Design and simulation of a PV-grid connected system

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Abstract: This work presents the design and simulation of 10 kW grid-connected photovoltaic (PV) systems as feasible power generators for the Hashemite University campus (32.05°N, 36.06°E). The simulation is performed to justify the accuracy and reliability of such design using PV-SOL and Meteonorm simulation software. In the primary simulation runs a set of parameters including the module power, PV-solar panel size, inverter type, global radiation and angle of inclination were used. The results of those runs lead to the final simulation parameters which are used for the 10 kW PV system. This work also presents a comparison between the performances of different PV panel sizes and different inclination angles. The final design of 10-kW PV-system consists of 33 PV panels of 300 W each and three inverters of 3.4 kW each. In order to highlight the economical and ecological effectiveness and the promising potential of the proposed system, a comparison between the costs of one kWh generated by our system with that of the public electricity tariff has been conducted.

Keywords: grid-connected PV system; solar panel; inverter; inclination angle.


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1 Introduction

Jordan imports approximately 97% of its primary energy, of which 30% is used to generate electrical energy (National Electric Power Company, 2010). Renewable-energy sources are becoming more and more attractive especially with the continuous fluctuation in oil prices (International Energy Agency, 2010). Photovoltaic (PV) system is considered one of the important alternative sources in this regard (Rehman et al., 2006). This clean and environment-friendly energy-source is very promising in Jordan where solar global-radiation is one of the highest worldwide (Ibrahim et al., 2009).

It is important to state that the sun is the largest regenerative source of energy in our planet. It is estimated that the total annual sun radiation amounts to $3.9 \times 10^{24} \text{J} = 1.08 \times 10^{18} \text{kWh}$, which is more than ten thousand times of the present annual global energy needs (Quaschning, 2005).

To understand PV operation, we need to state that the solar cells are made of semiconductors material, which have some weakly bonded electrons. Electrons and holes usually appear in pairs within solid matter. The characteristics of the semiconductor material make it easy for incoming photons of sunlight to release electron-hole pairs (Quaschning, 2005; Luque and Hegedus, 2003) which are collected to generate current through an output load.

Figure 1 Solar cell construction (see online version for colours)

However, the electron movements have no clear direction; therefore, to create electricity, it is necessary to collect electrons. The semiconductor material is therefore doped with ‘impure’ atoms. Two different kinds of atom produce an n-type and a p-type region inside the semiconductor material, as shown in Figure 1, and these two neighbouring regions generate an electrical field. This field can then collect electrons and draw free electrons released by the photons to the n-type region and the holes move in the opposite direction, into the p-type region (Quaschning, 2005; Luque and Hegedus, 2003).

However, not all of the energy from the sunlight can generate free electrons. There are several reasons for this. Part of the sunlight is reflected at the surface of the solar cell, or passes through the cell. In some cases, electrons and holes recombine before arriving at the n-type and p-type regions (Quaschning, 2005). Furthermore, if the energy of the photon is too low, which is the case with light of long wavelengths, such as infrared, then it is not sufficient to release the electron. On the other hand, if the photon energy is too high, only a part of its energy is needed to release the electron and the rest is converted to heat (Luque and Hegedus, 2003).

In this work, a 10-kW grid-connected PV-system is investigated as a case study in the Hashemite University. Many factors have motivated this study. Firstly, the campus is located in a desert area where the global radiation numbers are one of the highest in the world. Secondly, the campus has a plenty of safe building flat-roof areas to install solar panels. Thirdly, most of the power demand is during the daytime so that implementing a grid-connected PV system would save considerably in the electric bill. Finally, continuous increase of electric bill cost due to the increase of oil prices is another big motivation of this work.

2 Photovoltaic system

In general, PV electrical power generation can be divided in two categories; stand-alone PV-system and grid-connected PV-system. The first category is used in remote areas where it is too expensive to be reached by public grid system. Big disadvantage of this system is the use of batteries for night supply, since battery energy-loss is too high (Marouani and Mami, 2010).

The second category is grid-connected PV-system where the generated electricity is directly used and there is no need for storage. This study investigates this category since Jordan national public-grid covers 99.8% of the populated areas in the country (National Electric Power Company, 2010).

Figure 2 shows the main components of grid-connected PV-system. The connection to the public grid is achieved by using proper inverters. Care must be exercised to choose inverter units with the highest efficiency. During the daytime, the solar generator provides power for the electrical equipment and excess energy is supplied to the public grid. In addition, during the night-time, the load gets its electricity from the public-grid (Luque and Hegedus, 2003).
Grid-connected PV system can be installed in different establishments where the range of power needs can be in magnitude of watts to magnitudes of megawatts. This can be achieved by installing enough PV-generators for different establishments.

3 Materials and description

The study is based on the Hashemite University campus located 25 km north of Amman, Jordan (32.05°N, 36.06°E). This area is a desert area where radiation is one of the highest in the world, which makes solar energy an attractive source of energy. Jordan Meteorological Department has around 15 weather stations in the country that collect regular meteorological data including sun radiation. Wadi-Dhulail weather station is chosen for this study since weather conditions are close to the conditions in the university campus (Royal Jordanian Geographic Centre, 2009; Jordan Meteorological Department, 2000–2009). The campus obtains its electrical power from a public grid that is shared with other industrial and residential consumers.

The peak consumption in the campus occurs during the daytime where PV power generation is conveniently can be generated. The university power consumption for year 2009 is 6,106 MWh with a cost of $529,000 where the cost of 1 kWh is $0.19. Furthermore, the unused building flat-roof areas are close to 53,600 m², which provide safe location for huge number of PV panels.

The principle objective of this simulation study is to provide a modular 10 kW PV system that will be connected to the public power grid as shown in Figure 2. Additional PV modules can be added in the future as needed to meet campus needs.

The software used for the simulation is PV-SOL (Valentin Energy Software, 2003). This simulation programme is used to design and perform calculations of grid-connected and stand-alone systems. It calculates the output of a PV system, depending on its location and determines its economic efficiency.

Monthly meteorological data, global radiations and temperatures, from Jordan Meteorological Department, were obtained for the last ten years. Figure 3 shows the yearly global-radiation over the last ten years, which are exceeding 2,000 kWh m⁻².

The actual PV system yields can vary due to a variation in weather conditions and module and inverter efficiencies. In addition, the data fed to PV-SOL is based on hourly data. However, the data obtained from Jordan Meteorological Department is monthly averages and not hourly. Therefore, Meteonorm software (Meteotest, 2003) is used to obtain the hourly data needed for the simulation. Meteonorm 5.0 is a comprehensive meteorological reference, incorporating a catalogue of meteorological data and calculation procedures for solar applications and system design at any desired location in the world.

4 Methodology and discussion

The methodology used in this work is detailed in the flowchart as shown in Figure 4. It starts with checking the validity of the simulation results by comparing them with the measured ones. The validity check is successful if the error is less than 5%. The global radiation is scanned for tilt angles between 0° and 90° to find the optimal angles. The hourly data at the optimal angle is combined with predetermined PV module and inverter to run the simulation. As a result of this simulation, the overall numbers of modules and inverters are determined. In addition, economical and ecological data is also provided.

Global-radiation data from Jordan Meteorological Department is compared with data available from Meteonorm software. Result for this comparison is illustrated in Figure 5(a) where the maximum error equals 2.8% as shown in Figure 5(b).

Moreover, the temperature data from Jordan Meteorological Department is compared with data available from Meteonorm software. Result for this comparison is illustrated in Figure 6(a) where the maximum error equals 3.6% as shown in Figure 6(b).

Therefore, Meteonorm software data proves to be accurate and reliable to be used in this study. One important factor of PV generation is the panel inclination angle. A simulation was performed to obtain the optimal inclination angle as shown in Figure 7, it was determined that an angle of 30° gives the maximum power generation.
Figure 5  Comparison of measured and simulated values of the global radiation (see online version for colours)
Design and simulation of a PV-grid connected system

Figure 6  Comparison of the measured and simulated monthly average values of the temperatures (see online version for colours)

Table 1  Simulation runs of three PV systems

<table>
<thead>
<tr>
<th>PV-modules:</th>
<th>BP Solar BP350U</th>
<th>Evergreen Solar EC-110</th>
<th>SOLON Black 300/10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverter</td>
<td>SP1500-E-48</td>
<td>SP 3000-E-48</td>
<td>PV-PNS04ATL</td>
</tr>
<tr>
<td></td>
<td>1.7 kW</td>
<td>3.4 kW</td>
<td>3.4 kW</td>
</tr>
<tr>
<td>Number of module/inverter</td>
<td>200/5</td>
<td>90/3</td>
<td>33/3</td>
</tr>
<tr>
<td>Panel in series</td>
<td>5</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>PV-power (kW)</td>
<td>10.1</td>
<td>9.91</td>
<td>9.96</td>
</tr>
<tr>
<td>PV surface (m²)</td>
<td>85.10</td>
<td>78.17</td>
<td>56.7</td>
</tr>
<tr>
<td>PV-generator, radiation (kWh)</td>
<td>186,207</td>
<td>169,341</td>
<td>173,760</td>
</tr>
<tr>
<td>Produced energy (kWh)</td>
<td>14,518</td>
<td>14,378</td>
<td>16,711</td>
</tr>
<tr>
<td>Annual yield (kWh (kWp)⁻¹)</td>
<td>1,417</td>
<td>1,428</td>
<td>1,674</td>
</tr>
</tbody>
</table>

Figure 7  Global radiation versus panel angle of inclination (see online version for colours)

Source: Etier et al. (2010)

The configuration of the PV system has been illustrated in Figure 2. This proposed 10 kW PV system is made of a number of panels and inverters. Initially, it is important to determine the optimal PV panel and inverter sizes using PV-SOL software. Table 1 shows the simulation results of one of the best runs where 300 W-panel-size and 3.4 kW inverter produce a maximum energy.

5  Results

The PV-SOL simulation has been conducted and the inputs needed to run the final simulation are the climate data, the module power, PV-module size, inverter type, place and angle of inclination. As a result of the simulation, the 10 kW PV-system is obtained from 33 panels of 300 W each and three inverters of 3.4 kW as shown in Table 2.
Table 2  Final simulation results

PV-modules: SOLON Energy GmbH
SOLON Black
300/10-300 W
Inverter: Mitsubishi Electric Europe B.V.
PV-PNS04ATL-3.4 kW

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number module/inverter</td>
<td>33/3</td>
</tr>
<tr>
<td>Number in row</td>
<td>11</td>
</tr>
<tr>
<td>Place</td>
<td>The Hashemite University</td>
</tr>
<tr>
<td>Angle of inclination</td>
<td>30°</td>
</tr>
<tr>
<td>PV-power (kW)</td>
<td>9.98</td>
</tr>
<tr>
<td>PV surface (m²)</td>
<td>56.7</td>
</tr>
<tr>
<td>PV-generator, radiation (kWh)</td>
<td>173,760</td>
</tr>
<tr>
<td>PV generator, produced energy (AC) (kWh)</td>
<td>16,711</td>
</tr>
<tr>
<td>System efficiency (%)</td>
<td>17.5</td>
</tr>
<tr>
<td>Specific annual yield (kWh/kWp)</td>
<td>1,674</td>
</tr>
<tr>
<td>Avoided CO2-emission (kg/year)</td>
<td>15,148</td>
</tr>
<tr>
<td>Inverter efficiency (%)</td>
<td>96.2</td>
</tr>
<tr>
<td>PV-generator efficiency (%)</td>
<td>17.75</td>
</tr>
<tr>
<td>Cost (including maintenance)</td>
<td>$31,690</td>
</tr>
</tbody>
</table>

Figure 8  Resulted PV system diagram (see online version for colours)
The description of the designed system is shown in the diagram in Figure 8, the solar panels are arranged in three sets of 11 panels each, the 11 panels are connected in series to produce the suitable voltage necessary to run the 3.4 kW inverter. Then, the three inverters produce the needed 10 kW unit.

It is clear from the data shown in Table 2 that the system efficiency is 17.5% where it has a big room for improvement. In addition, the system cost is $31,690 where 66% of this cost goes for the solar panels. Furthermore, the area required is 56.7 m² and plenty of safe areas are available in the campus.

6 Conclusions

The optimal configuration of modular PV-grid connected system to serve as an alternative power generator to meet the demand of the Hashemite University has been finalised. The calculations of one kWh cost for the proposed PV-system is turned out to be about $0.09 without any public subsidy, while it is about $0.19 from national electric power company. Hence, the electrical bill can be reduced to half.

Moreover, most of the PV-system cost comes from the PV solar panels cost and a portion of it might be covered from public subsidies in the future. Furthermore, the PV panel cost is in continuous decrease owing to emerging technologies while fossil fuels prices are increasing as demand increases.

This work has addressed the implementation of a 10-kW unit. Therefore, 356 of such units are needed to meet the power demand of the HU campus.

Furthermore, considering the environmental impact, the PV system does not produce CO₂ emission and maintains clean and healthy environment. As shown in Table 2, this PV-system prevents emission of 15,148 kg year⁻¹ of CO₂.

Future work might include improving system-efficiency and optimising system components. This might be achieved by investigating a new mechanism to keep the sun radiation vertical to solar-panels, or using newer technologies for the fabrications of solar cells and inverters.

References


