Design of 100MW Solar PV on-Grid Connected Power Plant Using (PVsyst) in Umm Al-Qura University

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Abstract: ***Currently, the extensive use of energy generation based on fossil produced an excessive amount of CO_2 emissions which affect the environment. If this continuous, the atmosphere temperature is expected to increase, which increase storms, hurricanes, droughts, and floods. Therefore, Urgent action is needed nowadays to change the energy system to renewable energy since it results in a little to no emission. This paper presents the design and simulation of a solar PV grid-connected electricity generation system of 100MW capacity in Umm Al-Qura University (UQU). It also represents technical, economic potential, and annual performance of the solar PV system. The design is validated and simulated by using PVSYST software in order to determine the optimum size, the specifications of the PV grid-connected system, and the electrical power generation. The amount of electricity that a solar PV plant generates is 100 MW. This amount could be used to reduce the load of Saudi electricity company (SEC) and help to minimize the annual electricity bill of Umm Al-Qura University (UQU). The study provides an abridged financial evaluation of the solar PV plant along with the operation and maintenance costs. The results of this project should encourage Umm Al-Qura University to decide on installing a solar PV system to reduce load shedding and minimize the cost of supplying electricity to its facilitates. Moreover, the solar power plant helps to conserve oil and reduce environmental impacts. A project like this can also act as a guideline for possible solar systems in other different institutions.***

Keywords: Solar energy, Solar Photovoltaics; Renewable energy; Solar on-grid system; PV efficiency.

1. Introduction

Renewable energies have experienced significant growth in recent years, and It becomes a more critical type of energy in developed and developing countries in order to produce electricity. Among these technologies, solar energy considered an optimistic type of energy since it grows faster. It produces clean electricity from the Sun, which considers a stable and efficient energy technology. Due to the increase in electricity demand in the last years, it becomes necessary to reduce electricity consumption.

Solar energy is set to become an economical method in the coming years since it has better technology in terms of applications and cost.

Moreover, the sun is free and considered an unlimited source of energy. The significant advantage of solar energy over other traditional power generators is that the sunlight converted directly into solar energy with the use of a solar photovoltaic system.

In the present, the Kingdom of Saudi Arabia has announced Vision 2030 by the National Transformation Plan (NTP). It clearly outlines renewable energy goals under the King Salman Renewable Energy Initiative. In fact, Saudi Arabia will install 9.5 GW of renewable energy capacity by 2023 [1].

There are several types of research related to Solar Photovoltaic System have been studied through this paper to compare, mature, and develop the study of a Solar Photovoltaic System in Umm Al-Qura University (UQU).

Ranvijay Singh Meena and Savrabh Mishra (2012) explained a technology based on the phenomenon of direct conversion of radiations coming from a heat source into electrical energy using photovoltaic cells. The study introduces new possibilities for the environment-friendly generation of electricity and also demonstrated better utilization of waste heat energy [2].

Nur Dalilah Nordin and Hasimah Abdul Rahman (2016) presented a novel optimization method for sizing and design of the stand-alone photovoltaic system (PV). They explained the analysis of loss of power supply to arrange the PV arrays and batteries. The study discussed the design in terms of cost analysis [3]

Sanae Dahbi, Abdelhak Aziz, Abdelhafid Messaoudi, Imane Mazozi, Kamal Kassmi, Naima Benazzi (2017). They present a design of a new clean storage device for a photovoltaic system (PV) supported by the electrical grid. The photovoltaic system supplies power to a DC load, and when the power is insufficient, the electrical grid compensates the energy deficit [4].

V. Perraki and P. Kounavis (2016) evaluates the impact of temperature and irradiation on the behavior of monocrystalline silicon, Copper Indium diselenide (CIS) modules, and polycrystalline silicon. In a Mediterranean site, an outdoor experimental setup has been placed in order to collect data of panels to study the effect of temperature and irradiation [5].

Khadiza Umme Tahera, Raisa Fabiha, Md. Ziaur Rahman Khan (2018) studied the design of a grid-connected solar photovoltaic for a residential hall in BUET. They calculated the load rooftop area in order to get the system size and analysis of the system to reduce dependence on grid power. Their project considered a guideline to build such possible solar PV system [6].

Waqas Ali, Haroon Farooq, Ata Ur Rehman, Qasim Awais, Mohsin Jamil, Ali Noman, (2018) discussed the designing of stand-alone solar photovoltaic (PV) system. The study has guidelines, site selection, stand-alone application method, and technical considerations needed to design a solar PV system.[7]

Coc Okom, E.O Diemuodeke, E.O Omunakwe, E Nnamdi, (2012) presented the design analysis of a photovoltaic (PV) system to power the Laboratory. The study has a detailed analysis of economic viability and break-even point of the system in order to provide the optimum economic benefits.[8]

David A. Torrey and James M. Kokernak (2006) discussed the issues associated with developing solar PV system productivity. The study focused on comparing a series-parallel array to a series string array and the impact on energy production. Partial shade is used to highlight significant differences between the operation of the two arrays [9]

V. Tyagi, Nurul A. Rahim, N.Rahim, Jeyraj A. and L. Selvaraj (2013) demonstrated the efficiency improvement of solar cells for commercial use. The efficiency of monocrystalline silicon improves from 15% in the 1950s and reach 17% in 1970s. Nowadays, the efficiency increases up to 28%. In this study, the growth of solar PV technologies, efficiency, performances, and cost analysis discussed in detailed [10].

Wael Charfi, Monia Chaabane, Hatem Mhiri, Philippe Bournot, (2018) presented an experimental study of the photovoltaic panel with the self-cooled operation. The design has natural ventilation that helps to reduce temperature and improve the performance in high-temperature hours of the day. The study shows that this method will help to avoid dust accumulation on the solar PV surface. The project includes the 3D CFD model to demonstrate the performance of the solar PV system and compares the numerical results and experimental data [11].

Mohammad Al-Najideen and Saad S.Alrwashdeh have studied the Design of a solar photovoltaic system in order to satisfy the electricity demand for the faculty of Engineering at Mu'tah University in Jordan. The solar PV system provide more than 50 kW grid-connected, which efficiently reduce energy bill due to dropping the energy consumption as well as the electricity generation [12].
Engr. Dr. Okwu P I, Engr Okolo Chidiebere C, Engr Okeke Obinna, Engr. Matthew D. O, Engr Ajuzie Uche, (2017) has provided the guidelines for installing photovoltaic power systems in order to describe the design, and installation plans should be set to achieve the optimum result of using the right PV system [13].

Ching-Lung Lin, (2015) describes and evaluates the electric energy generation efficiency. He shows and provides analysis to improve the efficiency of the solar PV system. He further recommended methods that help to enhance the efficiency of solar photovoltaic electric energy generation around 30.18% [14]

Saeed Kamali, (2016) descussed the design to cover the residents' electricity and economic analysis of a standalone photovoltaic system during the winter. The study includes the PV peak power, PV panels area, inverter, the battery capacity, and charge controller. It shows how the standalone photovoltaic system is considered economically feasible and the better way to produce the energy [15].

Reinders, A., Verlinden, P., Sark, W. V., & Freundlich, A. (2017) explained the fundamental and application of Photovoltaic solar energy. They presented, in chapter 1 & 2, the basic functional principle of photovoltaics, including the introduction to semiconductor materials and topics related to solar cells device in general. Moreover, the second half of the book was focused more on the application of photovoltaics technologies. In details, Chapter 9 explore PV technologies that applied in space, and chapter 10 presented PV modules and their manufacturing processes. While, in chapter 11, PV technologies applied in systems, buildings, and various products are placed in the spotlight [16].

Reinders, A., Verlinden, P., Sark, W. V., & Freundlich, A. (2017) explained the fundamental and application of Photovoltaic solar energy. In chapter 3, they described the design aspects and the actual function of crystalline silicon solar cells, the most dominated solar technology in the current PV market. Thin-film solar cells in chapter 4 discussed while in chapter 4, they discussed the thin film silicon-based PV technologies. Also, organic PV cells and their application demonstrated in chapter 6 and 8 [16].

In this article, a Solar Photovoltaic System in Umm Al-Qura University (UQU) proposed because energy plays a significant rule in the development of civilizations. Therefore, many studies are discussed on the use of solar energy in order to increase efficiency, reduce the cost consumption, reduce power consumption, eliminate carbon emissions, and reduce the demand of fossil fuel. The primary function of this article is to use solar photovoltaic system (PV) in order to reduce the energy consumptions about 100MW of electricity in Umm Al-Qura University (UQU).

1.1 System Design and Objectives

Designing of PV plants are required thousands of PV panels, and each panel produced hundreds of watts. During the design procedures of the PV plant, the designer needs to select and choose the right number, size, and type of PV modules and inverters. Furthermore, components required to install the PV plants in order to increase the energy production as well as improve the lifetime maintenance of the plant. The PV plants design of 100MW requires a decent knowledge about the system and components. Therefore, the designer will need to know more about the site selection and solar data, components and specification, the efficiency of Solar PV, design optimization, and cost analysis.

1.2 Site selection and solar data of Solar Power Plant

Kingdom of Saudi Arabia is located in the middle east of Asia. Its holy city Makkah is located at 21° 25' North latitude and 39° 34' East longitude. Saudi Arabia is one of the most potentially productive regions among MEC for harvesting solar power [17]. The area of Makkah is considered an ideal location for solar energy utilization since it exposed to the sun's rays throughout the year for long hours during the days [18]. It has an average daily solar radiation rate of about 5,640kilowatt-hours per square meter per day (kWh/m²/day) [18]. Umm Al-Qura is a large public Islamic University located in Makkah with lots of free lands. This land could be useful to establish a solar power plant in order to cover some of its needs (100MW). The amount of solar produced will help to reduce the electrical energy consumption. Figure 1 shows the solar map of Umm Al-Qura University in Saudi Arabia, employing long-term satellite-based solar irradiation data.

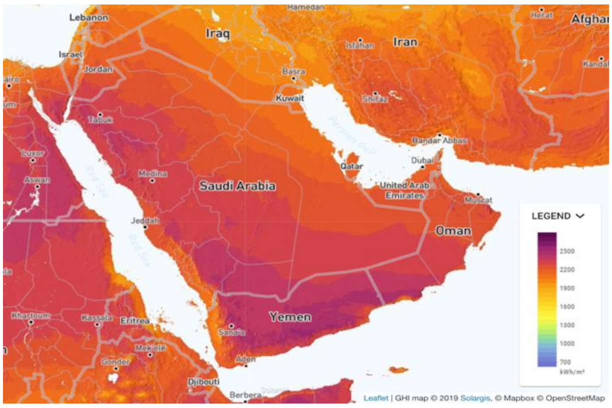

Figure 1: A Solar Irradiation Map of Saudi Arabia (kWh/m2/year) [19].

The following formula is used to calculate the solar time of Makkah city in Saudi Arabia. It gives the clear solar time period based on the standard civil time, Longitude at the location (L_{loc}), Longitude at which the standard time (L_{st}), and number of days (N) as shown below;

$$\text{Solar Time} = \text{Standard Civil Time} + 4\,(L_{st} - L_{loc}) + E \quad [20]$$

$$E = 9.87 \sin(2B) - 7.53 \cos(B) - 1.5 \sin(B) \quad [21]$$

$$B = 360\,(n - 81) / 364 \quad [22]$$

Table 1: Solar time of Makkah

Parameter	*Value*
Standard Civil Time	13.5
L_{st}	42.7
L_{loc}	27.8
N (day)	365
B	99.89
E	-3.51
Solar Time (hrs)	14.43

2. Selecting and sizing of Solar pv and inverter

Efficiency and cost are the factors that affect the selection of a PV module for grid-connected systems. So, selecting the right type of PV, whether to use Mono-crystalline or Poly-crystalline is essential. Mono-crystalline considered the most efficient type of solar panels with an overall efficiency of approximately 20% and a reasonable price. For this design, many PV panel options studied in terms of power, cost, type, and warranty. Therefore, commercial solar of 370 Wp production selected and adopted in this work. Electrical Data specification for commercial Solar Panel shown in Table 2.

Table 2: Electrical Data specification for commercial Solar PV

Type	*MONO CRYSTALLINE*
No's of module	1622
Maximum Power (Pmax)	370Wp
Maximum Power Voltage (Vmp)	39.9V
Maximum Power Current (Imp)	9.28A
Open-circuit Voltage (Voc)	48.5V
Short-circuit Current (Isc)	9.61A
Nominal operating cell temperature (NOCT)	45±2°C
Operating Temperature(C)	-40°C ~ +85°C
Module Efficiency	19.08%

inverters are used here for converting Direct Current (DC) into Alternating Current (AC) and suppressing the harmonics produced after the conversion. Therefore, 9 numbers of 165kW inverters are used in the plant. Electrical Data specification for commercial inverter shown in Table 3.

Table 3: Electrical Data Specification for Commercial Inverter

Type	*Grid Inverter*
Input DC voltage	800Vdc
Input DC current	118.0Adc
Output AC voltage	320Vac
No. of Phases	3 phases
Efficiency	96.64%
No of inverters	9

The PV array and inverter characteristics are considered one of the most important elements for selecting and designing the solar PV system, since the characteristics have the information of PV modules, array global power, array operation conditions, and inverter. The following Figure 2. Provided a report with a detailed description of the characteristics of both PV module and inverter.

PV Array Characteristics					
PV module	Si-mono	Model	**JKM 370M-72**		
Original PVsyst database		Manufacturer	Jinkosolar		
Number of PV modules		In series	15 modules	In parallel	108 strings
Total number of PV modules		Nb. modules	1620	Unit Nom. Power	370 Wp
Array global power		Nominal (STC)	**599 kWp**	At operating cond.	543 kWp (50°C)
Array operating characteristics (50°C)		U mpp	548 V	I mpp	992 A
Total area		Module area	**3143 m²**	Cell area	2769 m²
Inverter		Model	**PVI-165_0**		
Original PVsyst database		Manufacturer	ABB		
Characteristics		Operating Voltage	485-800 V	Unit Nom. Power	165 kWac
Inverter pack		Nb. of inverters	9 * MPPT 33 %	Total Power	495 kWac
				Pnom ratio	1.21

Figure 2: The PV array and inverter characteristics

2.1 The efficiency of Solar PV

This system requires an in-depth study of all the factors that affect the efficiency of solar PV. Usually, the maximum solar PV efficiency is around 25%. A study of factors that affect the solar PV system is considered significant since it helps to improve efficiency, as mentioned below:

1) **The PV module direction:** A direction change in the PV module not according to Azimuth, will reduce the current and lead to reduce the power [23]. Solar panels should face the south according to Umm Al-Qura University's location in the northeast side of the earth. There are two methods to find Azimuth angle. The first is to use the solar tracker, which help to move the PV to the maximum radiation. The second is manually by using a compass to south direction with a 15-degree angle.
2) **The PV module angle:** The angle is another factor to adjust after installing the PV module in the south direction. The solar angle of PV needs to face the sun, and the most suitable angle changes according to location and seasons of the year. A lower tilt angle is increasing in productivity of summer months. While in winter, higher tilt angles are used for lower irradiance conditions.
3) **The PV module irradiance:** The input variable irradiance affects solar modules efficiency. The irradiance is changed from 400W/m2 to 800W/m2, which change the output efficiency of a module [24]**.** If the irradiance increases, the maximum power is progressing, and the efficiency elevated.
4) **The PV module temperature:** The solar PV module operates according to a laboratory standard at 25°C temperature and 1000W/m2. The current and voltage decrease according to the temperature increases. The conversion efficiency of the module decreases with an increase in module surface temperature [25]. Therefore, selecting the right type of PV module according to the temperature and location is significant.
5) **The PV module shade:** A solar PV performance is reduced due to the shading effects such as the passing of clouds, near buildings, or trees [26]. In shading condition, the short circuit current leads to a decrease in power output. Therefore, the better performance of solar panels comes when there are no shading conditions.
6) **The PV module Ingress Protection (IP):** The IP is an indication tool used for water and dust protection. The tools have two digits; the first digit represents the level of water and the second digit represents the level of dust. The high number is, the more protection has, while the lowers indicates minimum [27,28].

3. Design based on software

Design and Estimate the results of a 100MW solar power plant by using PVsyst software version 6.8.4. The system is designed based on the above specification to provide the required energy. The following Figure.3 shows the geographical site parameters for Umm Al-Qura University. Also, Figure.4 displays the system design of the solar module, inverter, and array design.

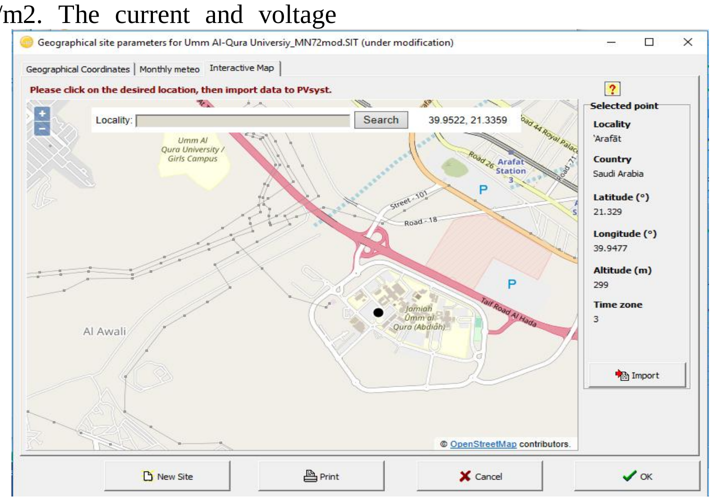

Figure 3: Geographical Conditions

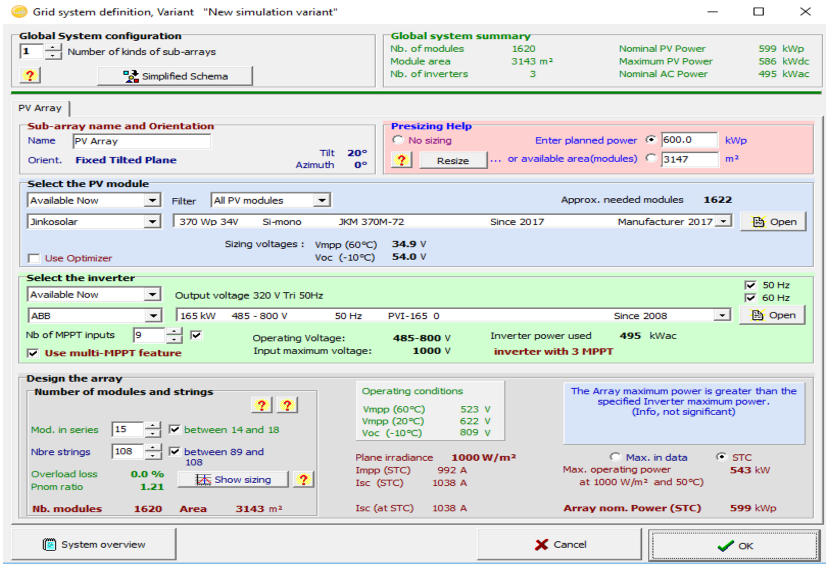

Figure 4: System Design (Solar Module, Inverter, Array Design)

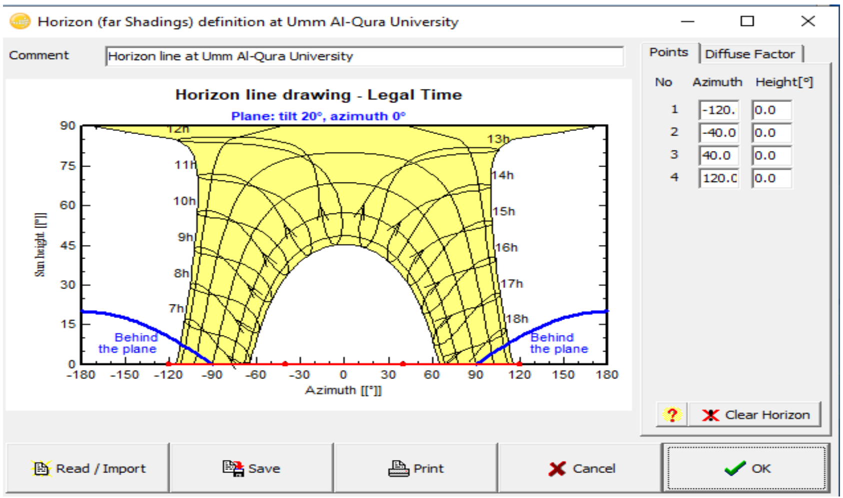

Figure 5: Solar paths at Umm Al-Qura University

4. Design layout

PV grid-connected system consists of PV array, inverters, user (load), and grid connection. A grid has no storage component as the generated energy is sold back to the main grid [29]. The proposed model is illustrated as shown in Figure 6. by the PVsyst software. It clearly shows how the system is connected and how the user gets the power from the PV power plant.

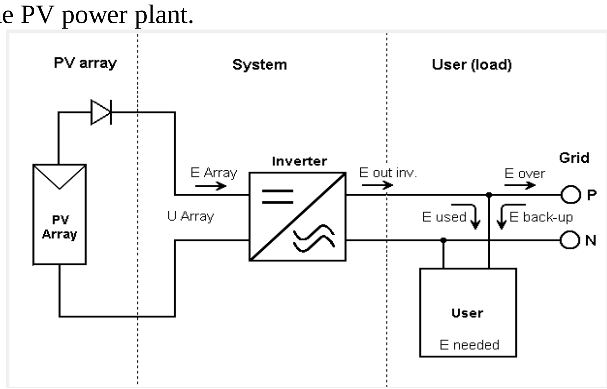

Figure 6: PVsyst Schematic Diagram of System

5. Calculation of required area

As solar modules are not energy-dense, they require a substantial amount of space in order to work. The solar module selected has a length of 1956mm (10956m) and a width of 992mm (0.992m). It means each panel has an area of

$$1.956 \times 0.992 = 1.94 \text{ m2}.$$

Therefore, the total modules area to design the plant = Total modules x Modules area.

= 1620 x 1.94 = 3142.80m2

The space between the panels needs to account (these panels need a stand). So, the total space required is estimated by dividing the total area by 0.7, which:

= 3142.80/0.7 = 4489.72m2

6. Results and Discussion

The simulation results of a proposed photovoltaic system analyzed in this section. The obtained result show from the simulation model of 100 MW MONO CRYSTALLINE photovoltaic system displayed in PVsyst as per the project specifications and constraints. In this simulation, mainly produced energy, specific production, and performance ratio. Obtained results analyzed for assessing the performance of the MONO CRYSTALLINE photovoltaic system.

6.1 Main simulation results

From the main simulation results, two parameters were assessed. First parameter is the total amount of energy produced from the 100 MWp MONO CRYSTALLINE photovoltaic system on annual basis which is referred as produced energy 1109.7 MWh/year. Second parameter is the annual average performance ratio (PR) is 78%.

Table 4: Balances and main result of 100 MWp Mono Crystalline photovoltaic system

Months	*GlobHor (kWh/m2)*	*DiffHor (kWh/m2)*	*GlobInc (kWh/m2)*	*GlobEff (kWh/m2)*	*E_Array (MWh)*	*E_Grid (MWh)*	*PR (%)*
January	148.9	35.56	189.6	185.4	96.2	92.6	0.814
February	165.4	33.53	198.5	194.1	98.8	95.1	0.799
March	184.9	64.36	199.9	194.6	98.7	95.1	0.793
April	207.1	65.59	207.6	201.9	100.7	96.9	0.779
May	241.1	59.69	225.7	219.3	107.3	103.3	0.763
June	221.0	76.60	201.8	195.3	96.3	92.7	0.767
July	215.3	85.11	199.2	192.9	95.2	91.7	0.768
August	197.3	87.33	193.1	187.5	92.6	89.1	0.770
September	183.6	74.63	192.8	187.4	92.5	89.1	0.771
October	180.1	51.71	206.9	202.1	99.9	96.2	0.775
November	146.2	42.62	182.1	177.6	90.7	87.4	0.800
December	128.2	45.12	164.5	160.1	83.6	80.5	0.816
Year	2219.0	721.85	2361.9	2298.1	1152.6	1109.7	0.784

Where;
GlobHor: Horizontal global irradiation.
DiffHor: Horizontal diffuse irradiation.
T_Amb: T ambient.
Glob Inc: Global incident in plane.
GlobEff: Effective Global, correspond for IAM and shadings.
EArray: Effective energy at the output of the array.
E_Grid: Energy injected into grid.
PR: Performance Ratio

6.2 Performance ratio and normalized production

6.3 Performance Ratio

The performance ratio is a quality factor that measures the quality of a PV plant. It describes the relationship between the theoretical and actual energy outputs of the PV plant. The PR shows the energy after deduction of energy consumption and losses. Usually, the Performance ratio is around 80% due to the unavoidable losses during operation. The more the PR is close to 80 %, the more the system will be effective and efficient. The following Figure. 7. shows the performance ratio (PR) of the PV plant of 100 MW using mono crystalline photovoltaic system. The PV plant monthly performance ratio is around 78.0 %, which is considered a valuable amount since the system cover 20% of Umm Al-Qura University.

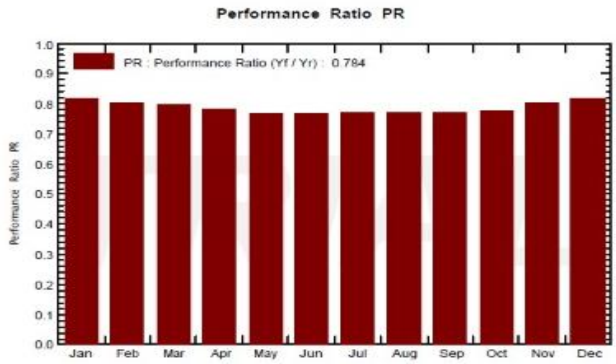

Figure 7: Performance ration (%)

The following Figure 8. Presents the normalized production of PV power plant. It gives the collection losses of PV array, system losses, and produced useful energy of inverter output. It clearly shows the monthly production and losses per kWh.

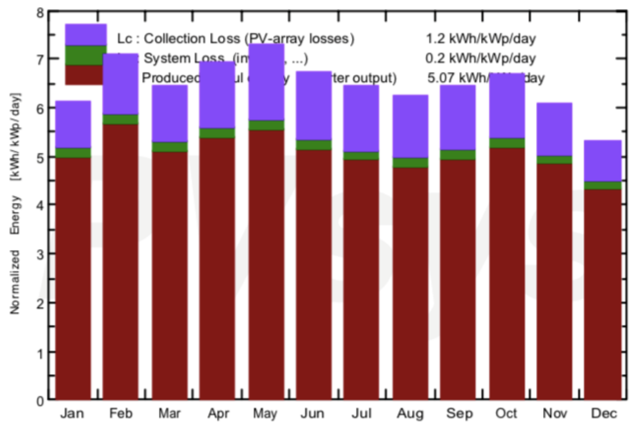

Figure 8: Normalized production energy per month

6.4 Fuel and CO_2 Consumptions

Using a PV power plant will provide a positive effect on the environment. It helps to reduce greenhouse gases during the generation of electricity from fossil fuels, such as nitrogen oxide (NOx), Sulphur dioxide (SO_2), and Carbon dioxide (CO_2). Also, it helps to reduce the cumulation of ash [30].

Table 5: Values for products by the power plants with fossil fuels with electricity production

By products of coal power plant	*Per kWh*	*For annual energy production of 1109.7 MWh*
NOx	2.59 g	2874.123 kg
SO_2	1.24 g	1376.028 kg
CO_2	970 g	75459.6 kg
Ash	68 g	1076409 kg

6.5 Cost Analysis

A cost analysis is a process that helps organizations to make decisions, systems, or projects. The analysis helps to develop reasonable conclusions around the feasibility of a decision or situation. The PV power plant in this project will help to reduce the power consumption bt1109.7MW. This amount is saving around 372859.20SR yearly, which consider 9% of total power produced by a traditional power plant. The following table 6. Shows the monthly power consumption and cost.

Table 6: Cost analysis of power consumption

Months	*Power consumption (kW)*	*Consumption tariffs (SR)*	*Cost (SR)*
January	204800	0.336	68812.8
February	285300	0.336	95860.8
March	261200	0.336	87763.2
April	230000	0.336	77280
May	165600	0.336	55641.6
June	407200	0.336	136819.2
Juley	403600	0.336	135609.6
August	408800	0.336	137356.8
September	460150	0.336	154610.4
October	355550	0.336	119464.8
November	2085200	0.336	700627.2
December	294000	0.336	98784
Total	5561400 kW		1868630.4

7. Conclusion

Using PV SYST simulation software, the energy yield analysis for 1109MW PV Solar power generation was performed for geographical site Umm Al-Qura University in Makkah, which is located at the latitude of 21.329 N and longitude 39.94 E. The performance ratio about 80%. The power production about 1109 MW. This amount of energy, which can be generated by establishing 100MW per month This paper presents design modelling and simulation as well as technical and economic potential of a solar PV grid-connected electricity generation plant of size capacity 100MW monthly in Umm Al-Qura University. The maximum energy injected into the grid is in the month of May 103.3MWh, and the least energy is in the month of December 80.5MWh. The average performance ratio (PR) of the mono crystalline PV system is operated at 78% in the simulated study for the planned location. This system is approximately equivalent to 20% of total electricity consumption at Umm Al-Qura University. From this study the following conclusions were: This project clearly shows the effect of temperature variation on the performance of photovoltaic modules on a daily and yearly basis. The efficiency is more sensitive to temperature than the solar irradiation. During morning time, the efficiency of the plant is high until the afternoon and then starting to decrease to sunset. The efficiency of modules ranges from 19.08% to 14.5%, with variation in the averaged module temperature from 40°C to 70°C. So, cooling of solar modules may be advisable to increase the efficiency.

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