Experimental Analysis for PV Cells Performance Operating at Different Conditions

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Abstract

Many factors affect the operation and performance of a PV module. These factors will be investigated experimentally using factorial experimental designs analysis method. Several factors will be considered in this study. The results of the factorial designs provided a comprehensive understanding about how the PV system actually works and interacts under the optimum conditions. These factors are surface temperature, tracking, cooling effect, time of operation. This design of experiment (DOE) will consist of two $2^k$ factorial designs. The main effects for each factor on the PV performance was measured and then analyzed statistically to calculate the interaction effects between factors and the higher order interactions.

Keywords: PV performance, Factorial Analysis, Design of Experiment DOE. ANOVA analysis

1. Introduction

The energy consumption in the world is increasing greatly owing to the growing population, and to increasing energy consumption per capita. This high energy consumption is associated with a high life quality. Due to this fact, and to the energy price and availability and to the potential threat of global climate changes, there is a great motivation to use energy from renewable sources such as solar energy [1].

Solar energy has the largest potential among all renewable energy resources. Today, solar energy is captured essentially by photovoltaic (PV) modules, solar thermal collectors, solar dryers, solar cookers, and solar water pumps fed by PV. PV module is converting the solar irradiation into electricity and they evolved considerably in recent years [9].

Photovoltaic cells (PV) present a prime source of clean energy that utilizes energy from sunlight. Solar energy is converted directly to power without intermediate production of heat.
Solar cells are used to heat water and PV cells to produce electricity. Photovoltaic cells are manufactured from fine films or wafers made from silicon[2, 3].

At present, almost 95% of available solar cells are made of silicon. More than 90% of produced solar cell every year is based on crystalline silicon wafers. Thus, silicon-wafer based technology is important for the production of PV cells at present time [4]. However, performance of mono-crystalline-silicon wafer is more expensive but better in performance than the multi-crystalline-silicon (also known as poly-crystalline) wafers [5]. Conversion efficiencies of commercial types of multi-crystalline –silicon cells are in range of 12–15% and could reach 17% [6,7].

Abdelkader et al. [1] evaluate the performance of different solar modules in semi arid climate as in Jordanian. They indicate that mono crystalline PV cells have higher efficiency value than multi crystalline PV cells. The efficiency of mono crystalline PV cells can reach 18% while efficiency of multi-crustalline PV cells reaches 16%.

Ugwuoke et al.[8] evaluate performances of three silicon photovoltaic modules of Siemens product (55WP mono-crystalline, 50WP poly-crystalline and 10WP amorphous silicon modules) as a function of solar radiation at University of Nigeria, Nsukka. Maximum efficiencies of 12.97%, 9.67% and 4.94% were achieved at irradiinance of 600W/m2 for the mono-crystalline, poly-crystalline and amorphous silicon modules respectively. However, at irradiance of 1000W/m2, the efficiencies dropped to 9.61%, 7.65% and 3.62% for the mono-crystalline, poly-crystalline and amorphous silicon PV modules respectively.

Sun tracking systems monitor the sun during the day as the sun is continuously moving. It is well known that the electricity generation capacity of a PV panel depends on exposure to solar radiation in which the sun tracking systems provide this matter.

Salah Abdallah [10] studied four tracking systems in Amman, Jordan: dual axis, single axis vertical, single axis east-west and single axis north-south. The power generation by each system is greater than that of a fixed system tilted at 32° by 43.9%, 37.5%, 34.4%, and 15.7% for the dual-axis, east-west, vertical, and north-south tracking system, respectively.

Helwa et al. [11] compared experimentally four PV systems: fixed system facing south and tilted at 40°, vertical axis tracker, tracker with 6° tilted axis (north-south tracker), and dual-axis tracker. The results show annual increase of collected radiation by azimuth, north-south and dual axis trackers by 18%, 11% and 30%, respectively, over the fixed system.

Abu-Khader et al. [12] compared and evaluated different types of tracking. Four systems have been constructed and studied: fixed, vertical axis tracking, north-south tracking, and east-west tracking. Experiments result showed that the north-south tracking was the optimum one and produces 30-45% more output power than the fixed system tilted at 32°.
Mehrtash et al. [9] investigate the performance of photovoltaic (PV) systems with different types of solar trackers in climate conditions prevailing in Montreal, Canada. Four PV systems were simulated; horizontally fixed, inclined fixed, azimuth tracking, and a dual-axis tracking. Annual analysis shows an increase of array irradiation of up to 16.8%, 50.1%, and 55.7% for tilted fixed, azimuth tracking, and dual-axis tracking arrays, respectively, as compared to the horizontal fixed array. Dual-axis tracking and azimuth tracking array have the highest efficiency among these systems. The annual efficiencies of fixed arrays are 11% and 11.7% for horizontal and tilted fixed arrays, respectively, while the azimuth and dual-axis tracking systems have the same efficiency of 12.2%.

Figueiredo et al. [13] focus on the optimization of the electric energy production by photovoltaic cells through the development of an intelligent sun-tracking system. Their results show an increase in power generation, in relation to other PV-systems, without tracking devices, is of similar magnitude (ca. 25%) as for other usual tracking solutions.

Eke et al. [14] study the performance of two double axis sun tracking photovoltaic (PV) systems at Mugla University campus. The performance is calculated that 30.79% more PV electricity is obtained in the double axis sun-tracking system when compared to the latitude tilt fixed system.

PV cells utilize a small fraction of the incident solar radiation to produce electricity and the remainder is turned mainly into waste heat in the cells and substrate raising the PV temperature.

In common, PV module converts only 4–17% of the incoming solar radiation into electricity. Thus more than 50% of the incident solar energy is converted as heat and the temperature of PV module is increased [15].

Excess temperatures on installed PV modules lead to efficiency loss and PV cooling protects them from this undesirable efficiency drop. Both water and air have been used for PV cooling but air is preferred due to minimal use of material and low operating cost despite its poor thermo-physical properties.

Teo et al. [16] investigate the electrical efficiency of a hybrid photovoltaic/thermal (PV/T) solar system with and without cooling. By varying the air flow rate through the duct, the operating temperature of PV module decreases from 68°C to 38 °C then the efficiency rises up from 8.6% to 12.5%.

Chandrasekar et al. [15] developed a simple passive cooling system with cotton wick structures for standalone flat PV modules. The thermal and electrical performance of flat PV module with cooling system consisting of cotton wick structures in combination with water, Al2O3/water nano-fluid and CuO/water nano-fluid are investigated experimentally. The experimental results show that the maximum module efficiency of 10.4% is obtained with the use of wick structures in combination with water while the efficiency is 9% without cooling.
arrangement. The module efficiency is about 9.7% and 9.5% when cooling is provided with wick structures in combination with Al₂O₃/water and CuO/water Nano-fluid respectively.

2. Experimental description

In this experimental the performance of PV module was tested, the following equipment have been used to conduct the experiment.

- The PV Analyzer is a complete electrical test solution for verifying photovoltaic array characteristics. The device used in the experiment was The Solmetric PVA-600 PV Analyzer.
- A pyranometer was used to measure broadband solar irradiance on a plan surface and solar radiation flux density (w/m²) of an angle view of 180º. The device used in the experiment is Daystar Digital Solar Meter DS-05A.
- Three different types of PV modules were chosen as shown in figure 1. Table 1 gives the specifications of each type;

<table>
<thead>
<tr>
<th>Model</th>
<th>Poly-crystalline</th>
<th>Mono-crystalline</th>
<th>Thin film (CdTe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power, P (w)</td>
<td>115</td>
<td>150</td>
<td>77.5</td>
</tr>
<tr>
<td>Open Circuit Voltage, V_{OC} (V)</td>
<td>22.10</td>
<td>23.09</td>
<td>90.5</td>
</tr>
<tr>
<td>Short Circuit Current, I_{SC} (A)</td>
<td>7.65</td>
<td>8.58</td>
<td>1.22</td>
</tr>
<tr>
<td>Maximum Power Voltage, V_{Pmax} (V)</td>
<td>16.93</td>
<td>18.62</td>
<td>69.9</td>
</tr>
<tr>
<td>Maximum Power Current, I_{Pmax} (A)</td>
<td>6.76</td>
<td>8.06</td>
<td>1.11</td>
</tr>
<tr>
<td>Maximum System Voltage</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Fuse rating</td>
<td>C</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>Fire rating</td>
<td>12</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td>Dimensions, L×W×H (mm)</td>
<td>1495 × 990 × 45</td>
<td>1495 × 670 × 45</td>
<td>1200 × 60 × 6.8</td>
</tr>
<tr>
<td>Effective Area (cells area{l×w}) × number of cells), A_{eff.} (mm²)</td>
<td>(156 × 156) × 54</td>
<td>(156 × 156) × 36</td>
<td>(117.5 × 57.5) × 1</td>
</tr>
</tbody>
</table>

*Figure 1: Types of PV modules.*
An air conditioning unit was modified to get a cold air at 10°C. The cooling capacity of unit was 12,000 BTU.

A flexible duct of 4 inch diameter with 10 m length was formed in six paths; three for entering the air and same for exiting. The duct system was combined with cooling unit to make a circulation process for air cooling.

An axial air fan unit of 50 cm diameter is faced directly to PV module to reduce the temperature using forced air convection.

3. Experimental Approach and procedures

The experimental investigation has been carried out at the venue of the Al-Huson University College in Irbid, Jordan (32°29' N, 35°53' E) and about 650 m above sea level. The experimental was performed in (20, April – 10, May). Measurements were taken from the three PV modules every two hours from (8:00 am) to (6:00 am) of each day.

A three different of tilt angle for PV modules were tested:

1) **Horizontal**: place the PV module on horizontal surface.
2) **Inclined**: Tilting the PV module toward the south at a fixed angle (30°).
3) **Full tracking**: make the PV module face directly to the sun.

The tilt angle was determined as the following:

- **Horizontal**: Place the PV module on horizontal surface above 50 cm from the ground to reduce the effect of earth temperature on the PV module.
- **Inclined**: The tilt angle for Al-Huson area, Jordan in the experimental period is around 18°.
- **Full tracking**: To simulate PV tracking system, a two of metal stems are positioned in two opposite corners. With moving the module manually until the shadows of stems are disappears, the module is faced directly to the sun.

And three different of cooling levels:

- **High cooling**: decrease the temperature of PV until around 30°C using cooling unit.
- **Intermediate cooling**: decrease the temperature of PV until 40°C using air fan.
- **Cooling**: there is no cooling system. The temperature of PV modules rises up above 50°C.

The parameters tested were:

- measured power (P, watts),
- irradiance (I, watts/m²),
- efficiency (η)
4. Results and discussions

Figures 2, 3 and 4 shows the data recorded for measured power (P), irradiance (I) and efficiency (η) respectively.

Refer to figure 2; the curves show that the measured power was increasing as the temperature of PV module decreases regardless of module type. The maximum measured power is recorded at period of midday about 2:00 PM.

For poly-crystalline PV module; the cooling effect has increased the maximum measured power from range of (80 – 100) watts in low cooling status to range of (100 – 115) watts in mid cooling status to range of (115 – 120) watts in high cooling status. These results show an increase of 15%, 20% for mid and high cooling status respectively. In mono-crystalline PV module; the maximum measured power is increasing from range of (80 – 100) watts in low cooling status to range of (120 – 140) watts in mid cooling status to range of (125 – 150) watts in high cooling status, with an increase of 40%, 50% for mid and high cooling status respectively. In Thin Film PV module; the maximum measured power was increasing from range of (15 – 35) watts in low cooling status to range of (35 – 50) watts in mid cooling status to range of (40 – 55) watts in high cooling status, with an increase of 25%, 57% for mid and high cooling status respectively.

The tilt angle has been affected as it was expected; the results showed that if the PV modules in tracking system, the measured power is the highest. The tilt angle as inclined angle has the second order and the horizontal status has the lowest recorded data.

The irradiance curves for different tilt angle as shown in figure 3 mention to the fact that as the PV module is almost face directly to sun, the radiation is more than other status.

The efficiency of PV module is defined as following:

\[ \eta = \frac{P}{I \times A_{eff}}. \]

where,

P: the measured power of PV module, watt.
I: irradiance of the sun, watt/m².
A_{eff}: the active area of PV module, m².

The calculated efficiency is graphed in figure 4. The interested values are in the period of (midday – 2:00 PM) where the irradiance is the highest. Each curve shows an average increase by 2.25% for each level of cooling from low to mid to high respectively for different tilt angle status (i.e. mono-crystalline in tracking status, 11%, 13%, 15% for low, mid and high cooling respectively). According to degree of cooling and type of PV module, the highest efficiency was recorded for mono-crystalline PV module at high cooling.
Figure 2: The measured Power curves.
Figure 3: The measured Power curves.
Figure 4: The efficiency curves.
5. Statistical Analysis

“Factorial designs are frequently used in experiments involving several factors where it is necessary to study the joint effect of the factors on a response. However, several special cases of the general factorial design are important because they are widely employed in research work and because they form the basis of other designs of considerable practical value.

The most important of these special cases is that of k factors, each at only two levels. These levels may be quantitative, such as two values of temperature, pressure, or time; or they may be qualitative, such as two machines, two operators, the “high” and “low” levels of a factor, or perhaps the presence and absence of a factor. A complete replicate of such a design requires $2 \times 2 \times ... \times 2 \times 2^k$ observations and is called a $2^k$ factorial design.

The $2^k$ design is particularly useful in the early stages of experimental work, when many factors are likely to be investigated. It provides the smallest number of runs for which k factors can be studied in a complete factorial design. Because there are only two levels for each factor, we must assume that the response is approximately linear over the range of the factor levels chosen.” [17]

In this study these factors are surface temperature, tracking, cooling effect, time of operation. This design of experiment (DOE) will consist of two $2^k$ factorial designs. The main effects for each factor on the PV performance was measured and then analyzed statistically to calculate the interaction effects between factors and the higher order interactions.

For this statistical analysis, Minitab 16 statistical software was used to analyze the data as shown in figures 5, 6, 7 and 8;
**Multilevel Factorial Design**

Factors: 3  Replicates: 6  
Base runs: 27  Total runs: 162  
Base blocks: 1  Total blocks: 1  
Number of levels: 3, 3, 3

**General Linear Model: efficiency versus Type, Tilt, Cooling**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Type</th>
<th>Levels</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>fixed</td>
<td>3</td>
<td>poly, mono, thin</td>
</tr>
<tr>
<td>Tilt</td>
<td>fixed</td>
<td>3</td>
<td>horizontal, inclined, tracking</td>
</tr>
<tr>
<td>Cooling</td>
<td>fixed</td>
<td>3</td>
<td>high, mid, low</td>
</tr>
</tbody>
</table>

**Analysis of Variance for efficiency, using Adjusted SS for Tests**

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>2</td>
<td>2930.61</td>
<td>2930.61</td>
<td>1465.30</td>
<td>236.61</td>
<td>0.000</td>
</tr>
<tr>
<td>Tilt</td>
<td>2</td>
<td>35.63</td>
<td>35.63</td>
<td>17.82</td>
<td>2.88</td>
<td>0.060</td>
</tr>
<tr>
<td>Cooling</td>
<td>2</td>
<td>242.76</td>
<td>242.76</td>
<td>121.38</td>
<td>19.60</td>
<td>0.000</td>
</tr>
<tr>
<td>Type*Tilt</td>
<td>4</td>
<td>22.15</td>
<td>22.15</td>
<td>5.54</td>
<td>0.89</td>
<td>0.469</td>
</tr>
<tr>
<td>Type*Cooling</td>
<td>4</td>
<td>5.09</td>
<td>5.09</td>
<td>1.27</td>
<td>0.21</td>
<td>0.935</td>
</tr>
<tr>
<td>Tilt*Cooling</td>
<td>4</td>
<td>4.90</td>
<td>4.90</td>
<td>1.22</td>
<td>0.20</td>
<td>0.939</td>
</tr>
<tr>
<td>Type<em>Tilt</em>Cooling</td>
<td>8</td>
<td>6.19</td>
<td>6.19</td>
<td>0.77</td>
<td>0.12</td>
<td>0.998</td>
</tr>
<tr>
<td>Error</td>
<td>135</td>
<td>836.06</td>
<td>836.06</td>
<td>6.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>161</td>
<td>4083.39</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$S = 2.48858$  $R$-Sq = 79.53%  $R$-Sq(adj) = 75.58%

*Figure 5: Minitab output.*

![Residual Plots for efficiency](image)

*Figure 6: Residual plots for Efficiency.*
**Figure 7:** Main effects plot for Efficiency.

**Figure 8:** Interaction plot for Efficiency.
Refer to Minitab output, main effects plot and interaction plot for efficiency the following statements are determined:

- The type of PV module has the largest effect on efficiency while the cooling temperature and tilt angle have fewer effects respectively.
- The mono-crystalline PV has the highest efficiency and thin film (CdTe) has the lowest efficiency while efficiency of poly-crystalline was in between.
- The best status for tilt angle is inclined then tracking and the worst was horizontal.
- As the temperature of PV module decreases the efficiency increases.
- In 2-way interaction, there is a small significance compared interaction to the main effects. For example the type of PV & Tilt angle interaction was less than the type of PV & Cooling interaction which was less than the Tilt angle & Cooling interaction.
- 3-way interaction is not significance.

6. Conclusion

A performance test of mono-crystalline and thin film (CdTe) PV models has been carried out in this experimental. This test was conducted in (20, April – 10, May) at Al-Huson University College in north of Jordan. Power and Irradiance were recorded of the tested PV models.

Efficiency has been calculated based on measured value of power, irradiance and the effective area of PV model. Findings indicate that efficiency of mono-crystalline is higher than that of other PV models. Factors found to be taken into consideration while comparing the three PV types include:

1) Type of PV materials.
2) Tilt angle.
3) Cooling temperature.

The comparison of the efficiency of three PV type modules indicates that the best status is: *inclined mono-crystalline PV module with high cooling.*

References


