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Research paper

Design of a solar photovoltaic system to cover the electricity demand for the faculty of Engineering- Mu'tah University in Jordan

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ABSTRACT

In this study, the reduction ways of the electricity demand for Engineering Faculty at Mu'tah University were investigated. The using of the available resources efficiently and effectively to reduce energy bill is one way to reduce the energy consumption as well as the electricity generation. On grid photovoltaic system considers the most promising way to achieve the target of saving. For that, the availability of the solar photovoltaic system as an electricity generation source for Faculty of Engineering proposed to design a 56.7 kW grid-connected as a solar photovoltaic power plant to cover the electricity demand. The analysis revealed that the Engineering Faculty at Mu'tah University consumed 96 MWh annually and by installing an on-grid photovoltaic system with a capacity of 56.7 KW the electricity production to the grid will be 97.02 MWh per year, which cover the electricity demand for Engineering Faculty at Mu'tah University with a capital cost of $117,000 and payback period about 5.5 years.

1. Introduction

Energy is one of the most promising candidates, which play a major role in the economic growth of the world's nations. Several factors such as urbanization, modernization and increasing of human population lead to a sharp increase in the energy demand of the world. In the developed countries the energy consumption is increasing at a rate of 1% per year and 5% per year for the developing countries [1–3]. The energy future trend shows that the needed energy amount will be doubled by 2020 according to the International Energy Agency (IEA) [4].

Nowadays, all the world countries' believe that the renewable energy is the alternative solution instead of using the traditional energy types [5–7,35,36]. Solar energy considers one of the most important types among all renewable energy types that for the advantages which are clean, carbon-free and the availability [8–11].

Jordan is one of the developing countries, which is completely dependent on the imported oil in order to meet it needs from the energy required for all sectors [12]. Jordan energy bill grew by an average of 14% per year from its gross national product (GNP) [13,14]. On the other side, Jordan considers a rich country of the solar energy with a high intensities of the solar radiations, along durations of sunshine hours and open land has a gentle topographical feature in most of it. The range of the solar irradiance in Jordan is in between 4–8 kWh/m^2 and the sunshine duration is more than 300 days per year with an average sunshine hours of 9 h/day and about 3311 h/year, which makes Jordan is one of the richest countries in the world with the solar energy [15,16].

Solar photovoltaic (PV) energy systems is a convenient investment for Jordan, that's because it needs a little maintenance and it doesn't cause a direct pollution or depletion of the resources [17,18,31]. Several researchers study the ability to use the PV systems for electricity generation in Jordan such as the design of the green building for the kindergarten in Amman which considers the PV systems as an alternative to cover the electricity demand for the building [19].

Total PV capacity installed in Jordan was 0.5 MW in the year of 2006 and 1.6 MW in 2012 and the future plan to install 100MW until the end of 2020. Most of the old units have been distributed in the remote areas of Jordan as shown in Fig. 1, to cover the need of the lighting and water pumping according to the National Center for Research and Development in Jordan [15]. In this study a PV system is designed in order to cover the energy demand needs of the faculty of engineering at Mu'tah University in Jordan and a simple economic approach is applied to calculate the payback periods for that design.

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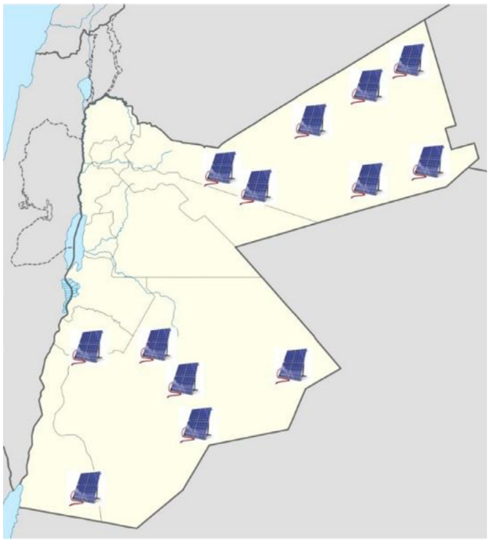

Fig. 1. Photovoltaic installations in the remote areas of Jordan.

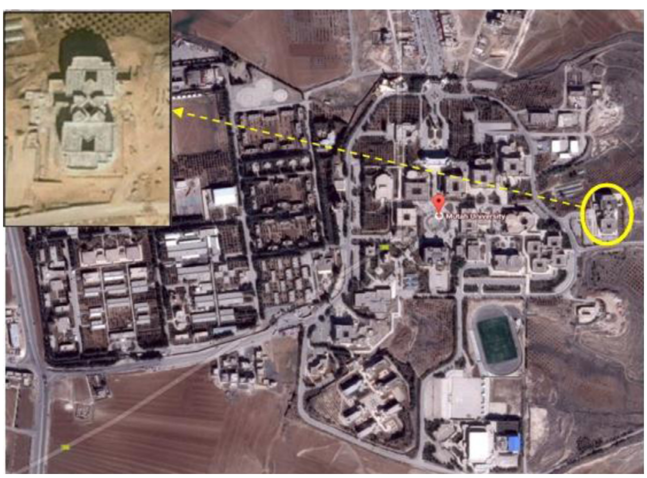

Fig. 2. Mu'tah University map and Faculty of Engineering inside the yellow circle.

2. Site overview

Engineering Faculty at Mu'tah University located in Al-Karak Governorate with a distance of 152 km to the south of Amman capital of Jordan (31°05′N, 35°43′E, and elevation 1153 m). The faculty building consists of three floors with basement, classrooms, academic staff offices, administration rooms and public facilities. Mu'tah University and faculty of engineering topography illustrated in Fig. 2. The proposed PV power plant site located on the faculty building roof to cover the electricity demand for it.

3. Electrical load

The electrical consumption as a monthly average for the Engineering Faculty at Mu'tah University is about 8 MWh (96 MWh annually) [20]. Thus monthly energy bill cost is about 1280 JD ($1800).

4. Solar radiation analysis

Jordan is blessed with a plenty of solar energy which is apparent from the annual daily average insolation intensity on a horizontal surface range between 4–8 kWh/m^2. Table. 1 shows clear days and average sunshine hours in Jordan [15].

Table 1
Average numbers of clear days and sunshine hours in Jordan.

Month	Average No. of Clear Days	Average No. of Sunshine Hours
January	20	232
February	22	260
March	24	296
April	25	275
May	25	348
Jun	30	405
July	31	380
August	31	390
September	29	334
October	25	280
November	26	264
December	22	233
Total	310	3697

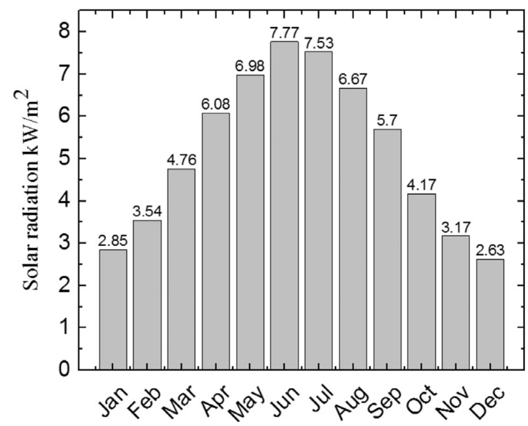

Fig. 3. Monthly averaged insolation incident on a horizontal surface.

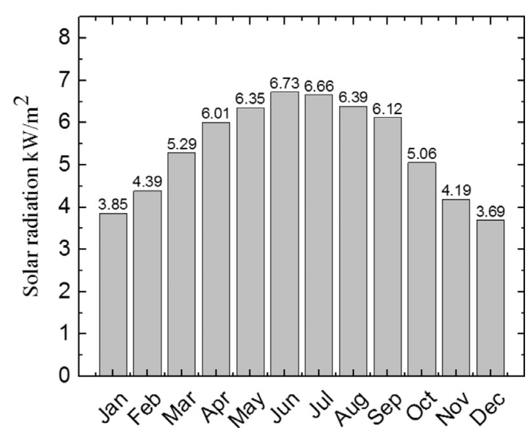

Fig. 4. Monthly averaged insolation incident on tilted angle (30°).

Solar radiation data is the key point for the planning and sizing of the PV systems, which is extracted through the calculation of the amount of the solar radiation for each square meter per day in the selected area. Fig. 3 shows the monthly average of daily solar radiation for different months, while the monthly solar radiation at tilted surface south-orientation (yearly optimum tilt-angle equal to 30°, approximately equal to the latitude of the selected site) is shown in Fig. 4 [21].

Generally, the solar radiation data measured on a horizontal plane. PV panels fixed with a tilt angle (β) relatively to the horizontal in order to get the maximum possible solar radiation through making the panels faced to the sun. Tilt angle has the major effect on the solar radiation incident on a surface. The maxi-

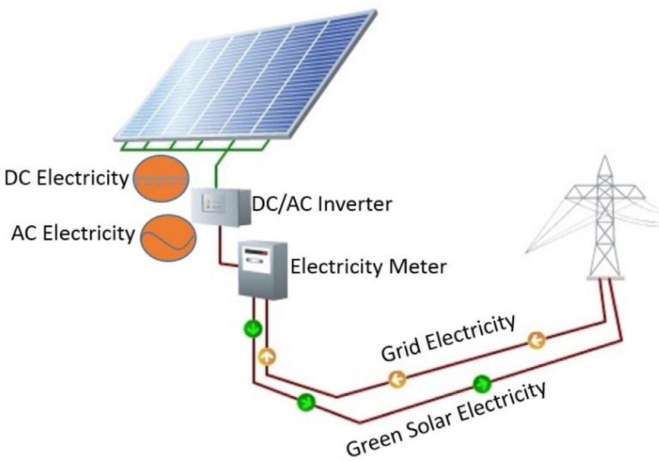

Fig. 5. Grid-tied PV system.

mum power output can achieve when the tilt angle is equal to the latitude of the location. However, the adjustable tilt angle can help to maximize the achievement of the solar radiation over the whole year [22,32–34].

For the selected site, it is clear that the solar irradiance for 30° tilted surface are higher than solar irradiance on the horizontal surface during winter season (October - March), while during the summer season the opposite is true. The annual average solar radiations for the horizontal and tilted surface are 5.15 and 5.4 kW/m^2.

As a result, the preferred PV plane at 30° tilt angle with annual average solar radiation 5.4 kW/m^2 and peak sun hours (PSH) about 6 hours at standard test conditions (STC) for the selected PV module. Consequently, Two benefits can be accomplished through this selection, which are reducing the investment cost and reducing the area used to install the system on the selected site.

5. On-grid PV system design

The design of the PV system is the only tool that helps in a proper selection of the system relative equipment's for an on grid or off grid connections [22]. The system sizing mean to calculate the number and type of solar panels needed to capture the solar energy, the battery capacity that will store and save the energy for the days of a little or no sunshine, and to be able also to determine the required characteristics for the rest of the elements related to the system such as: regulators, inverters, cables, etc., finally to ensure the maximum performance of the installation [23,24].

PV module produces power when it's uncovered to the sunlight. For that, there is a number of the components are required to properly conduct, control, convert, distribute, and store the energy produced by the PV arrays. For this research, an on-grid system will design as shown in Fig. 5.

5.1. Panel type and inverter selection

The solar cells usually fabricated from the silicon crystalline. Mono-crystalline cells having the highest efficiency compared to the Poly-crystalline cells and amorphous silicon cells. The selection of the cell type depends on the required application, as an example the small consumer products used generally the amorphous silicon cell. Several aspects characterize the solar panel type selection [22,25], and it can be summarized as cell type, system cost, the warranty and the size and watts.

For the intended system, the selected panel made from Mono-crystalline, Sun-Power 315-SOLAR PANEL**,** with an efficiency of 19.3% and 315 W as maximum power. Table. 2 lists some main characteristics of this type at Standard Test Conditions STC [26].

The converter device, which is used to convert the produced DC power from the PV panels to AC power is the inverter. Several inverters types are available in the market. However, an appropriate inverter selection depends on three main factors, that should be considered, which are: its output AC power, the DC-AC conversion efficiency and the capital cost. After an intensive search for a proper inverter choice, GermanPV TRIO-27.6-TL-OUTD-S2X manufactured by GermanPV Inc., the leading German company in this field, seems to be a good candidate, as it has a high value of CEC efficiency that equals to 98. And the price was relatively low compared with other brands. Several characteristics of this inverter are listed next in Table. 3 [27].

5.2. On-grid PV array sizing

The simplest PV installation system model is the on-grid model. In the on grid model the load is specified by the user and the suggested inverter is simply equal to the nominal array power. The energy available to the grid is what is produced by the array? And it can be expressed by the [22]:

$$E_{grid} = E_A \eta_{inv} \tag{1}$$

Where,
η_{inv}: The inverter efficiency
E_A: The array energy available to the load.

Depending on the grid configuration not all this energy may be absorbed by the grid. The energy actually delivered is:

$$E_{dlvd} = E_{grid} \eta_{abs} \tag{2}$$

Where,
η_{abs}: The grid absorption rate.

Total peak power of the PV generator required to supply a specific load depends on the total load needed, several factors taken into the account to indemnity for losses and temperature effect such as solar radiation, ambient temperature, power temperature coefficient, efficiencies of the inverter and on the safety factor. The Numbers of PV panels required is obtained as follows:

$$No.\,of\;PV\;Panels = \frac{P_{inv,in,kWh}}{P_{\max,actual}} \tag{3}$$

Where,
$P_{inv,in,kWh}$: Given by the following equation:

$$P_{inv,in,kWh} = \frac{P_{demand,\max}}{\eta_{inv}} \tag{4}$$

Where,
η_{inv}: The inverter efficiency
$P_{demand,\max}$: The maximum demand load.

$P_{\max,actual}$ The power produced by the module at each day given by the following equation:

$$P_{\max,actual} = [(1 - L_T) \times (1 - L_C) \times (1 - L_M)] \times P_{\max} \times PSH \tag{5}$$

Where,
L_T: The temperature losses coefficients
L_C: The cable losses coefficients
L_M: The module losses coefficients
$P_{\max}$: The module peak power at maximum irradiance.

The annual energy available to the grid is 94.08 MWh and the actually energy delivered annually is 97.02 MWh by using Eqs. (1 and 2), with inverter efficiency equal to 98% and grid absorption rate is 99%.

Table 2
Selected PV module specifications.

Electrical Data		
Measured at STC: irradiance of 1000/m², air mass 1.5 g, and cell temp. 25 °C		
Peak Power	P_{max}	315 W
Rated Voltage	V_{mp}	54.7 V
Rated Current	I_{mp}	5.76 A
Open Circuit Voltage	V_{oc}	64.6 V
Short Circuit Current	I_{sc}	6.14 A
Efficiency	η	19.30%
Maximum System Voltage	IEC, UL	1000 V, 600 V
Temperature Coefficients		
Power	−0.38% / °C	
Voltage (Voc	−176.6 mV/ °C	
Current (Isc)	3.5 mA/ °C	
NOCT	45 °C +/− 2 °C	
Mechanical Data		
Solar Cells	96 SunPower all-back contact mono-crystalline	
Weight	24 kg, 53 lbs	
Dimensions	1046 * 1559 * 46	
Warranty and Certifications		
Warranty	25 year limited power warranty 5 year limited product warranty	
Certifications	IEC 61,215, Safety tested IEC 61,730; UL listed (UL 1703), Class C Fire Rating	

Table 3
Selected inverter specifications.

Input (DC)	
Max. recommended PV power	30 kW
Max. DC voltage	1000 V
Rated MPPT voltage range	252- 970 V
Nominal DC rated power	28.6 kW
Number of MPP tracker inputs	2
Max. input current / per MPP tracker input	64 A / 32 A
Number of DC input pairs (parallel connection)	5
Output (AC)	
Nominal AC rated power	27.6 kW
Maximum AC output power	30 kW
Nominal AC rated line voltage	400 V
AC voltage rang	320–480 V
AC maximum output current	45 A
Nominal output frequency	50 Hz
Other Parameter	
Maximum efficiency	98.20%
Weighted efficiency	98.00%

The numbers of PV panels, $P_{inv,in,kWh}$ and the annual power produced by the module can be calculated by using Eqs. (3–5) as follow:

$P_{inv} = \ 97.96\,MWh$
$P_{\text{max,actual}} = 544.7\ (\text{kW}_\text{p}\text{h})$
$No.\,of\,PV\,Panels \ = \ 180\,Panels$

5.3. PV model arrangements

5.3.1. PV connections

From solar panel data sheet and Table. 2, the rated voltage for each panel is 54.7 V and the rated current is 5.76A while the maximum system voltage is 1000 V at standard test conditions. The number of the panels in series orientation can calculate by divided the maximum system voltage to panel rated voltage; that's mean 18 panels in series line, so 10 parallel lines we need. Ten parallel lines, each line have 18 Panel connected together in series (5.67 kW, 984.6 V, 5.76A) as shown in Fig. 6. The panel area according to the panel data sheet as mentioned in Table. 2 is 1.63 m^2 with its frame. So the required area is 293.4 m^2 in order to install PV panels, but shading effects must take in consideration for that row spacing was studied.

Fig. 6. Four zones area at the top of Engineering Faculty at Mu'tah University.

5.3.2. Row spacing

Shading can reduce the production of the PV arrays. For that, PV arrays should be installed in a shade-free location. However, grid-connected systems are usually found in urban areas and the modules are usually installed on roofs, where some shading is sometimes inescapable. To maximize the performance of the solar installation and to have the capability to install as many as possible panels in a given area. Two main factors which often considered are Orientation and Row Spacing or the Shading Distance [28].

To calculate the shading distance which is illustrated in Fig. 7. Eq. (6) [29], can be used;

$$X = Y\frac{Cos\gamma}{\tan\emptyset} \tag{6}$$

Where;
X: Shading Distance (m).
Y: Height of Titled PV Panel (m).
γ : Azimuth Angle (Degree).
α : Solar Altitude at Certain Solar Time (Degree).

Using the 315-SunPower solar panels with a length of 1.56 m make the value of Y at 31° solar altitude angle and at 30° tilt angle is equal to 1.3 m and The space length used for each panel is

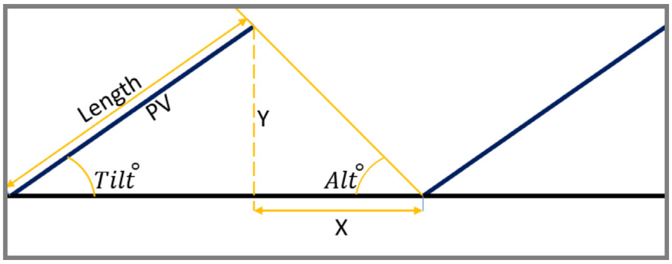

Fig. 7. Illustration of the values related to Eq. 6 for the shading distance calculations.

1.35 m (1.56 ∗ cos 30), so according to building roof we divided the available roof surface into four zones as shown in Fig. 6. After measuring the roof space, the results were;

- The available roof area for the faculty of engineering (after removing 1.3 m from borders) is 657 m^2, site located on the west side as shown in Fig. 6.
- Both zones 1 and 2 are equal in area = 170 m^2 for each.
- Zone 3 = 210 m^2.
- Zone 4 area = 107 m^2.

After measuring the used roof space, the roof space which can use for the PV system installation as:

- The area which can use in zones 1 and 2 to install PV system are equal = 127 m^2 for each.
- The area which can use in zone 3 = 188 m^2.
- Totally used PV area = 442 m^2.
- The residual area (215 m^2) can use for other equipment such as spare parts (Panels, Cables, washing tools, mechanical tools. etc.).

According to Fig. 8, the panels (109 to 126) are connected together by using the series connection also panels (127 to 144), (145 to 162) and (163 to 180). Group A in zone 3 consists of 36 panels (18 panels distributed in 2 lines connected together by using the series connection, and the two lines connected by using the parallel connection with another 2 lines). Group B have the same connection like group A. We used two inverters, each inverter connected with 5 parallel lines (90 PV-Panels, 28.35 kW, 984.6 V, 28.8A).

Table 4
PV system costs and system payback period.

Item	Cost
PV panels	$90,000 (63,000 JD)
Inverters (2 spices)	$8000 (5600 JD)
Cables	$3000 (2100 JD)
Balance of plant	$3000 (2100 JD)
Engineering	$10,000 (7000 JD)
Miscellaneous	$3000 (2100 JD)
Total PV cost	$117,000 (81,900 JD)
Electricity bill cost/ Year	$21,600 (15,336)
Payback period	5.5 Years

6. PV system economics

Nowadays and as a result of the technology improvements and economies of volume and scale the investment cost of the PV systems started to decrease. Investment costs, or total system costs, represent the most important barrier to the PV deployment today. Total system costs consist of the sum of module costs including mounting structures, inverters, cabling and power management devices.

Total system costs are sensitive to economies of scale and can vary substantially depending on the type of the application. For the proposed PV system cost and payback period with 4% of interest rate are illustrated in Table. 4 [30].

7. Conclusions

Jordan has 1.6 MW installed PV capacity in 2012, installed in the remote areas; the savings in the primary energy is equivalent to 399 toes. Solar irradiance with 30° tilted surface is higher than the horizontal surface during winter season while during the summer season the opposite is true. The annual solar average radiation by the horizontal and tilted-surface (30°) are 5.15 and 5.4 kW/m^2

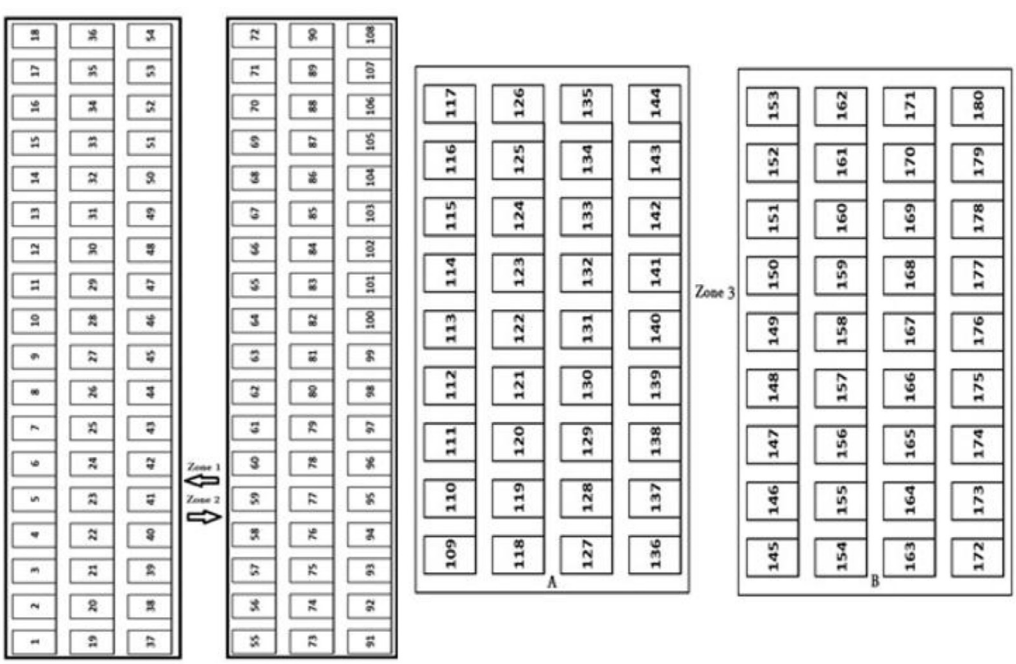

Fig. 8. Photovoltaic panels arrangement.

respectively. The average sunshine duration is more than 300 days and daily sunshine duration between 9 and 12 hours.

The faculty building consumes 96 MWh per year with a cost of more than 15,000 JD. On-grid PV system was fully designed with total capacity 56.7 kW for 25 operation years. PV system annual production delivered to the electric grid was 97.02 MWh by using 442 m^2 out of the available area which is 657m^2.

Economic costs for the proposed system was $117,000. While the electricity bill cost was $21,600. So the payback period for proposed system was 5.5 years and the system will lead to mitigation of about 85 tons of GHG emissions annually.

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