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Optimization of the Residential Solar Energy Consumption Using the Taguchi Technique and Box-Behnken Design: a Case Study for Jordan

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Abstract – *In this paper, the Jordan's adoption of renewable energy, in general, and the solar energy, in particular, is overviewed. The solar energy development in Jordan, within the last decade, is highlighted from various aspects. Energy consumption and efficiency are major issues for nations such Jordan that have few natural resources and high energy costs, especially in the context of climate change. In Jordan, the industry with the highest energy use is residential construction. Residential building rooftop photovoltaic (PV) systems may address the issue of rising power needs and the need for more sustainable energy systems. This research contrasted present and projected residential household power usage with the potential electricity consumption from PV systems placed on the available roofs of residential structures. Taguchi and Box-Behnken Design (BBD) approaches were used to predict and optimize the yearly power usage using a design tool in Minitab version 18. The findings showed that the yearly energy usage was significantly influenced by solar cumulative installed PV power, sun shine hours, and operation service factors. The investigation revealed that the combined ideal elements and reactions meet the highest demands of the annual power usage of 8.0940 MWh per capita. The annual increase of PV plants, connected to the Jordan electric grid, refer to the availability of this area to adopt more and more PV projects. The available land, moderate climate, and reliable electric grid are encouraging factors to accepting large PV projects. The result showed that the yearly energy usage was significantly influenced by solar cumulative installed PV power, sun shine hours, and operation service factors. The investigation revealed that the combined ideal elements and reactions meet the highest demands of the annual power usage of 8.0940 (MWh per capita).*

***Keywords**: Solar Energy, Consumption, Taguchi Method, Box Behnken Design, Residential, Optimization, Jordan*

Nomenclature

PV	Photovoltaic
GDP	Gross Domestic Product
CSP	Concentrated Solar Power
PPA	Power Purchase Agreement
BBD	Box-Behnken Design
RSM	Response Surface Methodology
PPAs	Direct Power Purchase Agreements
GCCF	Gulf Corporation Council Fund

I. Introduction

Jordan has faced issues because of rising energy demand during the previous two decades, owing to the country's limited resources. Since fossil fuels are becoming scarcer and have a negative impact on the environment, solar energy applications have drawn more attention. Jordan's national economy and energy strategy have undergone a strategic transition [1]. Jordan has supported the solar energy efforts. In the assessment, appropriate technology installation, demonstrations, and pilot projects were closely monitored [2], [3]. The usage of solar energy in Jordan has a tremendous potential for around 330 sunny days per year using solar panels due to Jordan's high and steady solar insolation of 5.5 kWh/m^2/day) [4]. Seasonal variations in solar radiation are also seen, with the higher sun rising in the summer and lower in the winter because of the earth's tilt [5].

This research compares the current and projected household energy use with the potential consumption of electricity from the available rooftop photovoltaic (PV) systems of residential buildings. The Taguchi and Box Behnken Design (BBD) approach was used to predict and optimize annual energy use using a design tool in version 18. Nevertheless, climate change has quickly become one of the most urgent environmental concerns facing the globe [6]-[9]. The demands placed on a building's energy supply will go up in tandem with an increase in the

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ambient temperature [10]-[12]. As a direct consequence of climate change, heatwaves are occurring more often in the Middle East, which will result in a considerable increase in total energy consumption, particularly in terms of electricity usage [13]-[15]. Residential building roof-mounted PV systems may provide a means of reducing the rise in future energy demand and may be crucial in the creation of clean and sustainable energy sources [11]. By 2030, it is anticipated that Jordan's population would have increased to 12.9 million. As a consequence of this, there will be an increase in the demand for energy in the residential construction sector [16]. It is now necessary for Jordan to import 94% of its oil and gas from other countries to satisfy its need for energy [17], which makes the country's fuel costs susceptible to fluctuation. Jordan's demand for energy is growing at a pace of 3% per year.

Because of this, the problem of Jordan's energy supply is one of the most serious difficulties the country confronts. Jordan's debts amount to 97% of its gross domestic product [18], and the majority of this debt is caused by Jordan's rising energy costs, which are mostly a result of the regional circumstances that have surrounding Jordan recently [18]. As a result, finding a renewable energy source to replace the pricey energy that is imported from other nations has become imperative for Jordan. In comparison to the other energy generation methods, solar power is often considered the most profitable [17], making it an obvious winner. The amount of energy needed to power buildings accounts for around forty percent of the world's total energy usage [19]. The use of energy in buildings is responsible for the production of one-third of the world's total emissions of greenhouse gases [20]. The rising number of people in the world is responsible for the rising need for energy [21]. The large amount of energy consumption may be attributed to heat gains and heat losses that occur via the building envelope. Increasing the building's energy efficiency will decrease the amount of heat gained or lost via the envelope [22], [23]. By 2030, it is anticipated that residential energy consumption would account for 67% of the overall energy demand [24], whereas 33% of the total will be made up of non-residential energy use. Twenty percent of Jordan's Gross Domestic Product (GDP) is attributed to energy costs [25].

This range varies depending on the available rooftop, which in turn varies depending on the style of apartment complex, specifically the number of stores and the number of apartments on each level [11]. Installing PV on apartment building roofs may provide homeowners with power ranging from around 50% to more than 100% of the electricity required to run the residential unit. Due to its position inside the world's solar belt and its average solar radiation range of 5 to 7 (kWh/m^2), Jordan has a significant solar energy potential. To significantly enhance the usage of renewable solar energy sources and meet the sustainable development objectives, PV technology is crucial [26], [27]. Also, solar PV panels have increased their worldwide power output to over 627 GW in 2019, up from less than 23 GW in 2009 [27]. As a consequence, residential PV systems and battery storage systems, as well as their installation in buildings and houses, have grown rapidly recently and are expected to grow further [12], [28]. Rooftop PV systems have emerged as a major renewable energy source in a number of nations. Furthermore, since renewable energy sources emit less emissions, PV systems can significantly reduce emissions from the household electrical sector [29]. As a result, several nations' energy plans and objectives now include the widespread use of PV technology for use on rooftops [28]. Rooftop PV systems have recently seen widespread adoption owing to their technical, economic, and social/environmental benefits [30]. Roof-mounted solar PV systems are an effective way to provide social, economic, and environmental benefits, and they may assist in enhance the stability and safety of the local energy supply [31]-[33]. This study optimizes and calculates the yearly consumption per capita of electrical energy used by installing solar panels on residential building rooftops to suit their energy needs. The residential sector is considered as the largest consumer of electricity in Jordan, accounting for around 46% of the total power consumption. With 22%, the industrial sector is followed by water plumbing (15%), commercial building (14%), and street lighting (2%) [17], [34]-[37].

II. Solar Energy in Jordan

In Jordan, the yearly average number of sunny days is 310, and the country receives an average of 5 to 7 kWh/m^2 of direct solar radiation [39]. The overall yearly irradiance ranges between 1800 and 2700 kWh/m^2, and on a horizontal surface, the yearly daily average global solar irradiation is around 5.6 kWh/m^2. The government wants to have 800 MW of solar energy by 2023. Since the renewable energy law was passed in 2012, it is anticipated that the nation has produced a total of 236.4 MW from the PV systems [38]. Now around 300 installation businesses are registered to do business in the nation, with roughly 20 of those companies actively operating in the market.

Direct Power Purchase Agreements (PPAs) of 200 MW were signed for projects in the Ma'an Development Area in 2015. An additional 75-100 MW PV project is now being assessed in the Quweirah region with assistance from the Gulf Corporation Council Fund (GCCF) in Aqaba [38]. In remote areas, such as villages, rural areas, and deserts, PV is used to pump water, light homes, and support other community activities, the top capacity of the electricity generating capability from stand-alone PV systems is 1000 kW. Around 20% of all homes have already solar water heating systems installed on their rooftops [39]. In accordance with the energy master plan, it is anticipated that by 2023, 30% of all houses will have installed a solar water heating system [39]. According to the national strategic plan [39], Aqaba will soon be home to the world's first Concentrated Solar Power (CSP) facility and the world's first solar desalination plant. In 2023, these plants will have a capacity of 300–600 MW and use CSP–PV hybrid systems.

First solar has entered a PPa with Jordan's electricity provider 20 years to manage the 52.5 MW PV solar facilities located in Shams Ma'an beginning in 2019. The evaluation of an additional 400 MW projects brings the total number of tender rounds to 2200 MW. A Power Purchase Agreement (PPA) to construct Jordan's biggest solar power plant to date (200 MW) was signed with Masdar, a firm located in the UAE, in October of 2019. It is anticipated that the plant, which will be given the name Baynouna, would fulfill the yearly power requirements of 110,000 homes in the southern region of the nation by the time 2018 comes to a close [39]. There were about 1.40 km^2 of solar water heating panels put on the building rooftops, in addition to 150 kWh of PV systems [40]. The majority of these panels are created locally by around 25 small businesses that specialize in solar water heaters.

These businesses build approximately 4500 solar water heaters annually [40]. Solar water heating systems are installed in around 30% of the nation's residential structures.

III. Materials and Methods

The quantitative methodology was used in this research to accomplish the study's primary goal. The case studies that were applied in this research were examples of optimizing solar energy consumption (MWh per capita) in Jordan by employing the Taguchi method, BBD, and Response Surface Methodology (RSM). Using the power generated by your solar panels to operate appliances and machinery inside of your house or place of business is an example of solar energy usage.

If you have a net energy meter, also known as a bi-directional energy meter, this will take care of itself automatically whenever you turn on household appliances while your solar energy system is still providing power. It is important to point out that the research data were collected from the literature [39]-[42].

Solar cumulative installed PV power, sun shine hours, and operation service are the key determinants of solar energy consumption; hence, they have been used as input parameters.

Solar cumulative installed PV power (at the end of the year) and megawatts variable were employed in this investigation, and the process variables used were 1359 MWh, 1404 MWh, and 1448 MWh. Besides, the sun shine hours were 6, 9, and 12. While the duty operation service variable of 10093 hr/year, 10927 hr/year, and 11760 hr/year were selected, as shown in Table I.

These variables will be taken into account at the same time to find the optimization that produces the best of the annual electricity consumption (MWh per capita) response.

The Taguchi method and BBD used in this study are examples of how the RSM can be used to fit a complete quadratic polynomial model, allowing for the presentation of superior experimental results by isolating the effects of individual factors and their interactions (response value).

The RSM is used for this purpose, and it may be used to fit a whole quadratic polynomial [43].

Taguchi and BBD approaches are examples of "Classical" response-surface optimization designs. Taguchi was named after the inventor of the BBD. Each experimental variable must be investigated a minimum of three times before a second-order model can be fitted to the data.

These designs allow or several layers of experimental variables to be accomplished in various ways. In BBD, it is common practice to employ three different levels for each experimental variable, similar to two-level factorial experiments, BBDs do not produce samples at the minimum and maximum values of the experimental variables.

This is because the way of design which is structured. Instead, the samples for the experiment are taken from the points where the borders of the experimental area overlap.

Each experimental variable is present at three different concentrations, allowing for an examination of the linear, quadratic, and interdependent effects of each [44].

As was previously indicated, the application of the research methodology, as well as the Taguchi technique and BBD, were carried out with the help of the Minitab 18 program. The BBD was used for this research, and in the outset, the researcher established the variables and entered the values. Table II provides an illustration of the design summary as well as the coded and uncoded variables values.

IV. Results and Discussion

IV.1. Taguchi Method Analysis

An eight-step process/product optimization technique, the Taguchi method, involves planning, conducting, and analyzing a matrix experiment to establish the best possible range for each control variable. The primary objective is to minimize the output fluctuation in the presence of noise.

A table of predicted regression coefficients is generated by Minitab for each response characteristic provided. The signal-to-noise (S/N) ratio and the mean were chosen as the response characteristics in this study.

The significance of each component using the p-values is determined and the relevance of each using the coefficients is then weighted. The response tables provide the average of each response characteristic for each factor level. The rankings in the tables are based on delta statistics, which measure the relative size of impacts.

TABLE I
STUDY VARIABLES AS INPUTS

Study Variables	Level 1	Level 2	Level 3
X1: Solar cumulative installed PV power (at end of year), megawatts.	1359	1404	1448
X2: Sun shine hours (hrs)	6	9	12
X3: Operation service (hr/year)	10093	10927	11760

TABLE II
CODED AND UNCODED VARIABLE VALUES USING MINITAB SOFTWARE

Experiment No.	Solar Cumulative installed photovoltaic (PV) power coded (X1)	Solar Cumulative installed photovoltaic (PV) power uncoded (X1)	Sun Shine Hours coded (X2)	Sun Shine Hours uncoded (X2)	Operation Service coded (X3)	Operation Service uncoded (X3)
1	0	1404	1	12	-1	10093
2	-1	1359	1	12	0	10927
3	1	1448	0	9	-1	10093
4	0	1404	-1	6	1	11760
5	-1	1359	-1	6	0	10927
6	0	1404	-1	6	-1	10093
7	0	1404	0	9	0	10927
8	1	1448	-1	6	0	10927
9	-1	1359	0	9	-1	10093
10	1	1448	0	9	1	11760
11	0	1404	0	9	0	10927
12	-1	1359	0	9	1	11760
13	0	1404	0	9	0	10927
14	0	1404	1	12	1	11760
15	1	1448	1	12	0	10927

The delta statistic is calculated by taking the highest subtracts the lowest average for each element. Minitab gives rankings based on delta values, with rank 1 being the highest, rank 2 being the second highest, and so on.

Determining which level of each element produces the greatest outcome using the level averages in the answer tables.

Table III shows the response table for signal - to - noise ratios, where rank 1 corresponded to the PV power factor, rank 2 to the sunshine hours, and rank 3 to the operating service, confirming the P test values and findings from Figure 1.

IV.2. Box Behnken Design (BBD) Method Analysis

The reaction research data may be modeled as a surface using surface design to isolate the variables that have the greatest influence on the outcome. This method is often used after factorial or fractional factorial trials conducted to determine the most important factors in a research process. The findings of the response regression surface design are shown in Table IV.

All the p-values in the analysis of variance are significant (p-value > 0.05), indicating that there is no statistically significant difference. According to the R2 value in Table V, the model accounts for 68.14 % of the variance in consumption, showing that it successfully fits the data. The anticipated R2 of zero suggests that this model is overfitting and should be decreased. To explain the connection between the response and the model variables, the regression equation is applied. The regression equation represents the regression line algebraically.

The linear model's regression equation looks like this: $Y = b0 + b1\,x1$. Y is the dependent variable in the regression equation; $b0$ is the constant or intercep, $b1$ represents the estimated coefficient for the linear term (also known as the slope of the line); and $x1$ represents the value of the linear term. The following equation depicts the regression analysis of the study's outcome (annual electricity consumption):

$$
\begin{aligned}
&\text{Response}\left(\text{Consumption}\right) = \\
&= 97 - 0.057\ \text{PV Power}\left(\text{MWh}\right) + \\
&-5.20\ \text{Sunshine hours} - 0.0063\ \text{Operation service} + \\
&-0.000016\ \text{PV Power}\ \left(\text{MWh}\right) \times \text{PV Power}\ \left(\text{MWh}\right) + \\
&-0.0835\ \text{Sunshine Hours} \times \text{Sunshine Hours} + \\
&-0.000000\ \text{Operation Service} \times \text{Operation service} + \\
&+0.00249\ \text{PV Power}\ \left(\text{MWh}\right) \times \text{Sunshine hours} + \\
&+0.000008\ \text{PV Power}\ \left(\text{MWh}\right) \times \text{Operation service} + \\
&+0.000298\ \text{Sunshine hours} \times \text{Operation service}
\end{aligned}
$$

To interpret the regression model's monomial coefficient value in the equation, PV power (X1) = 0.057, sunshine hours (X2) = 5.20, and operation service (X3) = 0.0063, and the order of priority amongst the main effect of impact factors was sunshine hoarse (X2) > PV power (X1) > operation service (X3).

TABLE III
RESPONSE TABLE FOR SIGNAL TO NOISE RATIOS

Level	PV Power	Sunshine Hours	Operation Service	Level	PV Power
1	13.73	14.44	14.70	1	13.73
2	14.81	14.71	15.03	2	14.81
3	15.92	15.30	14.72	3	15.92

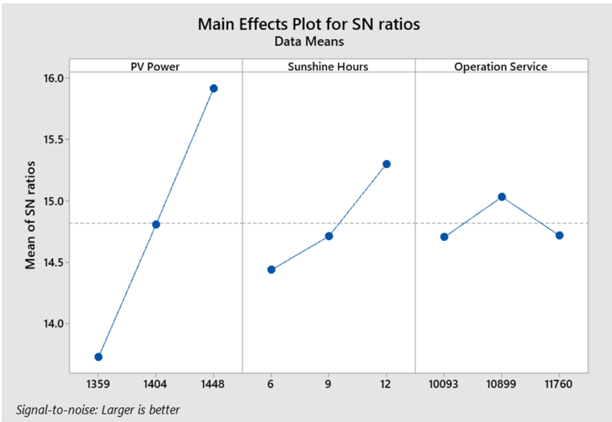


Fig. 1. Main Effects Plot for SN ratios of study data

TABLE IV
ANALYSIS OF VARIANCE

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Source	DF	Adj SS	Adj MS	F-Value	P-Value	Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	8.7222	0.96913	1.19	0.447	Model	9	8.7222	0.96913	1.19	0.447	Model	9	8.7222	0.96913	1.19	0.447
Linear	3	3.5444	1.18146	1.45	0.334	Linear	3	3.5444	1.18146	1.45	0.334	Linear	3	3.5444	1.18146	1.45	0.334
PV Power (MWh)	1	0.4329	0.43292	0.53	0.499	PV Power (MWh)	1	0.4329	0.43292	0.53	0.499	PV Power (MWh)	1	0.4329	0.43292	0.53	0.499
Sunshine Hours	1	0.1639	0.16388	0.20	0.673	Sunshine Hours	1	0.1639	0.16388	0.20	0.673	Sunshine Hours	1	0.1639	0.16388	0.20	0.673
Operation Service	1	2.9476	2.94759	3.61	0.116	Operation Service	1	2.9476	2.94759	3.61	0.116	Operation Service	1	2.9476	2.94759	3.61	0.116

TABLE V
MODEL SUMMARY

S	R-sq	R-sq(adj)	R-sq(pred)
0.903183	68.14%	10.78%	0.00%

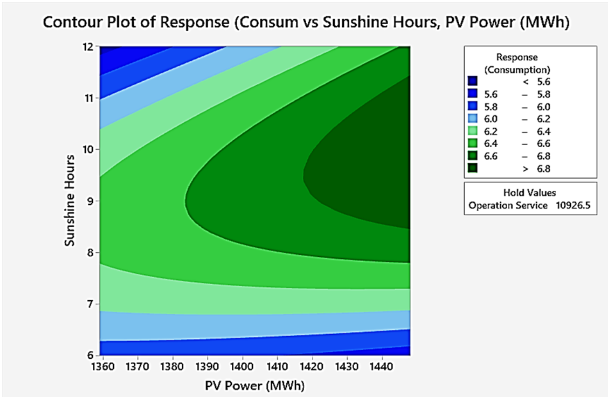
An ideal domain for the annual electricity consumption (MWh per capita) was simulated using two-dimensional (2D) contour plots, as shown in Figures 2.

The analysis of two variables at a time, while holding all other parameters constant, was shown to be more beneficial in identifying both the main and interaction effects of these two variables. Figures 2 depict the interactions between independent variables and the dependent variable. Contour plots are useful for showing the relationship between each two continuous variables and their fitted responses (annual electricity consumption).

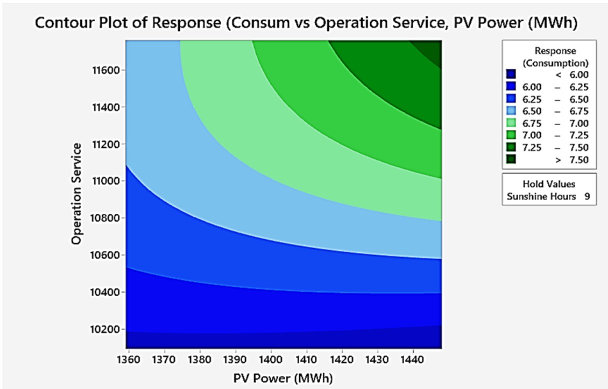
Two-dimensional contour plots show all locations with the same response joined to generate contour lines with constant responses. Ideal response values and operating circumstances may be easily be determined via contour plots. Only two variables may be included in a contour plot that is continuous. Whenever a model has more than two continuous variables, Minitab treats them all as constants. Minitab retains the category variables constant if the model comprises categorical variables. Consequently, these graphs can only be used with variables that have constant values. The outline may vary dramatically if they alter the holding levels. The data in the spreadsheet are not used in contour plots. Instead, Minitab uses a stored model to approximate the contours.

How well the model represents the true relationships between variables affect the accuracy of the contour plot. Because of the model's inclusion of statistically significant quadratic factors, the curves have a curved shape. As shown in Figure 2(a), sunshine hours and PV power interact to affect water supplies (annual electricity consumption). Lower-right-corner values of annual electricity consumption correlate to higher values of PV power and lower sunshine hours. Electricityconsumption is predicted to expand in response to rising PV power.

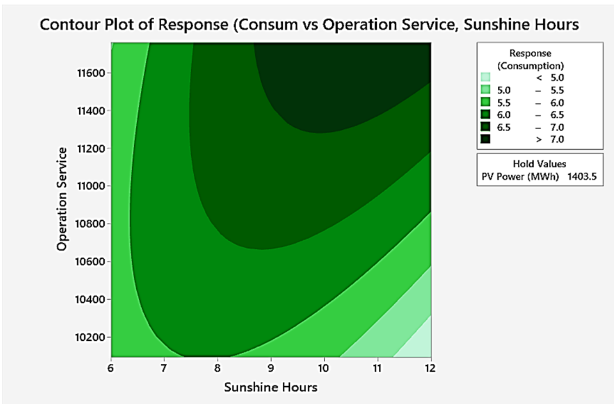
Conversely, the demand for electricity consumption in response to decreasing sunshine hours. It is noted that the value of the operation service was fixed as an average. While, Figure 2(b) illustrates the importance of operation service and PV power factors and its effects on the annual electricity consumption. It presents the interaction effects of operation service and PV power on annual electricity consumption.



(a)



(b)



(c)

Figs. 2. Contour plot: (a) sunshine hours and PV power, (b) operation service and PV power (c) operation service and sunshine hours

The highest values of annual electricity consumption are in the lower right corner of the plot, which correspond with high values of both operation service and PV power.

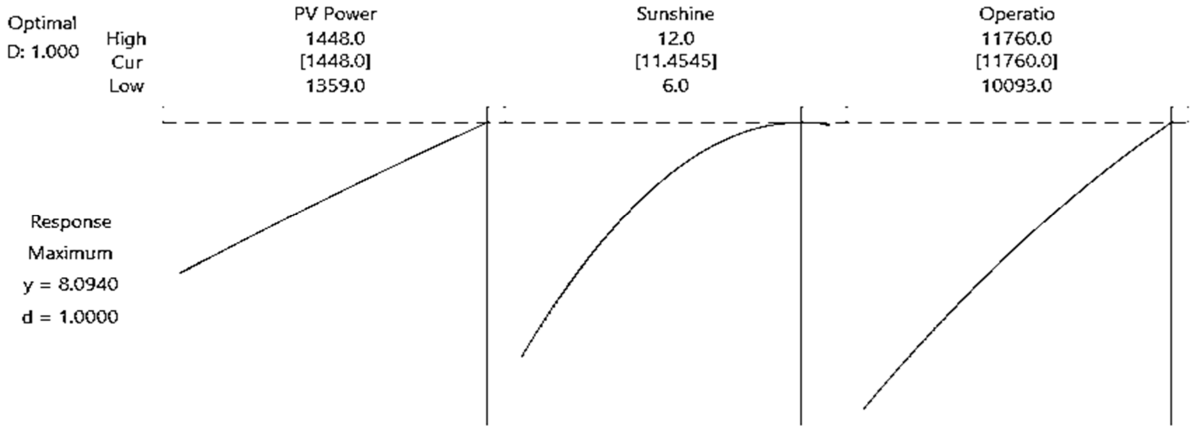


Fig. 3. Combined Response Optimizer Chart for the response (Annual electricity consumption)

It can see this clearly from the figure, as the higher the operation service, the more PV power we need, and this means putting pressure on the annual electricity consumption. It can be observed from the figure that the values of the sunshine hours were fixed as an average.

Finally, Figure 2(c) illustrates that operation service and sunshine hours interact to affect annual electricity consumption. Higher-right-corner values of annual electricity consumption correlate to higher values of sunshine hours and lower operation service. Annual electricity consumption is predicted to expand in response to rising sunshine hours and increasing operation service. Conversely, operation services increases in response to decreasing sunshine hours. It can be noted from the figure that the values of the PV power were fixed as an average.

IV.3. Response Optimization

Use the response optimizer's variable input parameters to fine-tune a single answer or a series of answers. Minitab will generate an optimization graph and then the optimum solution has been calculated. It is free to play about with the input variables in this interactive display to see the effects such changes on the overall result. To determine the input variable values that combined to provide the optimal (y) outcome, response optimization may be used.

To satisfy the set's (y) response conditions, the composite desirability, a measure for joint optimization, must be at least 8.0940 (MWh per capita) (Annual electricity consumption). By assessing how well a collection of input variables satisfies the response's goals, one may assess a response's attractiveness. A response's individual desirability (d) and a group of responses' composite desirability (D) are both assessed.

There is a scale of desirability from 0 to 1. As demonstrated in Figure 3, when a response is outside the acceptable range, it receives a score of 0. According to Figure 3, the join optimum factors that the responses fulfill the maximum requirements of annual electricity consumption 8.0940 (MWh per capita) and with composite desirability 1 are as follows:

- X1= PV Power = 1448 MWh;
- X2= Sunshine hours = 11.45 h;
- X3= Operation service = 11760 hr/year.

V. Conclusion

The installation of PV systems on the roofs of residential buildings in Jordan has not been evaluated or optimized for power generation. This is although it is essential to incorporate renewable energy sources to mitigate the effects of climate change and meet the rising demand for electricity. This study proposes various characteristics that may be used to determine a country's level of electricity consumption and has conducted an empirical analysis and optimization of Jordan's aggregate electric consumption function for the period of 2012-2021. The Solar cumulative installed PV, sun shine hours, and operation service are the three independent variables included in the multivariate time series model created. In the field of optimization, one of the most often used experimental designs is the RSM. It is a valuable strategy, because it enables to evaluate the impact of several factors and their interactions on one or more response variables at the same time. In this study used the Taguchi technique and BBD as an effective tool to examine the factors/variables response that depends on the independent variables. Generally the results prove that the solar cumulative installed PV power, sun shine hours, and operation service variables were significant effect on the annual electricity consumption. The study suggests that regulating energy use in such a way that certain appliances, such washing machines, irons, and electric water heaters, are powered by solar energy during the daytime and then by conventional electricity later in the day night. Additionally, the use of solar photovoltaic hybrid systems that are equipped with direct current inverters is significant to supply and run daytime heating and air conditioning equipment that have a high energy consumption level during the daylight hours. Last but not least, the implementation of energy management and rationalization in residential structures. The result showed that the yearly energy usage was significantly influenced by solar cumulative installed PV power, sun shine hours, and operation service factors. The investigation revealed that the combined ideal elements and reactions meet the highest demands of the annual power usage of 8.0940. (MWh per capita).

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