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Research Article

Optimization of Solar Energy Harvesting: An Empirical Approach

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Renewable energy is the path for a sustainable future. The development in this field is progressing rapidly and solar energy is at the heart of this development. The performance and efficiency limitations are the main obstacles preventing solar energy from fulfilling its potential. This research intends to improve the performance of solar panels by identifying and optimizing the affecting factors. For this purpose, a mechanical system was developed to hold and control the tilt and orientation of the photovoltaic panel. A data acquisition system and electrical system were built to measure and store performance data of the photovoltaic panels. A design of experiments and Response Surface Methodology were used to investigate the impact of these factors on the yield response as well as the output optimization. The findings of the experiment showed an optimum result with a tilt of 60° from the horizon, an azimuth angel of 45° from the south, and a clean panel condition. The wind factor showed insignificant impact within the specified range.

1. Introduction

The relation between man and the sun is ancient. The sun has played a massive role in the history of mankind. Some old civilizations even had spiritual belief in the power of the sun. According to Hsieh (1986), the sun is a giant nuclear reaction that transforms four million tons of hydrogen into helium per second. The earth will receive only a tiny amount of the sun generated energy [1]. The radiated energy from the sun must be equal to the energy it produces to ensure its structural stability. The evidence of this stability over the last 3 billion years can be seen by the relative stability of the temperature of the earth's surface. Oxidized sediments and fossil remains reveal that the water fluid phase has been presented through this time [2]. The earth's orbit around the sun is slightly elliptical, making the distance between the two vary throughout the year. The earth and sun are 91.4 million miles apart in January compared to 94.5 million miles in July; this leads to an annual disparity of 3%–4% in the irradiance at the edge of the atmosphere [3]. Although the earth receives just a tiny fraction of the sun's generated energy, it is still a massive amount of energy. The earth's radiation reception rate is $1.73 * 10^{17}$ J/s, and, in a year made up of 365.25 days, the total amount of radiation is $5.46 * 10^{24}$ J [3]. Boylestad and Nashelsky (1996) stated that the received energy at sea level is about 1 kW/m^2 [4]. There are strong links of all known forms of energy resources to the sun and how they are used by mankind [5].

The fossil fuels used today were formed over the course of thousands of years, but they are consumed rapidly. In 2009, the world consumed 11,164.3 million tons of oil equivalent. Comparing this consumption with the amount of received solar radiation during the same year, one will find that the input of solar radiation was 11,300 times greater than the world's total primary energy consumption [3]. This increase in consumption of the limited fossil fuel resources and the environmental concerns plus the fluctuations in the oil market have led humanity to search for more clean and renewable sources of energy. For a long time, solar energy has been one of the most promising, sustainable energy sources. Generating electricity from the incident light has many challenges, and one of the greatest challenges is the drop in efficiency.

Solar energy is now estimated for one-third of the United States new generating capacity in 2014, surpassing both wind energy and coal for the second year in a row [6, 7]. However the current photovoltaic (PV) panels are not highly efficient.

Table 1: The specification of the monocrystalline photovoltaic panel.

Open circuit voltage	44.9 V
Optimum operation voltage (Vmp)	37.08 V
Short circuit current (Isc)	5.55 A
Optimum operating current (Imp)	5.15 A
Maximum power at standard conditions (Pmax)	190 W
Cell efficiency	17.04%
Operating temperature	−40°C to 85°C
Maximum system voltage	1000 V
Pressure resistance	227 g steel ball falls down from 1 m height under 60 m/s wind

The performance and efficiency of the PV panels depend on many factors such as the following [8–14]:

(i) The manufacturing and material specifications where the maximum theoretical efficiency is limited

(ii) Improving the power conversion for the PV panels systems, where the conversion from the generated DC into AC causes losses in efficiency

(iii) Environmental factors (e.g., temperature, wind)

(iv) Status of the PV panels (e.g., orientation, tilting)

Many PV system optimization efforts have utilized these factors from performance and economic perspectives [15–26]. In this research the focus is on the environmental factors and status of the PV panels where the designated location and time/date play a significant role in the performance of the PV panels. The purposes of the research are to identify the significant factors, their range, and the optimum settings to improve the performance of the PV panel. The controllable factors include tilt, orientation (azimuth), wind, and the level of cleanness.

Figure 1: The mechanical system design, manufacturing, and assembly.

2. Material and Methods

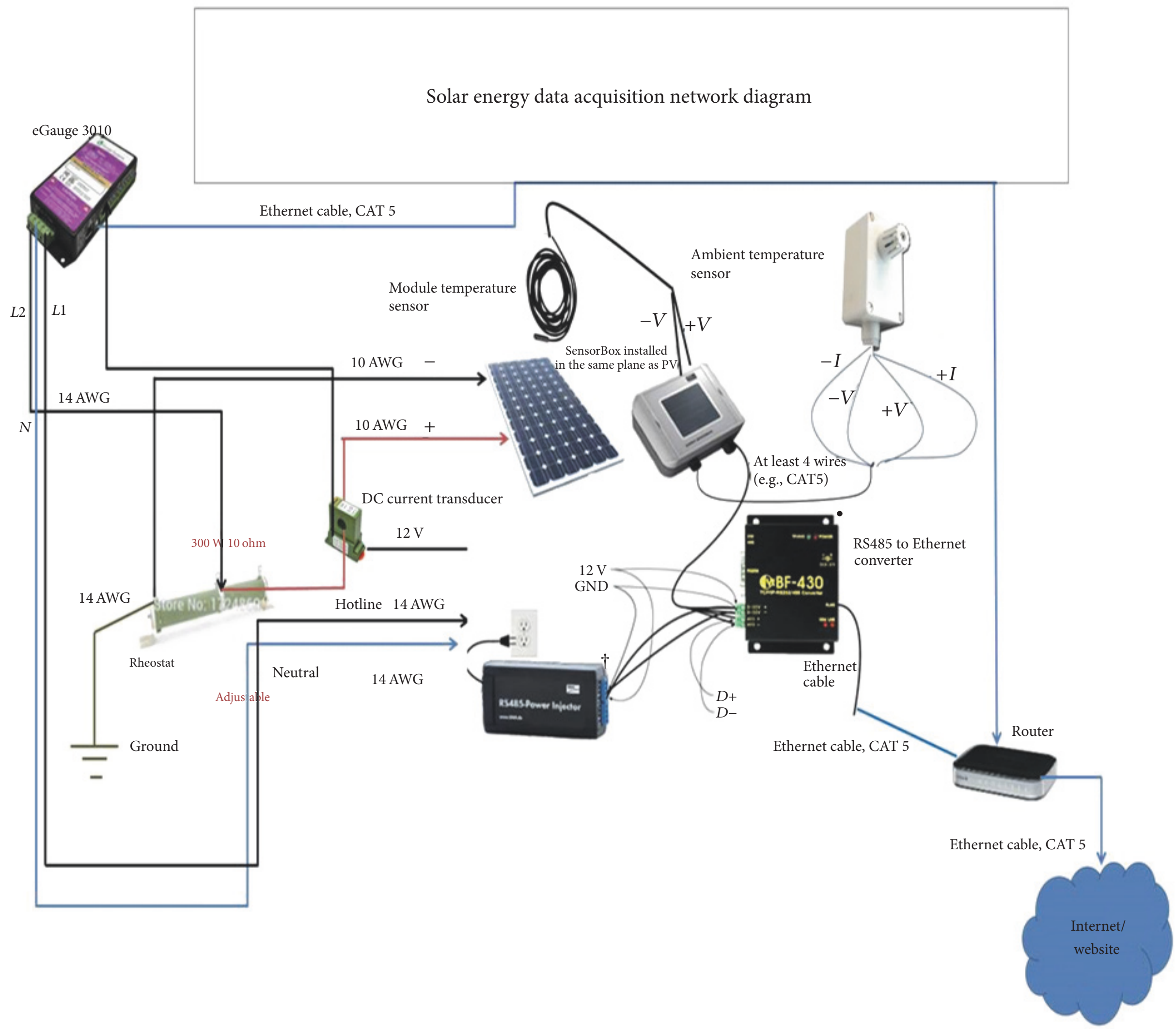
2.1. Infrastructure. Suitable infrastructure to conduct this research has been developed. The infrastructure includes a mechanical system (Figure 1), to hold and control the tilt and orientation of the photovoltaic panel, the photovoltaic panel (Table 1) and an electrical system (i.e., wire-wound, adjustable, tube resistors), and a web-based data acquisition system (Figure 2). The data acquisition system used in this research consists of the eGauge, DC current transducer, power injector, RS485 to Ethernet converter, sunny sensor box, ambient temperature sensor, the PV panel temperature sensor, router, Ethernet cable, and wires [27].

2.2. Optimization Approach. The experiment was designed using Response Surface Methodology (RSM). The selection of the method was based on both the objective of the experiment and the number of factors and levels. RSM can be defined as a combination of mathematical and statistical techniques effective for establishing, refining, and optimizing processes. It can be also used for the design and creation of new products as well as improving current ones [28]. The RSM inputs are the identified independent variables and the output will be the yield response which represents the performance measure of the process. The unknown response can be approximated to a first-, second-, or third-order model. The most used model is the second-order model (quadratic) especially if curvature in the response is suspected. In this model main effects and interaction between factors can be identified. In general, the second-order model is

$$\eta = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum_{i<j} \sum \beta_{ij} x_i x_j, \quad (1)$$

where x_i and x_j are variables i and j, respectively; β_0, β_j, β_{jj}, and β_{ij} are parameters of second-order model; and η is model response.

Variables (x_i and x_j) usually are coded variables transformed from natural variables. The independent variables are called natural variables when they are expressed with natural units. "…Natural Variables can be transformed to coded variables who are dimensionless with mean zero and the same spread or standard deviation" (Montgomery 1997, p. 3) [29].



•BF-430 sold by eGauge___

†Power Injector comes with SunnyBox

Figure 2: The wiring diagram of the system used in the research.

An experiment, as described by Montgomery (1997), is a test or sequence of tests where deliberate adjustments are made to the input variables of a system so that we may detect and distinguish the causes of the changes in the output response. Designed experiments are used in many disciplines and their impacts can be seen in almost every aspect of our lives. They help to build our knowledge about certain processes and systems, which give us insight to enhance and improve performance. Engineering fields are one of the biggest venues where design of experiment is used. Lower costs, new ideas, new processes, new products, and new systems are invented due to the practice of design of experiments.

3. Response Surface Methodology

3.1. Factors Identification. The first stage of the Response Surface Methodology is to identify the important factors and their levels. They should have significant impact on the yield response. In this experiment independent variables with multilevels are identified with a goal to study their effect on the response yield and to find the optimum setting of the factors' levels. A model of typical process is applied with input, independent variables, uncontrollable factors, and output. The photovoltaic effect is considered as the process. Two PV panels are used as the input materials. The irradiance is considered another input to the process. The date, time, and location were also considered as inputs to the process. The temperature of the PV panels and the ambient temperature, though measured, were considered as uncontrollable factors. General weather conditions were considered as uncontrollable factors including the clouds and humidity. Tilt angle, azimuth angle, wind intensity, and solar panel cleanness were considered as the controllable factors.

Table 2: The four uncoded factors with their three levels.

level	A = tilt angle	B = azimuth angle	C = wind	D = panel cleanness
Low	0	−45	0	0
Mid	30	0	5.5	20
High	60	45	10	40

3.2. Factors Levels in Feasible Ranges. For four independent variables three levels in the feasible ranges were identified: A: tilt angle with three levels of 0°, 30°, and 60° from the horizon; B: azimuth angle with three levels of 0°, 45°, and -45° from the south; C: the wind with three levels of 0, 5.5, and 10 Km/h. The wind factor has been achieved through the use of a fan with multiple speeds. The speed of the fan was measured through the use of a wind sensor. The fan placed in front of the panel with two-feet distance from the center of the PV panel. The fan was set to oscillate to make the air waves cover the entire PV panel. Finally, D: the cleanness of the PV panels with three levels. Talc was used to emulate the cleanness of the PV panels. Three levels of cleanness were determined based on the amount of the talc scattered randomly on the surface of the PV panel. The levels were absent of talc as 0 grams, ten shakes of talc which equal 20 grams as second level. The third level of cleanness was twenty shakes of talc which is equal to 40 grams.

The two PV panels used in the experiment were identical. One panel was placed on the dual axis mechanical system while the other was flat on the ground. The rheostats loads that were used in the electrical system were identical. To overcome the minor discrepancy of the initial output power of the two PV panels, a small calibration was applied to them with $R1 = 7.1\,\Omega$ and $R2 = 7.4\,\Omega$. The irradiance of the flat PV panel was determined as the input of the process and it was measured through the use of an irradiance sensor placed flat beside the flat PV panel. Another irradiance sensor was attached to the mechanical system and it was subjected to only two factors which were tilt and azimuth angles (orientation of the PV panel) and their three levels (Table 2). The second sensor was recording the irradiance changes due to the changes in the tilt angles and the azimuth angels. The yield response of the process was determined to be the recorded power differences between the two PV panels. The selection of the power difference as an output was to minimize the effect of the variation of the irradiance during the experiment on the process. The four factors were selected with high, mid, and low levels.

3.3. Design of Experiments. Experimental design has been implemented to characterize the process in terms of how input parameters affect the power output. The main two kinds of designs of Response Surface are Central Composite designs and Box-Behnken designs. The selection of the type of Response Surface design is the second stage. In this experiment Box-Behnken was used. The advantages of using Box-Behnken designs are to have less design points than Central Composite designs, which will make it less costly. High efficiency is needed to estimate the first- and second-order model coefficients. The disadvantages are the incapability to use runs from a factorial experiments, the limitation of three levels per factor while the Central Composite can have up to five, and finally they cannot have runs with the extreme value of the factors.

The software is used for the design of experiment and to analyze the result is Minitab. The setting included the selection of three replications and randomization to reduce the bias. The software generated the following 81 uncoded runs.

3.4. Conducting the Experiment. The experiment was conducted on 17th and the 18th of December 2015. The readings were collected from the data acquisition system and were inputted to the runs' charts. These runs were later compared to the data saved in the system to guarantee the accuracy.

3.5. Results: Data Analysis. The next stage of the RSM is to analyze the data and find the RSM coefficients. Minitab is used to perform the aforementioned tasks. The confidence level used during the analysis was 95%, and it was two-sided.

The normal probability plot on Figure 3(a) shows normal distribution of the residuals. The histogram plot in the same figure shows the frequency of the residual. The highest residual frequency is around zero. Unusual high residuals (−60) can be seen with low frequency. The residuals-versus-fits plot shows no pattern, which supports the regression model. The residual versus observation order shows randomization, which support the independence assumption.

The calculated P values through the ANOVA indicate the significance of the factors and their interactions on the yield response. Some of the factors have a high P value and they were removed from the edited equation (higher than 0.05). These factors or their interactions are C, C^2, AC, AD, BD, and CD. Some of the second-order parameters have a critical P value and are kept in the final equation. These include BB and AB with a P value equal to 0.05 and 0.052, respectively. The wind factor and its interactions showed insignificant impact on the response except the interaction with the azimuth angle (orientation) of the PV panel. This might be due to uncontrollable natural wind occurred during the experiment.

The final equation is as follows.

Regression Equation in Uncoded Units

$$\begin{aligned}\text{Power Difference} = {} & 4.1 + 2.272A + 0.241B - 50.8D \\ & - 0.01299A^2 - 0.00562B^2 \\ & + 12.06D^2 + 0.00964AB \\ & - 0.328BC.\end{aligned} \tag{2}$$

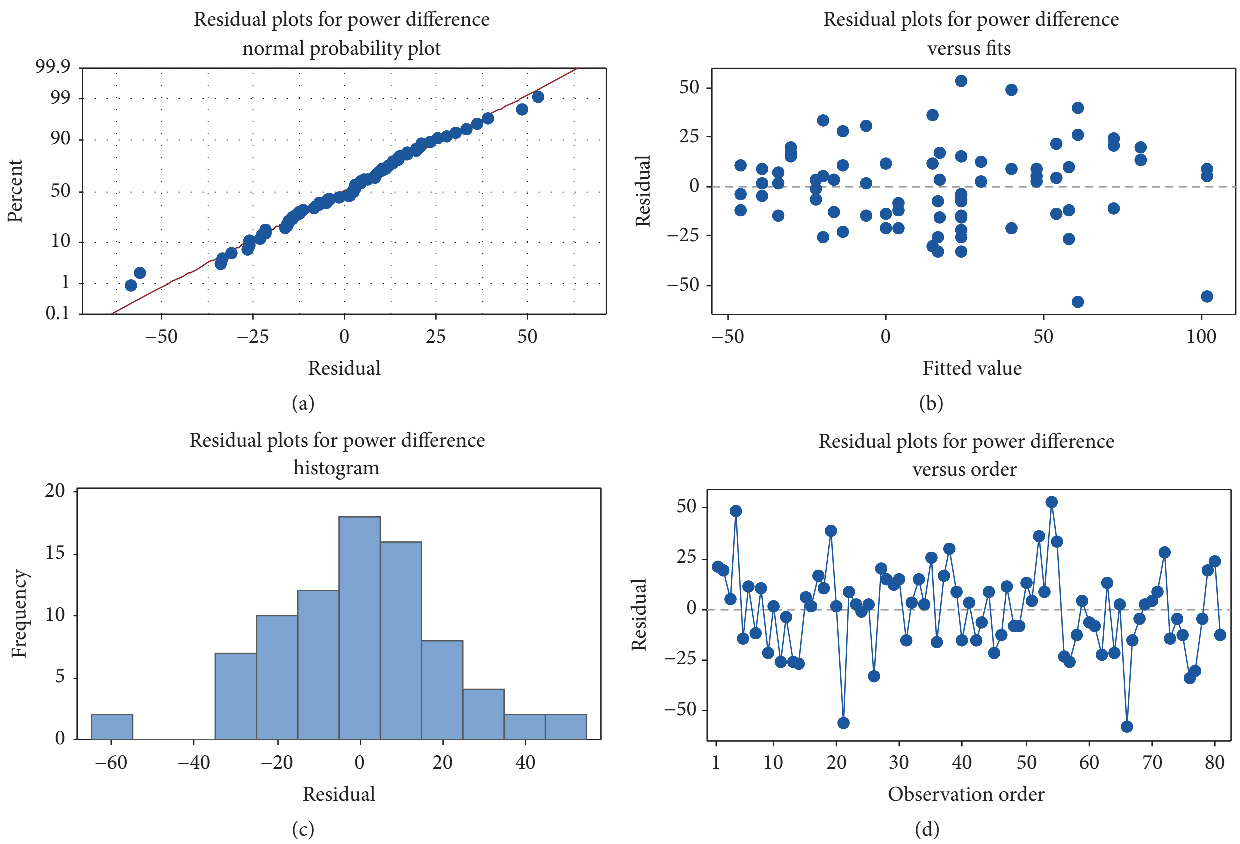


FIGURE 3: Four-in-one residual plot generated by Minitab.

3.6. Results: Optimization. The optimization of the response was determined by Minitab. The software generated the optimum settings of the factors to maximize the yield response. Table 3 and Figure 4 show the Minitab generated optimum results.

The Minitab calculations show the optimum settings to maximize the power difference are achieved when the tilt of the PV panel is 60° and the PV panel is oriented toward the west and there is no wind and dirt on the surface of the panel.

3.7. Validation. The PV panel was subjected to the founded optimum levels of treatments on the 26th of February. A sample of the data was collected from 27th record and results were close to the predicted value in the model (119 W) (Table 4).

Based on the results from validation experiments, power difference for two PVs was 109.31 Watts.

$$\text{Power difference from validation experiment} = 109.31\ \text{Watts}. \tag{3}$$

For similar setting (Table 3), power difference from model is predicted as 119 Watts.

$$\begin{aligned}\text{Power difference from model} &= 4.1 + 2.272\,(60) + 0.241\,(45) - 50.8\,(0) \\ &\quad - 0.01299\,(60)^2 - 0.00562\,(45)^2 + 12.06\,(0)^2 \\ &\quad + 0.00964\,(60)\,(45) - 0.328\,(45)\,(0) = 119.\end{aligned} \tag{4}$$

TABLE 3: Multiple Response Prediction.

Variable	Setting
A	60
B	45
C	0
D	0

Therefore, the model predicted the power difference with about 8% error.

Model versus validation difference = (119−109.31)/119 = 8%.

4. Discussion: Investigation of the Sun's Position and Its Effect on the Optimum Point

One element, which was ignored during the study and optimization process, is the fact that sun's position was changing during the data collection of the experimental runs. It is obvious the optimum positon for tilt and azimuth is when PV is pointed exactly toward the sun (continuous sun tracking). However, for the fixed level settings and since conducting experiments may take several hours, assuming a fixed position for the sun is inaccurate (Figure 5).

Further investigation of the data showed that the optimum point for the tilt angle changes simply by changing the

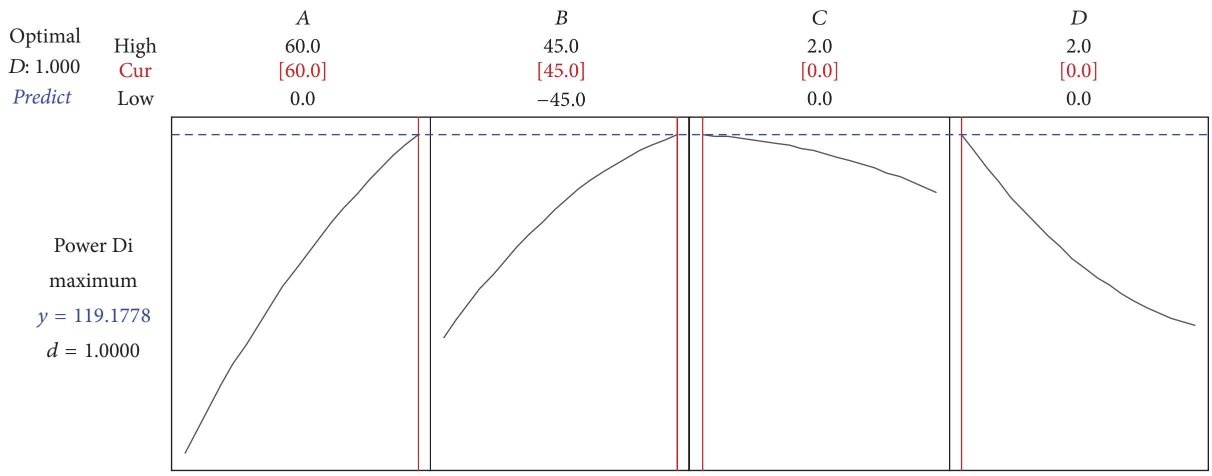


FIGURE 4: The optimization graph generated by Minitab. The four factors and their optimum setting are shown in red.

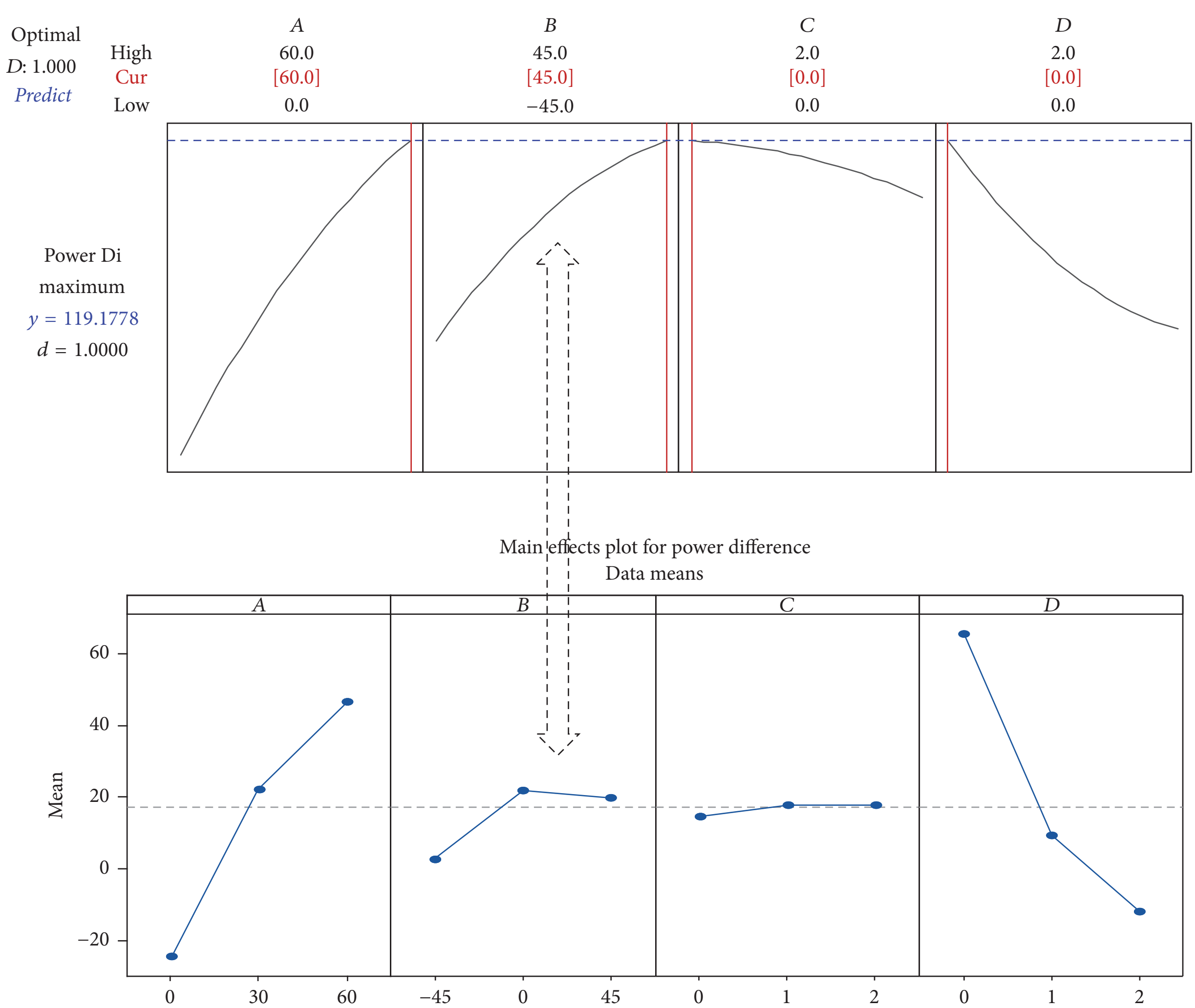


FIGURE 5: Optimum versus main effect inconsistency for factor B: azimuth angle (degrees from south).

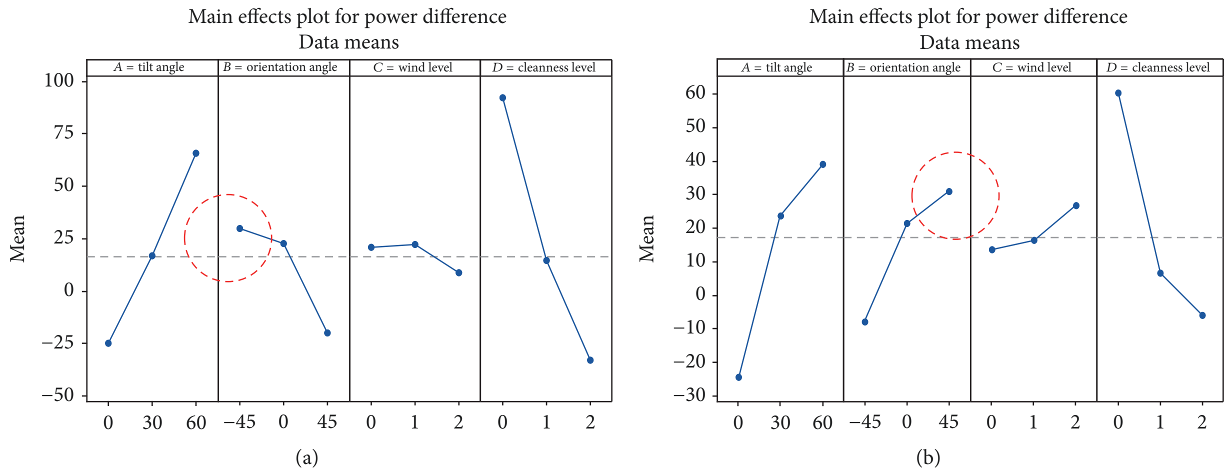


FIGURE 6: The main effect for the runs before midday. The highest achieved response is when the PV panel is pointed toward the east (a) and the main effect plot for the runs in the afternoon. The highest achieved response is when the PV panel is pointed toward the west (b).

TABLE 4: Validation sample of data. A sample of data from the 27th of February 2016 with the optimum settings of 60° and 45° from the south, 0 wind and 0 talc.

Date and time	Power 1	Power 2	Power difference	Irradiance 1	Irradiance 2
Feb 27	169.8 W	60.5 W	109.31 W	1000.8 W	394.25 W

time of the day when the runs were conducted. To show this effect, in this study, the experiment was conducted during two consecutive days, the 17th and 18th of December. Midday on these two days was around 12:28 PM. The runs were divided into two groups, before and after midday. The runs before midday were 22 runs with the following run orders [1 to 5; 42 to 58] and after midday were 59 runs with the following run orders [6 to 41; 59 to 81]. The main effect plots were generated using Minitab for each group. The maximum power differences for the runs before midday were achieved with the PV panel oriented toward the east. The maximum power differences for the runs after midday were achieved with the PV panel toward the west. This shows the significant importance of tracking the sun for the PV panel (Figures 6(a) and 6(b)).

5. Conclusion

(i) The research used design of experiments and Response Surface Methodology to plan, analyze, and optimize the experiments.

(ii) The three out of four factors investigated in this research to optimize the performance of the PV panels have significant impacts on the power output.

(iii) In addition to these factors, other variables such as the date/time and the location of the PV panels affect the performance of the PV panels as well.

Disclosure

Sponsors are not responsible for the content and accuracy of this article. This article is a portion of a Master of Science thesis by Almusaied reported in [27].

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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