ISSN 0003-701X, Applied Solar Energy, 2021, Vol. 57, No. 1, pp. 13–22. © Allerton Press, Inc., 2021.
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DIRECT CONVERSION OF SOLAR ENERGY INTO ELECTRICAL ENERGY

Monitoring Effect of the Meteorological Parameters on Electrical Energy Generation by Solar Cells

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Received January 27, 2020; revised March 20, 2020; accepted May 23, 2020

Abstract—In this paper, we introduced an effective and valuable method for monitoring effect of meteorological parameters on electrical energy generation by solar cells based on collecting real data for one year. The sun is the most readily and widely available renewable energy source capable of meeting the energy needs of the whole world. The aim of this paper is to study the effect of metrological parameters on electrical energy generation by solar cells in state of Kuwait. To achieve the objective of this study, two methods were used the first method is the descriptive method by using visualization and the second method is the multiple linear regression. The results showed that the sunlight hours are the most important factor for the electrical power generation. The temperature has a negative impact, when the lower temperature rises to more than 31.8°C; the relative humidity has a negative impact, when the minimum relative humidity rises to higher than 49%; and the wind speed can remove the accumulated light dust from panels and it reduces the air temperature around panels. The results of the multiple linear regression showed that for global irradiance, sunlight, temperature, relative humidity, and wind speed is very high of value 0.955. The recommendation of this study is encouraging individuals and organizations to use PV systems.

Keywords: visualization, weather phenomenon, electrical power generation, solar cells, PV systems

DOI: 10.3103/S0003701X21010023

INTRODUCTION

The electricity generated in the world is mainly produced by using fossil fuel. The burning of fossil fuels produces Green House Gases (GHGs) and leads to environmental degradation and climate change. The world faces an energy crunch. This has provided a renewed impetus to the growth and development of renewable energy sources.

Globally, there have been difficulties that face power generation, which are the environmental risks caused by pollution due to gas emissions. As a consequence, there is more focus on renewable and clean energy production [1]. Fossil fuel burning causes grave environmental harm. A great deal of these harmful effects can be avoided by using the renewable resources such as reducing the environmental impact by every kiloWatt-hour (kW h) of electrical produced with renewable resources [2].

The alternative sources of electrical generation technology are renewable and non-pollutant like wind, solar, and tidal to generate electrical power. Renewable energy cannot be supplied to generate power as required like conventional fuels, as they are naturally available and they basically depend on environmental conditions [3]. Clean energy sources have become an integral part of energy. The goal of renewable energy sources using is to decrease the pessimistic impacts of non-renewable energy sources such as coal, oil, and natural gas. Renewable sources of energy protect the environment against the hazards of fossil fuel emissions [4]. Solar energy has the largest ability to provide clean, safe, and reliable energy [5].

Material or land shortages do not restrict the use of photovoltaic systems and the sun is a nearly infinite source of energy. Electricity generated from photovoltaic systems has much less environmental impact than traditional electrical generation techniques. Solar systems do not lead to acid rain or worldwide warming [6]. Solar energy is the conversion of light energy directly to electrical energy – photovoltaic (PV). Photovoltaic is the science of conversion of solar radiation into direct current electricity. The basic conversion device is the cell. It employs semiconductors which, when exposed to solar radiation, results in current generation [7].

Table 1 shows the world and the top six countries which generated electricity from renewable sources in 2017. The renewable power capacity is 2.189 GW. The three largest renewable power capacity are 647 GW, 239 GW, and 112 GW for China, United States, and Germany. The solar PV technology is the third rank, according to the world power capacity is 402 GW [8].

Table 1. The renewable power capacity in GW for the world and top six countries in 2017 [8]

Technology	World	China	USA	Germany	India	Japan	UK
			GW				
Hydropower	1.114	313	80	5.6	45	23	1.9
Wind power	539	188	89	56	33	3.4	18.9
Solar PV	402	131	51	42	18.3	49	12.7
Bio-power	122	14.9	16.7	8	9.5	3.6	6
Geothermal power	12.8	0	2.5	0	0	0.5	0
Total	2.189	647	239	112	106	80	40

This paper is studied the effect of metrological parameters on electrical energy generation by solar cells in state of Kuwait.

LITERATURE REVIEW

The photovoltaic effect was discovered by the French physicist Alexandre-Edmond Becquerel, who built the first photovoltaic cell in 1839, by placing silver chloride in an acidic solution, and observed voltage on the connected platinum electrodes. Willoughby Smith, an English electrical engineer in 1873, first observed the light sensitivity of selenium when exposed to sunlight its conductivity increased [9].

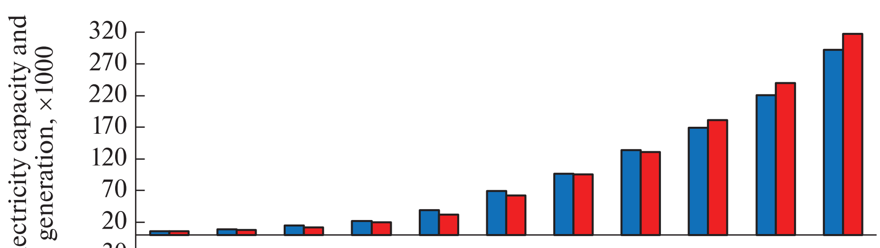
There are different types of silicon solar cell with different efficiencies. The multi-junction cells type has the highest efficiency which is 46%, and there are 28 different PV cell subcategories, which are indicated by distinctive colored symbols. The families of semiconductors are multijunction cells, single-junction gallium arsenide cells, crystalline silicon cells, thin-film technologies, and emerging photovoltaic [10].

A solar cell is an electrical device that converts the energy of light directly into electricity by the PV effect, a form of photoelectric is a cell. Solar cells are the building blocks of photovoltaic modules, which form the solar panels [11]. The amount of electricity that one single solar cell can produce is just around 2 W. Therefore, a series of solar cells are connected together and this series of solar cells is called a module [12]. Solar cells generate electricity directly from visible light. These cells are made of different semiconductor materials [13]. The module, sandwiched between protective materials, may have 48, 60, 72, or higher number of cells. For having higher power outputs, modules are connected in a series to form parallel arrays of solar panels [14].

The potential of solar energy makes it favorable in several ways. Solar energy increased because the electrical generation using solar energy is appropriate for rural and urban regions. Figure 1 shows the world solar power electricity capacity and generation from 2006 to 2016, in 2016 the solar power electricity capacity is 292.170 MW and Electricity Power Generation (EPG) is 317.673 GW h [15].

Solar energy has attracted investors in the field of electrical power generation. The newly installed capacity of solar photovoltaic power increased by 32% in 2017. This energy is capable of producing more efficient solar cells at lower costs. The current solar cell technologies are well established and provide a reliable product, with a guaranteed energy output for at least 30 years. The cost of Direct Current (DC) electrical power generated by a PV module in 2017 has dropped below USD 0.022 for each one kW h in many places world-wide [16].

The performance of PV system results that appear after the performance of its components, are affected by meteorological parameters and associated losses [17]. The performance ratio formula (PR), actual sys-



	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
EC (MW)	6.108	8.712	14.68	22.48	39.06	69.60	96.97	134.0	169.6	220.3	292.2
EG (GW h)	5.492	7.440	11.94	20.13	32.20	62.18	95.93	131.1	181.7	240.1	317.7

Fig. 1. The world solar electrical power capacity and generation [15].

tem output can be analysis period time in kW h, and irradiation values on system location in kW h is solar irradiation at the surface of PV system multiply by efficiency of PV modules [18].

$$\mathrm{PR} = \frac{\text{Actual system output in kW h}}{\text{Irradiation values on system location in kW h}}. \quad (1)$$

The meteorological parameters that have an obvious influence on the performance of plants such as; sunshine duration, temperature, relative humidity, and wind speed conditions at the site [19]. The impact of the temperature on solar panels is varied, a degree of 25°C is the standard grade for solar cells that produce the highest amount of energy and fall by a 10% reduction in electrical power generation if the temperature reaches or exceeds 45°C [20]. The efficiency of the PV modules decreases progressively in realistic circumstances with time as the temperature of the PV increases, during summer, the PV modules operate at different temperature ranges. The high temperature values lead to a drop-in efficiency with temperature increase [21].

There is a drop in electrical power generation in cities where the humidity ranges in (40–78%) this results in a minimal layer of water vapor at the front solar cells directly facing the sun. There have been approximate losses of about 15–30% of the energy [22]. The temperature has a direct negative relation with relative humidity, when the relative humidity is low, the output current increases as well as the power efficiency of the PV modules hence solar electrical generation is high [23]. The wind speed increase causes the dust drop deposition on panel surface, and the high humidity helps formation of dew on the solar cell surface that leads to more dust deposition on panel surface. However, PV panels tilted with larger angles let less dust get accumulated on the surfaces [24].

Reference [25] proved in their study in Nigeria stated that relative humidity reduces electrical generation by solar energy. As well as reference [26] in Nigeria stated the ambient temperature of the area during dry and rainy seasons influence on the performance of a stand-alone PV solar system. In Korea reference [27] showed in their study that the sunlight duration has a strong correlation of value 0.930 with electricity power generation. In Finland, reference [28] found out that the weather conditions had a significant impact on solar power production by using data constrained on the weather parameters. In Latvia reference [29] stated that the electrical power generation has a strong correlation of value 0.957 with solar radiation. In Ukraine reference [30] proved that the atmospheric climatic factors, temperature and wind parameters effect on the operation of the photovoltaic modules of a power plant.

MATERIALS AND METHODS

The experimental method is a way that gives results that are related to observation and generalization of these observed facts, it studies the cause and impact relationship, it determines the influence of the dependent variables on the independent ones [31]. The annual production of solar energy in any city depends on various factors; incidental solar radiation at the installation site, tilt and orientation of panels, presence where there is no shading, and technical performance of the modules and inverters [32].

The photovoltaic continuous monitoring of the operation with long-term measured values in graphical and numerical form, enables the operational and dispatching personnel to visually analyze the plant operation, monitor its performance, and obtain production reports by periods with plotting of curves [33].

The system used in this study were originally manufactured from a monocrystalline type photovoltaic module of maximum power capacity is 300 W, efficiency is 18.3%, open circuit voltage is 39.4 V, and the short circuit current is 9.97 A. The dimension of the module is 1.660 mm length, 990 mm width, 50 mm depth, 20 kg weight. The total number of cells is 60, each cell size is 156 mm^2. Four modules used in this system of total power capacity is 1200 W.

Figure 2 shows the system PV web user interface that used to monitor the solar PV systems, describe the PV systems, weather conditions at a system location,

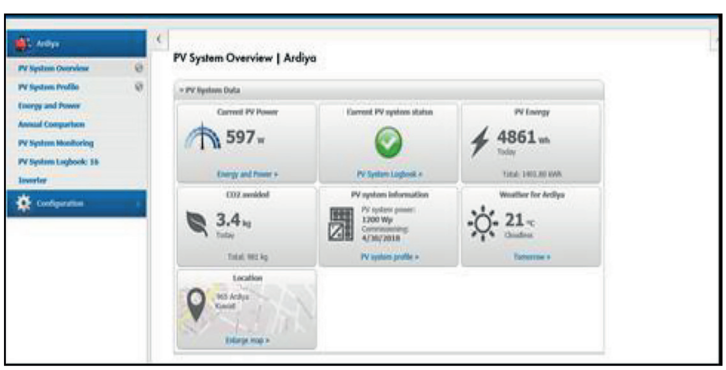


Fig. 2. The PV system web user interface.

Table 2. The hourly electrical power generated with the meteorological parameters in the 1st May 2018

№	Time (hh:mm)	EPG (W)	Temp (°C)	RH (%)	WS (m/s)	WD	SL (hh:mm)
1	5:00	0	22.4	58.9	1.5	228	00:00
2	6:00	0.026	23.7	57.1	0.8	285	00:24
3	7:00	0.219	26.9	46.6	1.9	235	00:18
4	8:00	0.482	29.8	32.7	1.7	311	01:00
5	9:00	0.672	31.9	26	1.3	105	01:00
6	10:00	0.787	35.2	22.8	0.9	38	01:00
7	11:00	0.855	34.5	19.4	1.8	115	01:00
8	12:00	0.870	35	18.8	1.4	106	01:00
9	13:00	0.810	34.3	20.1	5	55	01:00
10	14:00	0.689	34.4	21.6	4.2	46	01:00
11	15:00	0.517	34.5	20.2	3.6	56	01:00
12	16:00	0.311	34.5	19.2	3.8	54	01:00
13	17:00	0.116	33	21.9	3	113	00:20
14	18:00	0.020	31	25.2	2.1	108	00:00

current PV power, current PV system status, PV energy, and CO_2 avoided by solar power generation.

The data of this paper were collected for one year from 1st May 2018 to 30th April 2019, the readings of the electrical power generated from the PV system was registered every 15 min, then the average of the four readings for each hour calculated and represented in this paper as an hourly reading, where the total yearly readings are 24 (hour) × 365 (day) = 8.760 readings. The meteorological parameters were collected from the Kuwait Meteorological Department, these parameters are: air temperature, relative humidity, wind speed, wind direction, daylight percentages sunlight during hour, global shortwave radiation, and daily weather phenomena; Distant Lightning (DL), Drizzle (DZ), Dust Storm (DS), Fog (F), Haze (H), Mist (M), Rain (R), Rising Dust (RD), Sand Storm (SS), Suspend dust (S), and Thunder Storm (TS).

Dust is the tiny solid and dry particles found in the air. The wind impacts the suspension of dust and rising dust in the air. Thunder Storms are a rain bearing cloud that also produces lightning. Lightning is a visible electrical discharge produced by a thunder storm [24]. Haze is considered air pollution, a suspension in the air of small, dry particles that are invisible. Fog is suspended visible water particles at the earth's surface that reduce horizontal visibility to less than 1 km. Mist is visible small water particles suspended in the atmosphere that reduce visibility to fewer than 11 km but more than or equal to 1 km. Drizzle is very small droplets of water falling. Rain forms of droplets of water falling larger than drizzle [34, 35].

RESULTS

The PV system works only during the sunlight of the day, and the meteorological parameters have an effect on power production. Table 2 shows a sample of the hourly Electricity Power Generated, for the PV system for one day 1st May 2018, during the sunlight from 5:00 to 18:00, with the meteorological parameters; Temperature (Temp), Relative Humidity (RH), Wind Speed (WS), Wind Direction (WD), and Sun-Light (SL). The electrical power generated is 0.026 kW at the beginning of the day when sunlight is 00:24 h, then it was increased to 0.870 at 12:00 after that the electrical power generation was gradually decreased to 0.020 kW at end of the day.

To investigate the causes on the variation of electrical power generation, the descriptive analysis of the daily meteorological weather phenomenon was added in this analysis. Table 3 illustrates the 12 days' electrical power production (kW h) from 1st to 12th May

Table 3. Daily electrical power generation with the weather phenomenon from 1st to 12th May 2018

Day	Electricity production (kW h)	Weather phenomenon
1st	6.342	H
2nd	4.650	S
3rd	3.918	H + S + R + TS
4th	4.580	H
5th	5.398	H + S
6th	5.791	H + S
7th	5.519	H
8th	2.985	H + S + DS
9th	**1.589**	H + S + RD + M + R + TS
10th	5.987	H + S + M + TS
11th	4.167	H + RD + DS + M + R
12th	5.203	H + S + RD + DS

2018, the weather phenomena such as; haze, mist, suspend dust, dust storm, rising dust, sand storm, thunder storm, rain, and fog. The highest electrical power production is 6.342 kW h in 1st May 2018, during this day the weather had only haze, while the lowest electrical power production is in the 9th May 2018, with only 1.589 kW h, this was due to the weather phenomenon of thunder storms causing rising dust, haze suspended dust which might rain lead to mist. This indicates that the weather phenomenon has an effect on electrical power production.

Figure 3 visualizes the data of the selected samples for the highest electrical power generation for one day in each month from 1st May 2018 to 30th April 2019 to show the influence of temperature, relative humidity, and wind speed through the day hours. The aim of this figure is to show visually the behavior of daily electrical power generation, in order to determine the hours and period of the highest electrical power generation for each month related to the meteorological parameter.

The results of the highest daily electrical power generation visualization showed that sunlight hours are the most important factor for the electrical power generation. The temperature, relative humidity, and the wind speed have less impact on the electrical power production. With a clear sky, the temperature has a negative impact on PV power generation, when the temperature rises to more than 31.8°C as a minimum level; the relative humidity has a negative impact on PV power generation, when the relative humidity becomes higher than 49% as a minimum level; and the wind speed has a multiple effect on PV power generation, it can remove the accumulated light dust from panels, and the amount of wind reduces the air temperature around panels at the high temperature. For example, in 22nd April 2019 the highest electrical power production was 7.109 kW h, which is the highest production day during the period of one year from 1st May 2018 to 30th April 2019, but the production during winter months were unstable due to the weather phenomenon like haze, mist, fog, rising dust, thunder storms, and rain. The hours of sunlight days in the summer months are longer than the winter months; the sunlight days hours are between 12–14 h from June to October, while in winter the sunlight days are between 10–12 h from November to May.

The lowest electrical power production was noticed when the sky was cloudy, with thunder storms, and rainy weather during the day hours, such as in November. Figure 4 visualizes the selected samples for the lowest electrical power generation for one day in each month from 1st May 2018 to 30th April 2019 to show the effect of temperature, relative humidity, and wind speed. The aim of this figure is to show visually the behavior of daily electrical power generation, to determine the hours and period of the lowest electrical power generation for each month, related to the meteorological parameters.

The results of the lowest daily electrical power generation showed that the weather phenomenon obscured the PV panel's access to sunlight, which reduced the electrical power production. During the summer season months from June to October, the days which recorded low electrical power production, the weather had phenomenon such as; level of haze, suspended dust, rising dust, dust storms, and rain. For example, the electrical power generated in 13th August 2018 was 5.206 kW h, when the weather had only rising dust, this day is one of the best electrical power production day compared with other days in the figure. The weather during November to May was usually unstable in addition to many weather phenomena such as rain, thunder storms, mist, fog, rising dust, and haze. These phenomena have a negative influence on electrical power generation.

The averages of the monthly electrical power production were calculated to eliminate the variation of the number of days during twelve months for the same period of data collection. Figure 5 shows the highest average production that was in August with an average 6.112 kW h, the lowest average production was in January 3.907 kW h. This indicates that the electrical power production in summer months is more than the other months because of having long sunlight hours in summer, hence the panels have the maximum sunlight intensity and clear skies.

The correlation test was applied to test the influence of meteorological parameters on the electrical power generation taken from the solar system. Correlation is the degree of association between two variables. Table 4 shows the strength of correlation coefficient (r) sizes. The same values in this table were used for the factor of determination (r^2) [36].

Table 5 shows the results of testing correlation; these results indicate that the global irradiance has a very high positive correlation of a value 0.945 on the electrical power generation. This result was supported by the results of reference [25] study and also the results of the reference [25] study. The sunlight has a direct high correlation value of 0.847 on electrical power generation, which is supported by reference [27] study where their results showed that this correlation is high with a value of 0.930.

The correlation between temperature and electrical power generation is 0.300, has a low correlation, which corresponds with the results of reference [28], while reference [37] proved that the temperature has a negative correlation, when the temperature raised above 30 OC. The relative humidity has a negative low correlation with electrical power generation, its value is –0.323. This result was proven by the studies of reference [25, 38, 39]. The wind speed has less correlation to the value of 0.264 with electrical power generation.

The multiple linear regression analyses were used to find out the influence of the meteorological parameters on electrical power generation. The results of testing the five factors global irradiance, sunlight, temperature, relative humidity, and wind speed, showed that correlation is very high of value 0.955, and the factor of determination r square is 0.911, which is a

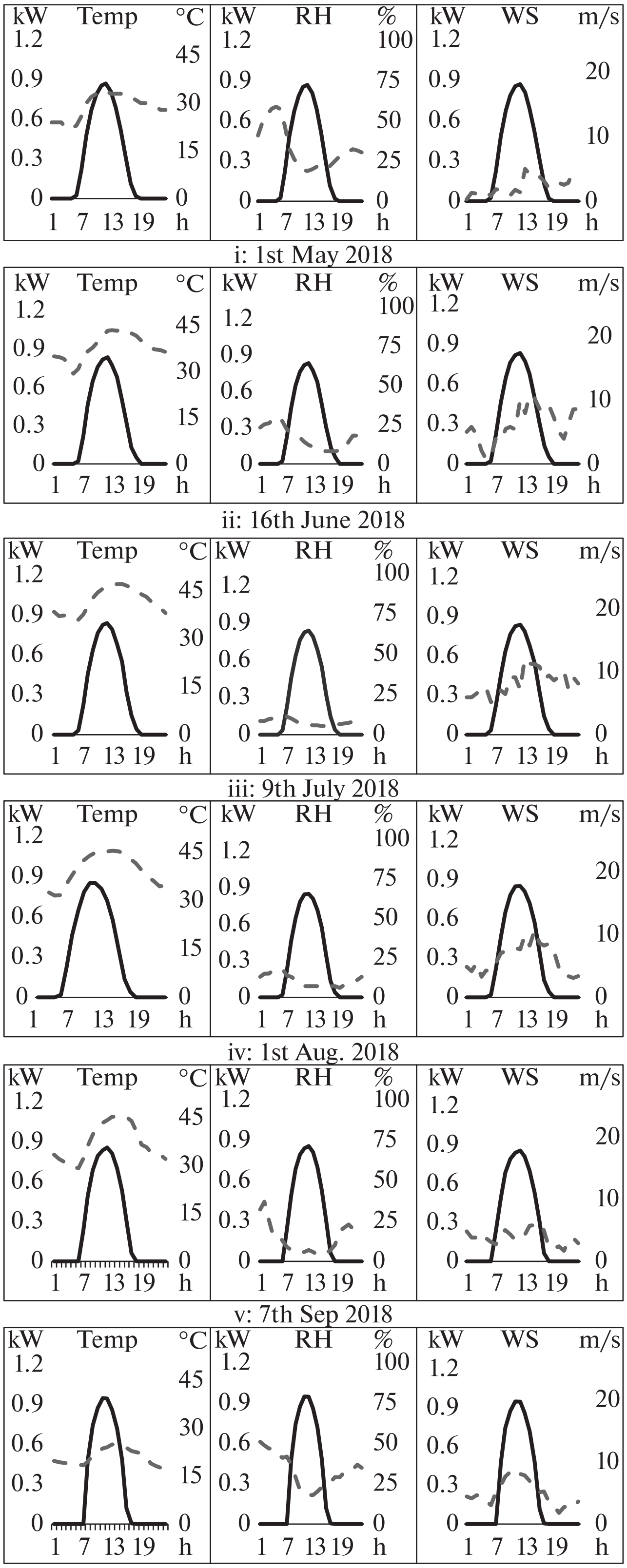


Fig. 3. Highest electrical power generation in one day selected for each month from 1st May 2018–30th April 2019.

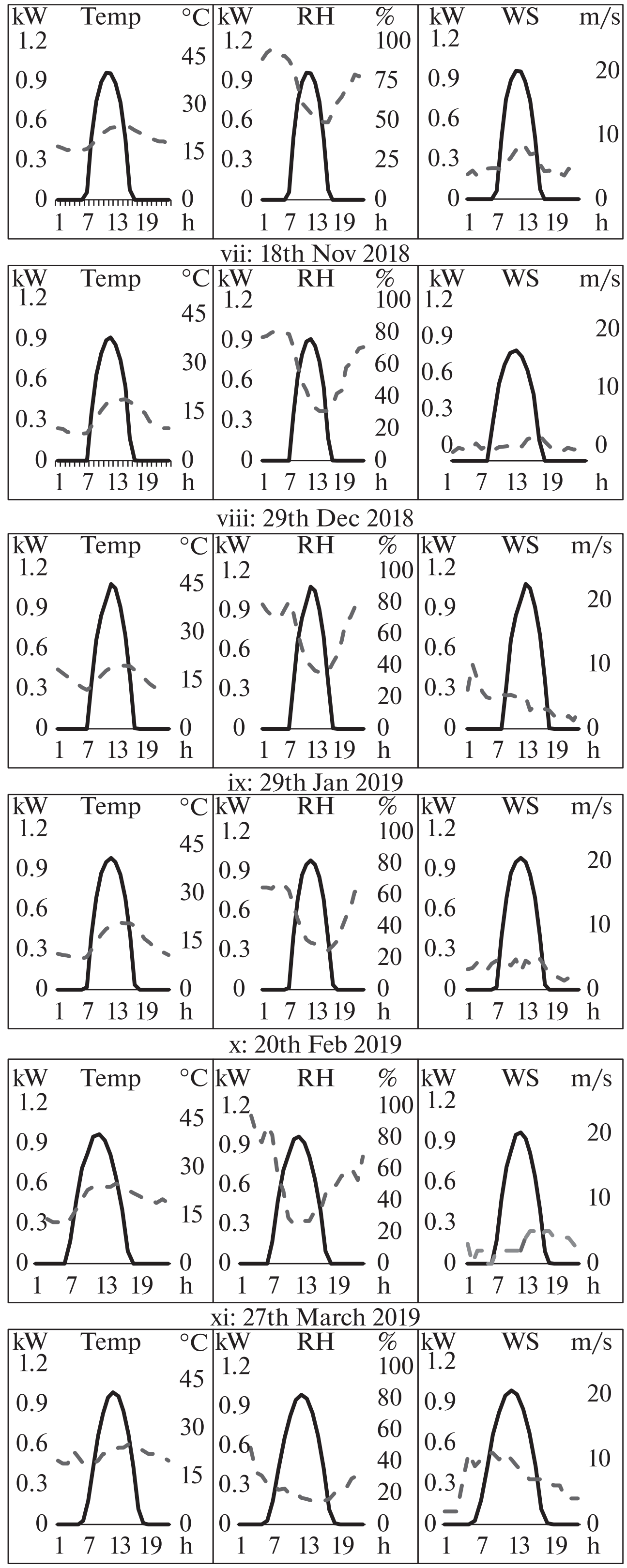


Fig. 3. (Contd.)

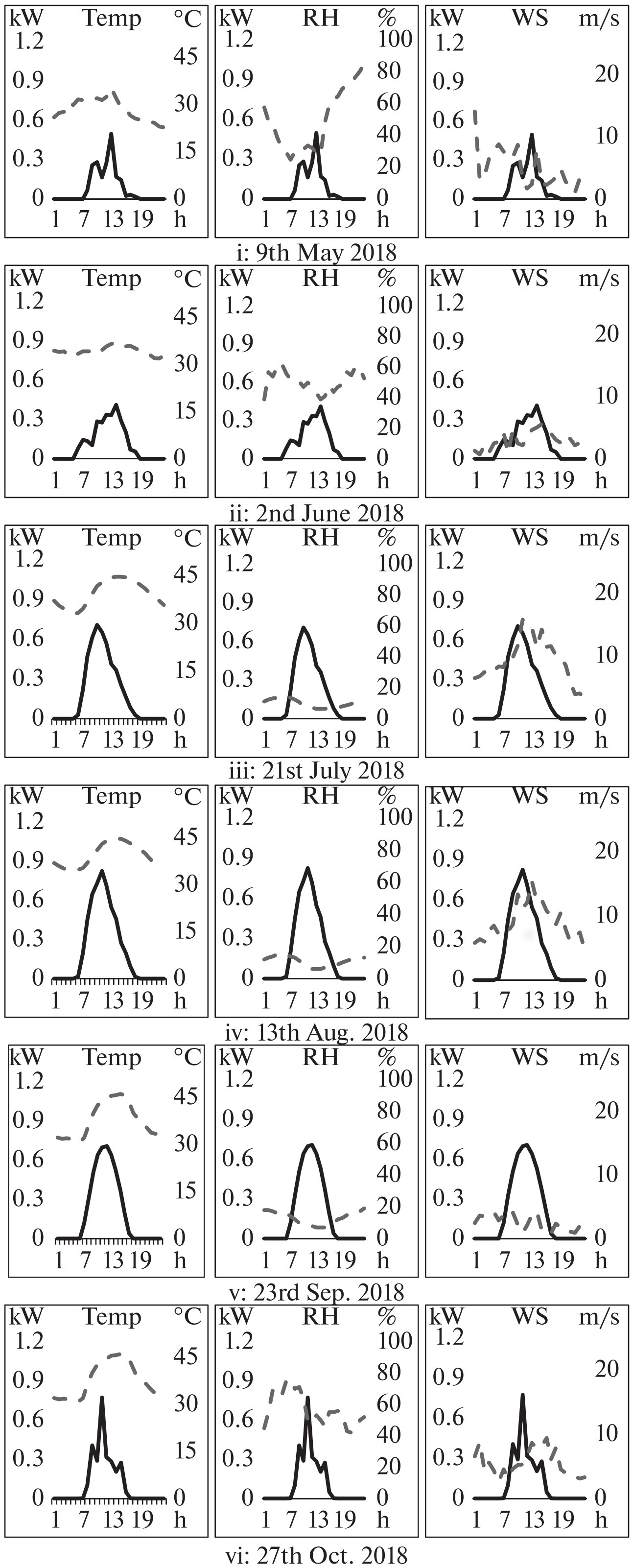


Fig. 4. Lowest electrical power generation in one day selected for each month from 1st May 2018–30th April 2019.

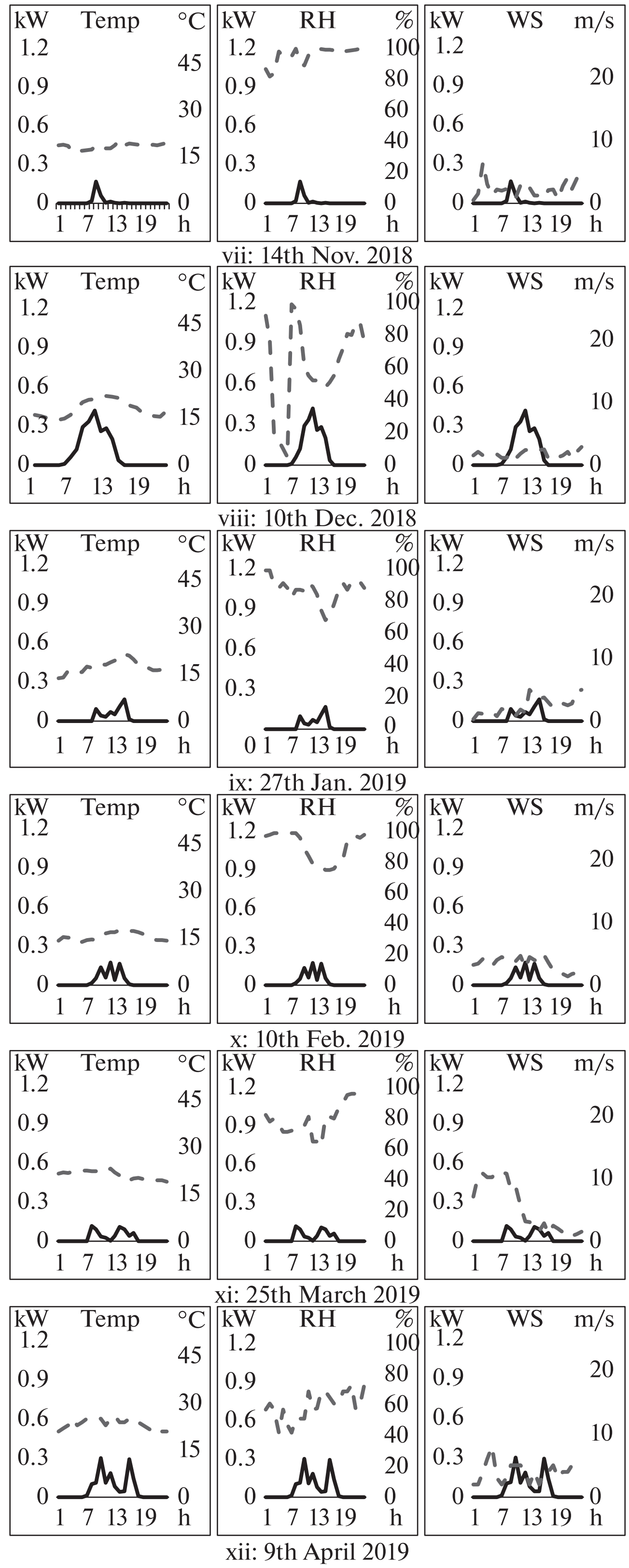


Fig. 4. (Contd.)

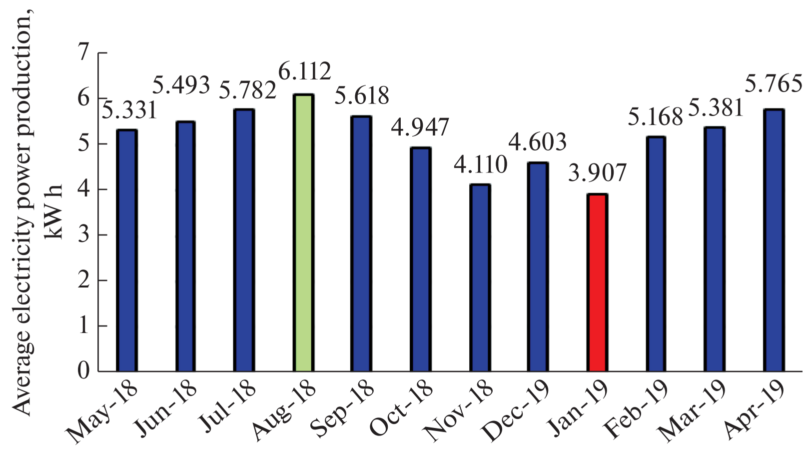


Fig. 5. The averages of monthly electrical power production from 1st May 2018–30th April 2019.

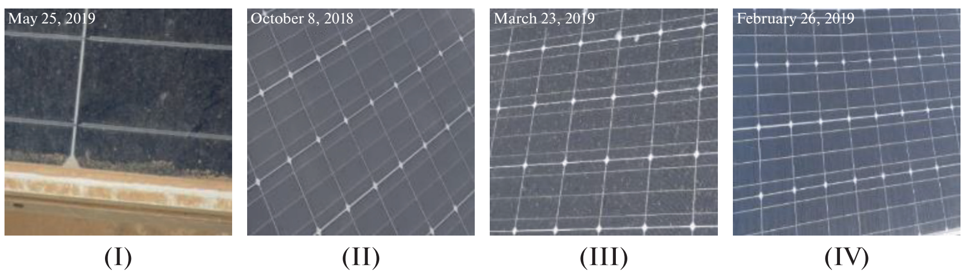


Fig. 6. The dust deposition on the PV surface from May 2018 to April 2019.

very high influence of global irradiance, sunlight, temperature, relative humidity, and wind speed on electricity power generation and the sig value is 0.000, which is less than ($\alpha = 0.05$), it indicates that there is a statistically significant influence of global irradiance, sunlight, temperature, relative humidity, and wind speed on electricity power generation, the regression equation is:

$$\mathrm{EPG} = 0.124 + 0.001(\mathrm{GI}) + 0.044(\mathrm{SL}) - 0.005(\mathrm{Temp}) - 0.0003(\mathrm{RH}) + 0.001(\mathrm{WS}). \quad (2)$$

In this case the relative humidity has low influence, because it has 0.0003 factor.

Dust deposition impairs the PV panels performance. Figure 6 shows the dust through four photos. The wind usually helps in reducing the dust concentration on the PV surface. Figure 6-I shows in 25th May 2018, the dust deposition at the panel bottom, due to the weather haze, dust, with a temperature between 31–41.6°C and wind speed between 1.9–8.8 m/s. Figure 6-II shows the panel with less dust deposition in 8th October 2018, during this day the weather had haze during the previous days, the temperature was between 25–41.6°C and the wind speed was between 0.4–4.6 m/s. Figure 6-III shows the photo of the panel in 26th February 2019, the dust deposition layer with heavy points due to the weather of rain, drizzle, thunder storms, fog, and thunder dust during the previous days, and a wind speed of 0.9–3.6 m/s. Figure 6-IV shows the panel in 23rd March 2019, the dust deposi-

Table 4. Strength of correlation and impact [35]

Size of *r*	Interpretation
0.90 to 1.00	Very high correlation
0.70 to 0.89	High correlation
0.50 to 0.69	Moderate correlation
0.30 to 0.49	Low correlation
0.00 to 0.29	Little if any correlation

Table 5. The correlation between electrical power generation and meteorological parameters

Factors	Electricity power generation
Global Irradiance (GI)	0.945
Sun Light (SL)	0.847
Temperature (Temp)	0.300
Relative Humidity (RH)	–0.323
Wind Speed (WS)	0.264

tion layer was low due to the light rain, thunder storms, fog, haze, and dust storm during the previous days, and a wind speed of 0.8–4.4.6 m/s.

The dust deposition on the PV surface is different during the year, it depends on relative humidity and rain. The wind speed and wind direction help in removing the dust from the PV surface. The dust deposition usually in summer months is less than the other months.

DISCUSSION

The performance ratio (PR) is important for assessing the efficiency of the solar system, which is the ratio of actual system output and potential energy. The PV system performance is calculated by equation (1), for one year from May 2018 to April 2019, the solar irradiation = 1979.542 kW h/m^2, area of the PV system = 6.5 m^2, PV modules efficiency = 18.3%, and the actual electrical power produced = 1892.242 kWh.

Where:

The irradiation values on system location: the solar irradiation × Area of the PV system = 1.979.542 kW h/m^2 × 6.5 m^2 = 12.672 kW h.

The actual system output = irradiation values on system location*PV modules efficiency = 12.672 kW h × 18.3% = 12.672 kW h × 0.183 = 2318 kW h.

$$\mathrm{PR} = \frac{\text{Actual system output in kW h}}{\text{Irradiation values on system location}} = \frac{12.672\text{ kW h}}{2.318\text{ kW h}} = 0.81.$$

This indicates the performance is 81, and 19% is the consequence of heat loss due to PV modules heating or weather parameters and phenomenon.

CONCLUSIONS

The major goal of this paper is to help in providing the world the air quality for all the citizens with a healthy sustainable living environment for generations in the future, by depending on renewable energy.

The novel contribution of this paper, it was mixing the descriptive and visualization data analysis methods to obtain optimal results. The results report that, the hourly data are very important because they showed the influence of meteorological parameters such as; sunlight, temperature, relative humidity, and wind speed on the PV electrical power generation. The sunlight hours are the most important parameter for electrical power generation, high temperatures and relative humidity have a negative influence on PV power generation, but the wind speed has a positive influence on PV power generation. The daily visualization showed that the optimal electrical power production days are in the spring season, while the lowest electrical power production days in autumn season. Clear skies have a very high probability for production electrical power.

The correlation and multiple regression tests were used to measure the correlation and the factor of determination. The sunlight had a high positive correlation on electrical power generation. The temperature and wind speed had a positive correlation on electrical power generation. The relative humidity had a negative correlation on electrical power generation. The multi linear regression showed that the global irradiance, sunlight, temperature, relative humidity, and wind speed had a very high influence on electrical power generation.

The results prove that, the PV system performance ratio between the actual and theoretical energy output is 81% of one year in this study, the 19% loss is due to the weather parameters and phenomenon. These results are very important to any organization want to take decision to use solar cells, that about 80% is the PV system performance ratio we can obtain from them, moreover any country decide to use solar cells to generate electricity must apply a research like this research paper by collecting real data for at least one year.

FUNDING

The authors declare that there is no funding from any organization regarding the cost of solar panels system and the data collection. The authors covered all the costs of this research paper.

ACKNOWLEDGMENTS

Authors would like to thank all colleagues for sharing their advices and suggestions, during preparation the current study.

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