 inverters is:

$$\frac{Total\ Energy}{Number\ of\ inverters} = \frac{107723}{20} = 5386.15MWh / inverter$$

By adding another inverter, the energy per inverter is:

$$\frac{Energy_{21inverters} - Energy_{20inverters}}{Change\ in\ number\ of\ inverters} = 415MWh / inverter$$

Further increasing the number of inverters to 22 results in a 142 MWh/inverter increase. Since the increase in energy for 21 inverters and 22 inverters are very low relative to the average increase of the first 20 inverters it is decided that only 20 inverters will be used even if the system shows an error saying the inverter is undersized. This will reflect positively on the economics of this project.

Soiling Losses

Performance variation due to environment factor like dirt is something difficult to predict and is subjected to the surrounding environment. Residential regions and regions which has medium rain falls has almost negligible soiling factor or less than 1%. Industrial region contributes high percentage for the soiling losses. It has been reported that the effects of metallic dust near railways, which causes further pollution, contributes a high percentage of soiling losses. Areas with a lot of birds suffer an increased yet small soiling loss of 2% due to bird droppings which do not get washed away by rain. Since this project is in an arid desert region, soiling coefficient has been taken as 3% to account for heavy dust and relatively little rain.

PVsyst Loss Diagram

As can be seen from Figure 9 the energy density at the collectors is 2423kWh/m² after IAM factor losses and soiling losses, 21.15% of this energy is utilized by the PV array (at STC). The energy output from the PV array is 110482 MWh at Maximum Power Point (MPP). The energy output from the inverter to the grid is 107723 MWh. The loses breakdown is as follows: the highest losses were 5.77% due to thermal losses followed by 3.0% losses due to soiling. 1.22% ohmic wiring losses (at STC). 1% module mismatch losses. 0.8% Module quality losses while the lowest losses were 0.10% losses due to strings mismatch

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losses. In Figure 10, the amount of useful energy produced (red), the amount of energy lost due to PV-array (blue) and system losses (green) are displayed. it can be observed that during the winter months (November, December, January and February) the collection losses are low while the system losses are high while the opposite is true for summer (June and July). Overall, the amount of useful energy harvested every month varied. Reaching its peak in March and dipping to its lowest value in January.

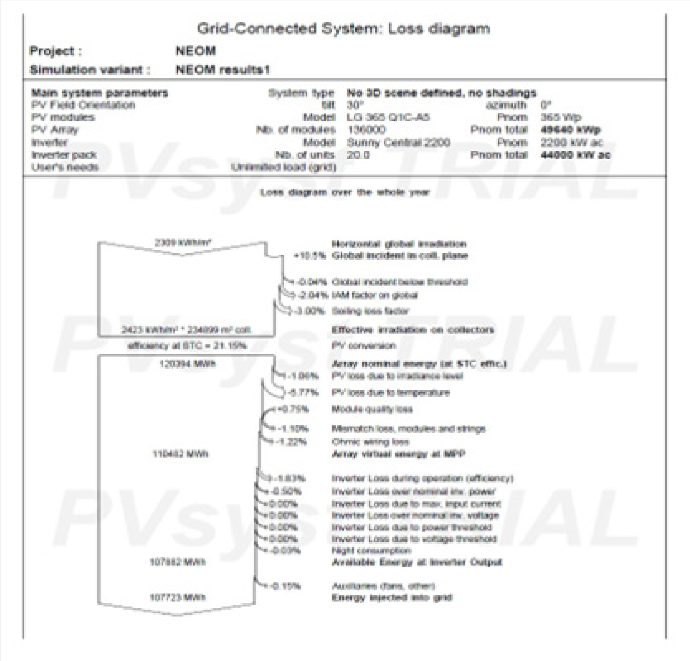

Figure 9: Losses breakdown.

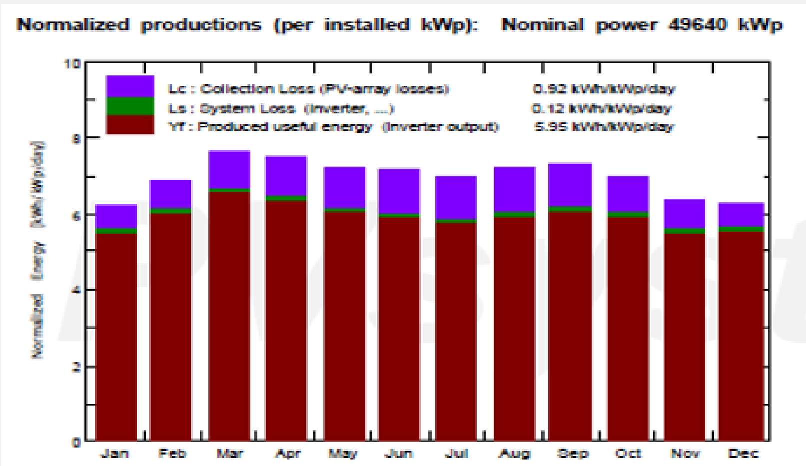

Figure 10: Normalized energy production.

As can be seen from Figure 11 the energy injected into the grid throughout the whole year is almost within the same range, that is to say, there is no large difference between the energy produced in summer over energy produced in winter. The reason for that could be due to the tilt angle being chosen for year-round optimum (Figure 8-c) instead of summer optimum. The month that showed the most energy production is March and the month with the least energy production is November. Figure 12a shows the average module temperature during running for every month. January had the lowest temperature of around 27°C and August the highest of around 46°C. Figure 12b shows the ambient temperatures throughout the year. By comparing the two graphs, a direct correlation between average monthly ambient temperatures and average monthly module temperatures can be observed.

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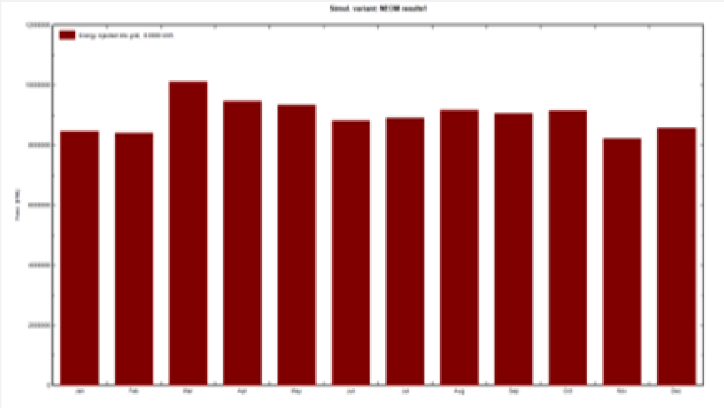

Figure 11: Energy injected into the grid.

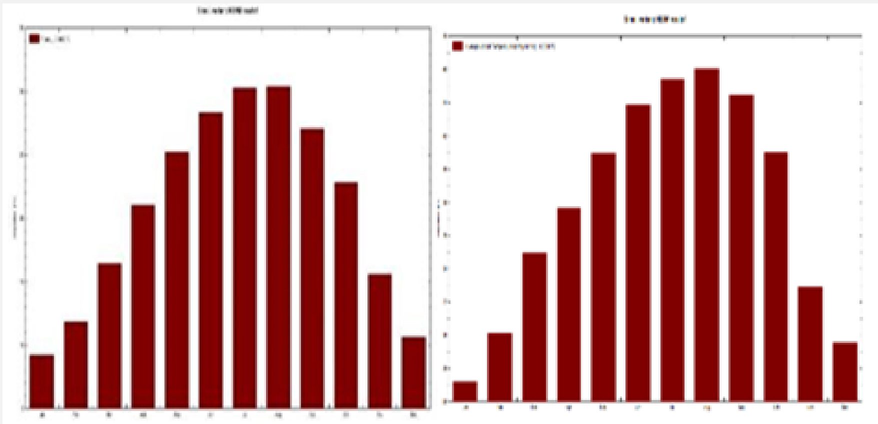

Figure 12: a) Average monthly module temperature. b) Average monthly ambient temperature.

Figure 13 shows the array temperature vs the effective global irradiance in the current project. It can be compared to similar plots from other studies. Such as the one in Figure 14 which was obtained from [27] and was conducted in Malaysia. By comparing the two plots, it can be observed that the system in this project achieved lower module temperatures at higher irradiance. This can be due to the ambient climate reducing the module temperature, a higher quality PV module being used resulting in lower heat losses or due to geographical and meteorological differences between the two locations.

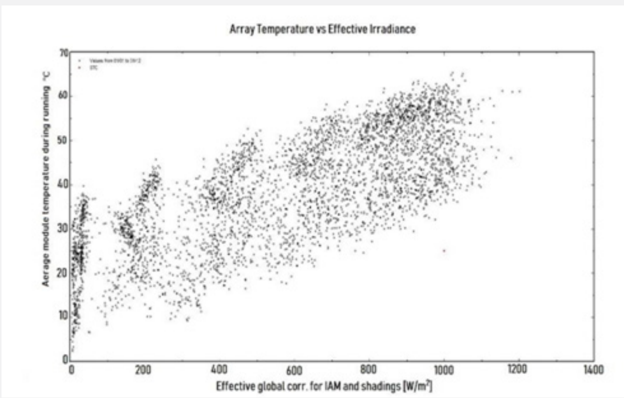

Figure 13: Irradiance vs Module temperature (for proposed system) scatter plot.

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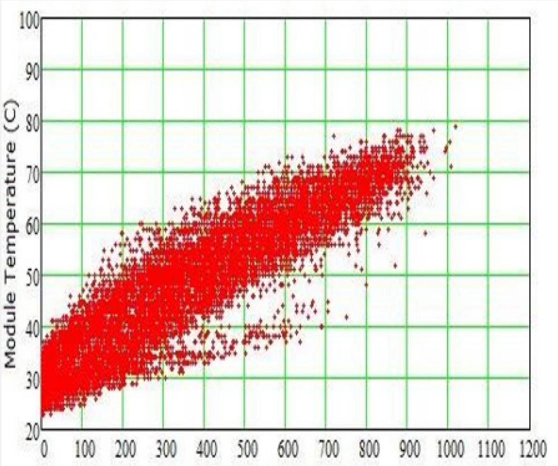

Figure 14: Irradiance vs Module temperature from reference.

Table 5 shows comprehensive data for each of the 12 months of the year. The horizontal irradiation starts low in January and February, ends low in November and December and peaks during April may June July and August. A similar trend can be observed for the diffused horizontal irradiation. In conjunction with the increased sunlight, the ambient temperature also increases and decreases accordingly. The global incident on the collector plane however is much more evenly distributed peaking at 238 kWh/m^2 in March of every year. The effective global irradiation shows the value of the irradiance after IAM and Shading losses have been deducted from it. The sixth column shows the energy output at the output of the PV array here the maximum output is 10335 MWh, which also happened in March. The second to last column displays the amount of energy injected into the grid for each month and finally the last column shows the performance ratio which peaked in winter (November, December, January and February) and dipped in summer (June and July) this is possibly due to the tilt of the panels being more optimized for year round optimum instead of summer optimum.

Table 5: Summary of Results.

	Global Horizontal (kWh/m²)	Diffuse Horizontal (kWh/m²)	Ambient temperature (°C)	Global incident on global coll. Plane (kWh/m²)	Global Corr. For IAM and Shadings	Energy output of the array (MWh)	Energy injected into the grid	Performance ratio
January	131.9	32.52	9.19	193.7	185.1	8657	8473	0.881
February	144.1	30.87	11.82	192.5	183.8	8590	8411	0.88
March	203.5	35.19	16.44	238	226.7	10335	10115	0.856
April	221.4	47.4	21.06	224.8	213.4	9665	9467	0.849
May	247.5	52.86	25.25	223.8	211.5	9520	9336	0.84
June	250.3	45.75	28.35	213.8	201.6	8988	8821	0.831
July	247.5	52.08	30.27	217.5	205.1	9078	8909	0.825
August	231.9	48.03	30.44	223.8	211.9	9350	9167	0.825
September	199.8	42.24	27.07	219.5	208.4	9253	9066	0.832
October	171.6	38.59	22.83	217.2	207	9340	9152	0.849
November	132.8	32.47	15.59	190.1	181.6	8404	8233	0.872
December	126.3	25.11	10.65	195.2	186.8	8758	8575	0.885
Yearly	2308.7	483.13	20.79	2549.9	2422.9	109937	107723	0.851

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Economic Analysis

In economics, a common equation for the difference between retail price and wholesale price is:

$$Retail\ \ Price = 2\ to\ 2.5 * Wholesale\ \ Price \quad (8)$$

This means that there is at least a 50% discount for buying in wholesale. For the purpose of this project, a conservative 25% discount is assumed. Bringing the cost of the PV panels down to 34.125 million USD, the cost of inverters down to 5.94 million USD and the cost of supporting structure to 3.457 million USD. The project lifetime in this study is 25 years. In [28] it is mentioned that the CAPEX for utility scale solar in 2019 is as low as 0.5 to 0.65$/Watt while in 2017 half the utility scale projects achieved a CAPEX of 0.8$/Watt or less. Values of different components before and after discount are shown in Table 6.

Table 6: Cost Summary.

Component	USD/Watt	Total (million USD)	Total after discount (million USD)
PV module	0.91	45.5	34.125
Supporting structure	0.09	4.61	3.457
Inverter	0.18	7.92	5.94
Total before BOS	1.18	58.03	43.52
Total after BOS			52.227

In [29] the O&M cost for developed countries was 10$/kw. The report also mentions that LCOE levels are lower in the Middle East due to the lower O&M costs, but an exact rate was not specified. For this project 10$/kw will be used as the operations and maintenance costs. Therefore, the total yearly O&M cost is 500000 USD. The previous figures are inputted into PVsyst as can be seen in Table 6.

According to [30] in which the authors produced a comprehensive study on feed-in tariffs they concluded by saying that 0.18SAR/kwh is the best tariff for Saudi Arabia which is equal to 0.048$/kwh. Another value for the feed in tariffs found [31] is 0.0853$/kwh which is almost double the previous rate. the research in [31] is directly from a Saudi university working in conjunction with the Saudi electricity company therefore it is seen as the more accurate source and 0.0853$/kwh inserted in the tariff section of PVsyst. The energy cost was 0.024 USD/kwh. Tables 7 & 8 show some of the result of the economic simulation it shows that the payback period for the project is 6 years (year 2026) with a 315.9% return on investment (ROI) and 164 million USD net profit by the end of the project lifetime (25 years). Cummalative cash flow diagram is shown in Figure 15.

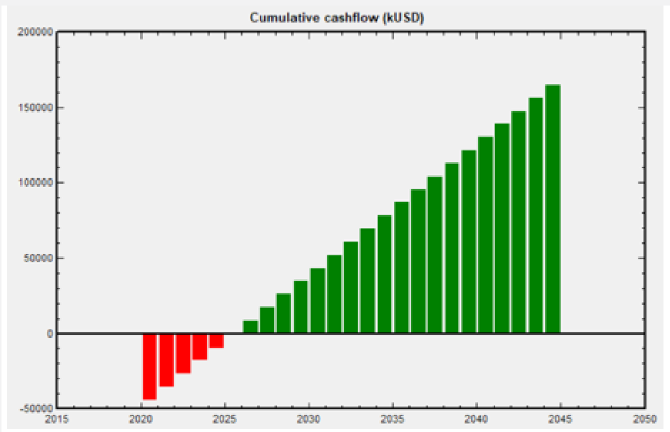

Figure 15: Cumulative Cashflow diagram.

LCOE calculation is not currently present in PVsyst but it will be added in the future according to the creators of the software. Overall, this project is very profitable and worth the investment. According to the carbon balance tab in PVsyst. By undergoing this project Saudi Arabia should be able to save more than 1.68 million tons of CO_2 emissions over the project lifetime which is approximately 0.67 million tons per year as can be seen from Figure 16 and Table 9. Initially the panels and all labor and components involved in the project create a negative carbon balance but around the 1st year of this project's operation CO_2 balance turns positive and keeps on increasing until the 25th year.

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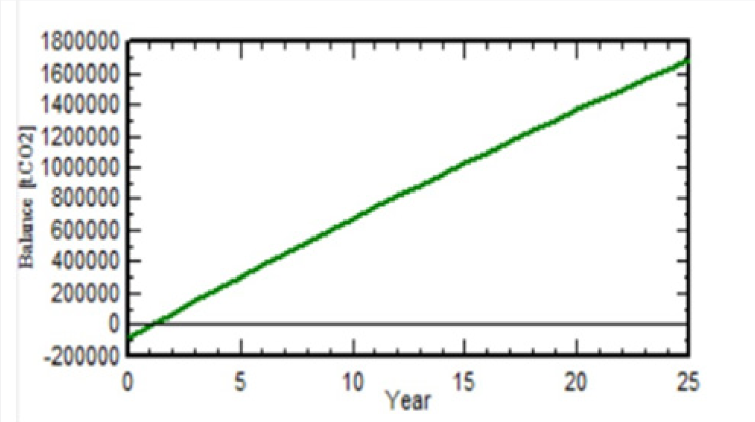

Figure 16: CO_2 emission reduction.

Table 7: PVsyst Economic Analysis.

Parameter	Value
Currency	USD
PV modules	34,125,000
Supports for modules	3,457,120
Inverters	5,940,000
BOS	8,704,000
Gross investment	52,226,000
Project lifetime	25
O&M Yearly costs	500,000
Energy cost	0.024 USD/kWh
Payback period	6.0 years
Net profit at end of lifetime	164,994,000 USD
Return on investement	315.90%

Table 8: Economic Detailed Results.

Year	Profit	Cummulative profit	Return on investment (+100%)
2020	8,689,000	8,689,000	16.60%
2021	8,689,000	17,378,000	33.30%
2022	8,689,000	26,067,000	49.90%
2023	8,689,000	34,756,000	66.50%
2024	8,689,000	43,445,000	83.20%
2025	8,689,000	52,134,000	99.80%
2026	8,689,000	60,823,000	116.50%
2027	8,689,000	69,512,000	133.10%
2028	8,689,000	78,201,000	149.70%
2029	8,689,000	86,890,000	166.40%
2030	8,689,000	95,579,000	183.00%
2031	8,689,000	104,268,000	199.60%

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2032	8,689,000	112,957,000	216.30%
2033	8,689,000	121,646,000	232.90%
2034	8,689,000	130,335,000	249.60%
2035	8,689,000	139,024,000	266.20%
2036	8,689,000	147,713,000	282.80%
2037	8,689,000	156,402,000	299.50%
2038	8,689,000	165,091,000	316.10%
2039	8,689,000	173,780,000	322.70%
2040	8,689,000	182,469,000	349.40%
2041	8,689,000	191,158,000	366.00%
2042	8,689,000	199,847,000	382.60%
2043	8,689,000	208,536,000	399.30%
2044	8,689,000	217,225,000	415.90%

Table 9: Carbon Balance.

Parameter	Value
Energy injected into grid	107723.2 (MWh)
System lifetime	25 years
Annual degradation rate	1.00%
LCE grid	743 g CO2/kWh
LCE system	91759.3 tonnes CO_2
Carbon balance (lifetime)	1686522.057 tonnes CO_2
Carbon balance (per year)	67460.882 tonnes CO2/year
Carbon balance (per kWp)	33.975 tonnes CO_2/kWp
Carbon balance (per kWp per year)	1.359 tonnes CO_2/kWp/year

Conclusion

In conclusion, Saudi Arabia plans to generate 9.5GW of its energy from renewable sources by 2023. However, there is a lack of literature regarding the design and feasibility of a large-scale solar project in the country. This project went through different design steps with proper justification in designing a 50 MW solar farm. Site selection was carried out based on results of previous literature and using Solar GIS to find the optimum location in terms of temperature, irradiance, terrain, proximity to roads and air temperature. Then a PV module was selected from a comprehensive list of all available models in the market by filtering and sorting the data based on fill factor, efficiency, degradation rate, power density and module price. LG365Q1C-A5 was the selected PV module and Sunny central SC-2200-Us was the chosen inverter. The number of PV modules in series is 20 and in parallel is 6800 while the number of inverters is 20. PVsyst was then used to simulate the project and the results were displayed and discussed. These results include Loss analysis, energy generated analysis and temperature performance. In the losses analysis the highest losses were 5.77% due to thermal losses followed by 3.0% losses due to soiling. Overall, the amount of useful energy harvested every month varied. Reaching its peak in March and dipping to its lowest value in January. This designed system achieved better temperature performance than a reference, receiving higher irradiance while keeping lower module temperatures. Next, an economic analysis was carried out which showed that the payback period for this project is 6 years, with a 315.9% return on investment (ROI) and 164 million USD net profit by the end of the project lifetime (25 years). Finally, CO2 balance analysis was reported which showed that over the project lifetime Saudi Arabia would be able to save more than 1.68 million tons of CO_2 emissions.

Future Work

Further studies can be made following this one that focus on including storage options such as hydropower, hydrogen cell or batteries. Different scenarios for maximizing the power can be investigated such as adjusting the tilt angle so that it maximizes summer energy generation. Thirdly, bifacial panels or panels with axis tracking can be used to find the effect on energy harvested and the economics of the project.

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