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Experimental Study of Environmental Impact on the Efficiency of a House-Hold PV Panel

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Abstract

House-hold PV panels are widely used; however, their performance is significantly degraded under real operating conditions. Environmental factors such as ambient temperature, wind speed, and solar irradiance has a major impact on the house-hold PV panel efficiency. In this paper an experimental study was conducted during the winter period in a single building in Minqin county, Gansu province, China. The experimental measurements were used to quantify the house-hold PV panel performance and operating characteristics. Based on the experimental results the house-hold PV panel performance is basically affected by the PV surface temperature, therefore, multilevel of energy is detected. Approximately 3% efficiency variation is detected due to the impact of the environmental factors.

Keywords

House-Hold PV Panel, Environmental Factors, Photovoltaic Efficiency

1. Introduction

Among all the available electricity sources, solar photovoltaic (PV) is the most popular for installation [1]. PV technology witnessed a significant reduction in the cost and appreciable progress in increasing the efficiency [2] [3]. Generally, the standard test conditions are considered in most cases to address the PV performance specification, however, there is a considerable variation when the actual conditions are adopted.

A part of the irradiance received by the PV panel is transformed into electricity, and the other is transformed into heat losses which is responsible for reducing the PV panel efficiency [4] [5]. Altitude and azimuth play a crucial role in determination of sun position during the day [6]. It is evidence that the maximum reception of solar radiation occurs when the PV panel is perpendicular to the sun radiation [7] [8]. Many publications accounting 0.08% of loss takes place when the location of the PV panel is diverged from the south particularly in azimuth angle [9]. Basically, the PV panel output power is directly proportion to the solar radiation [10]. Due to the approximate linearity the PV current is increased in accordance with the increment of the solar radiation [11] [12] [13]. Regarding this approximate linearity, the influence of the solar irradiance on the PV output current is hard to enumerate [14] [15].

In order to address the influence of ambient temperature on the PV panel functionality, two parameters exist short circuit current I_{sc} and open circuit volts V_{oc}. When the PV module temperature is increasing, the short circuit witnessed an insignificant increase (ranged between 0.04 and 0.09%/K), in contrast to open circuit voltage, it suffers a considerable degradation (up to −0.45%/K for crystalline silicon) [16] [17]. The efficiency of the PV panel is varied according to the PV type under consideration. In the body of literature, it was reported that when the ambient temperature increased by 1˚C, the efficiency is reduced within the range of 0.35% - 0.8% [18] [19] [20] [21]. An experimental work concerns the effects of temperature coefficient on several silicon-based PV types, which reveals a loss of 3% - 5% occur as a result of 10˚C variation [22].

Some publications addressed the influence of ambient temperature on the PV panel performance considering geographical localization. Within the context, the Crystalline PV panel showed a reduction of 0.45% when the temperature rises 1˚C in [23] and 0.5 in [24]. For materials such as amorphous silicon, cadmium Telluride and copper-indium-gallium-diselenide which are used in thin film PV panels, the performance degradation falls in the range of 0.21% - 0.36% [25] [26] [27] [28]. Generally, the increment in the ambient temperature is correlated with performance degradation, and this fact is revealed in [29] [30]. By considering a water-based cooling technique, the PV surface temperature witness a reduction ranged 5˚C to 23˚C which enhance the performance from 0 % to 22% [31].

Many researchers have proposed different approaches regarding the influence of wind on the PV module temperature. Wind has the ability of cooling the PV module within the range of 15˚C - 20˚C when the wind speed is 10 m/s under 1000 W/m^2 of solar irradiance [32]. A considerable variation on the PV panel operation characteristic is detected due to the high dynamic nature of the Wind [29] [33]. In highly dynamic wind regions, the PV panel performance reaches up to 18%, according to the experimental results in [34]. However, the influence of the wind speed on the PV panel performance is quietly trivial in contrast to the ambient temperature and solar irradiance. A method known as in-situ is considered in order to examine the experimental data and for validation purpose. One drawback associated with this method is that, the experimental data need to be substituted by numerical weather prediction [35] [36].

Generally, the house-hold PV panel is affected by numerous environmental factors such as seasonal variation, humidity, rainfall, positioning, etc. However, the influences of these factors are not considered in this investigation.

Regarding the unique weather conditions of Minqin County, the house-hold PV panel performance is expected to vary in many aspects. Accordingly, the main objective of this work is to quantify the performance of the house-hold PV panel and reveal the operating characteristics as well based on the experimental results.

A house-hold PV panel system was built and tested as well. The environmental factors are measured and recorded through the data acquisition equipment. The experimental results are extensively analyzed and discussed.

2. Photovoltaic Surface Temperature Theory

The relationship regarding the ambient temperature (T_a) and the photovoltaic surface temperature (T_{pv}) is nearly linear. Basically, the variation of (T_{pv}) and (T_a) is a function of solar irradiance, and this result is associated with the effect of wind speed. The parameter (T_{pv}) is a function of (T_a) insignificantly influenced by solar irradiance (G) and wind speed (v). By taking into account the standard values for beta coefficients 0.74, 0.33, and −0.11 respectively, the corresponding linear correlation is obtained [37].

$$\begin{aligned} T_{pv} &= 2.08(\pm 0.13) + 1.038(\pm 0.004)\cdot T_a + 0.0182(\pm 0.0001)\cdot G \\ &\quad -1.13(\pm 0.02)\cdot v\left(R^2 = 0.96\right) \end{aligned} \tag{1}$$

The most common expression addressed the PV module temperature is given in Equation (2)

$$T_{pv} = T_a + \frac{1}{G_{(NOCT)}}\cdot\left(T_{NOCT} - T_{a,NOCT}\right) \tag{2}$$

where T_{NOCT} is the temperature at nominal operating cell temperature ($G_{(NOCT)}$ = 800 W/m^2, T_a = 20˚C, v = 1 m/s), T_{NOCT} is varying according to the PV technology a typical value for T_{NOCT} is 45˚C. According to the literature, the typical PV operating temperature is at 45˚C, the best at 33˚C and the worst at 58˚C [38]. This expression does not consider the wind cooling influence.

A compact PV temperature expression is given by:

$$T_{pv} = T_a + 0.035\cdot G \tag{3}$$

In order to consider wind speed factor, the following expression can be used:

$$T_{pv} = T_a + \frac{0.032}{8.91 + 2\cdot v}\cdot G \tag{4}$$

3. PV Efficiency Theory

The efficiency of the PV panel is positively influenced by wind speed. However, this influence is not vital. Within the body of literature, it is reported that, the wind speed influence varies between 1.3 and 1.65 m/s [28] [29] [30] [31] [32]. However, regarding the high dynamic nature of wind factor, it is quite difficult to be quantified. The factor that has a vital influence on the PV efficiency is the T_{pv}. By associating these values 0.85, −0.39, and 0.32 respectively, for standard beta coefficient, the following linear correlation is obtained to address the actual PV efficiency (η%)

$$\eta = 6.2\cdot(\pm 0.2) - 0.0312\cdot(\pm 0.0004)\cdot T_{pv} - 0.176(\pm 0.007)\cdot AM + 4.2(\pm 0.2)\cdot \tau\alpha(\theta)\left(R^2 = 0.53\right) \tag{5}$$

where α and τ are absorptance and transmittance respectively. AM is the air mass (1.6) [39], and θ is the solar zenith angle.

Another expression that associates the actual operating condition and the standard test condition (STC) is given by:

$$\eta = -1.7(\pm 0.2) + 0.631(\pm 0.008)\cdot \eta_k - 0.176(\pm 0.007)\cdot AM + 4.2(\pm 0.2)\cdot \tau\alpha(\theta)\left(R^2 = 0.53\right) \tag{6}$$

where η_k is efficiency under specific STC conditions.

Based on Equation (5) and Equation (6) the actual efficiency is addressed as:

$$\eta = 7.8(\pm 0.2) - 3.74(\pm 0.07)\cdot 10^{-2}\cdot T_{a,x} - 3.2(\pm 0.2)\cdot 10^{-4}\cdot G + 0.8(\pm 0.3)\cdot 10^{-2}\cdot v - 0.197(\pm 0.008)\cdot AM + 2.6(\pm 0.2)\cdot \tau\alpha(\theta)\left(R^2 = 0.51\right) \tag{7}$$

The amount of average deviation when Equation (7) is considered to calculate the photovoltaic efficiency is about 2% of the actual measured efficiency. It is evidence that Equation (7) can be used to predict the photovoltaic efficiency regardless region variation, environmental factors and season variation [37].

4. Experimental Setup

This experiment is conducted in a single building in Minqin county. The lowest average solar radiation on the tilted surface of the local altitude is 13 MJ/m^2 while the peak solar irradiance is 15 MJ/m^2.

The PV panels are fabricated by Xinsheng PV Technology Co. Ltd. A total of 10 monocrystalline silicon PV is utilized. The PV specifications are listed in **Table 1**. The overall DC of the batteries group is 24 V, the inverter efficiency is 80%, and the battery depth is 60%.

The list of the experimental instruments is presented in **Table 2** followed by the schematic of the experiment setup **Figure 1**.

5. Experimental Analysis

For this experiment the following factors are considered and quantified, the wind speed (v, m/s^2), solar irradiance (G, W/m^2), ambient temperature (T_a, ˚C), photovoltaic surface temperature (T_{pv}, ˚C). This experiment is conducted over one week started at 9 Feb. 2015 and ended on 15 Feb. 2015. The process of collecting data extended from 0800 o'clock to 1900 o'clock, each day 8286

Table 1. PV panel specification.

Peak Power (Pmax)	100 w
Voltage at Pmax	18 V
Current at Pmax	5.55 A
Current at Pmax	21.6 V
Open circuit voltage	21.6 V
Short circuit current	5.95 A
Size	1200*540*30 mm
Weight	9.0 KGS

Table 2. The experimental instruments.

Parameters	Device model	Specifications	Manufacturer
Wind speed	YGC-FS Wind speed sensor	Range: 0 - 45 m Accuracy: ±(0.3 + 0.03 V) Resolving power: 0.1 m/s	Wuhan Yi Valley Science and technology Company Limited
Temperature	PT 100 Temperature sensor	Range: −50˚C - 100˚C Accuracy: ±1˚C	Beijing science and technology Saiyiling Limited company
Photovoltaic array output voltage	CJ-DA61-D DC voltmeter	Range: 0 - 50 V Precision: 0.5 s	Shanghai Chu Jing electric Limited company
Photovoltaic array Output current	CJ-DA61-D DC ammeter	Range: 0 - 25 Ah Accuracy: 0.5 s	Shanghai Chu Jing electric Limited company
Data acquisition instrument	34972A		Agilent Technology Limited company
Solar irradiance	CG-07 Solar Radiometer	Sensitivity: 7 - 14 mv/kW·m^{-2} Range: 0.3 - 3.2 μm	Handan Development Zone Qing Yi Electronic Technology Co., Ltd.

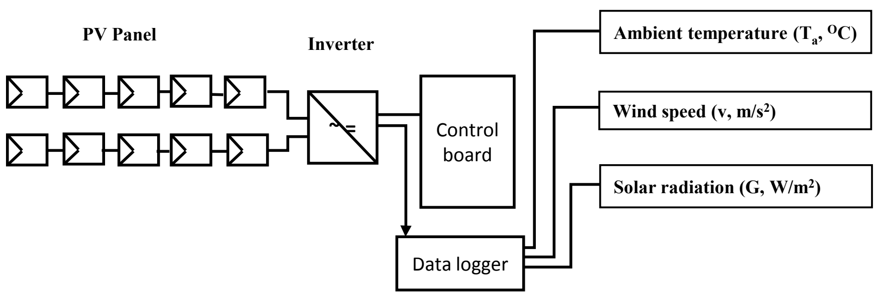


Figure 1. Schematic diagram of the experiment setup.

measurements are recorded. Figure 2(a) presents the temperature for the entire week, and boxplot is adopted to present the measurements. Measurement ranged 1st to 3rd quartile is included within the box and the difference is known as the interquartile range (IQR). The minimum and the maximum are presented by whiskers below and above the rectangular respectively. Measurements that are three times or greater than the 3rd quartile or three times the inter quartile range or lower than the 1st quartile are designated outlier and plotted as red plus signs.

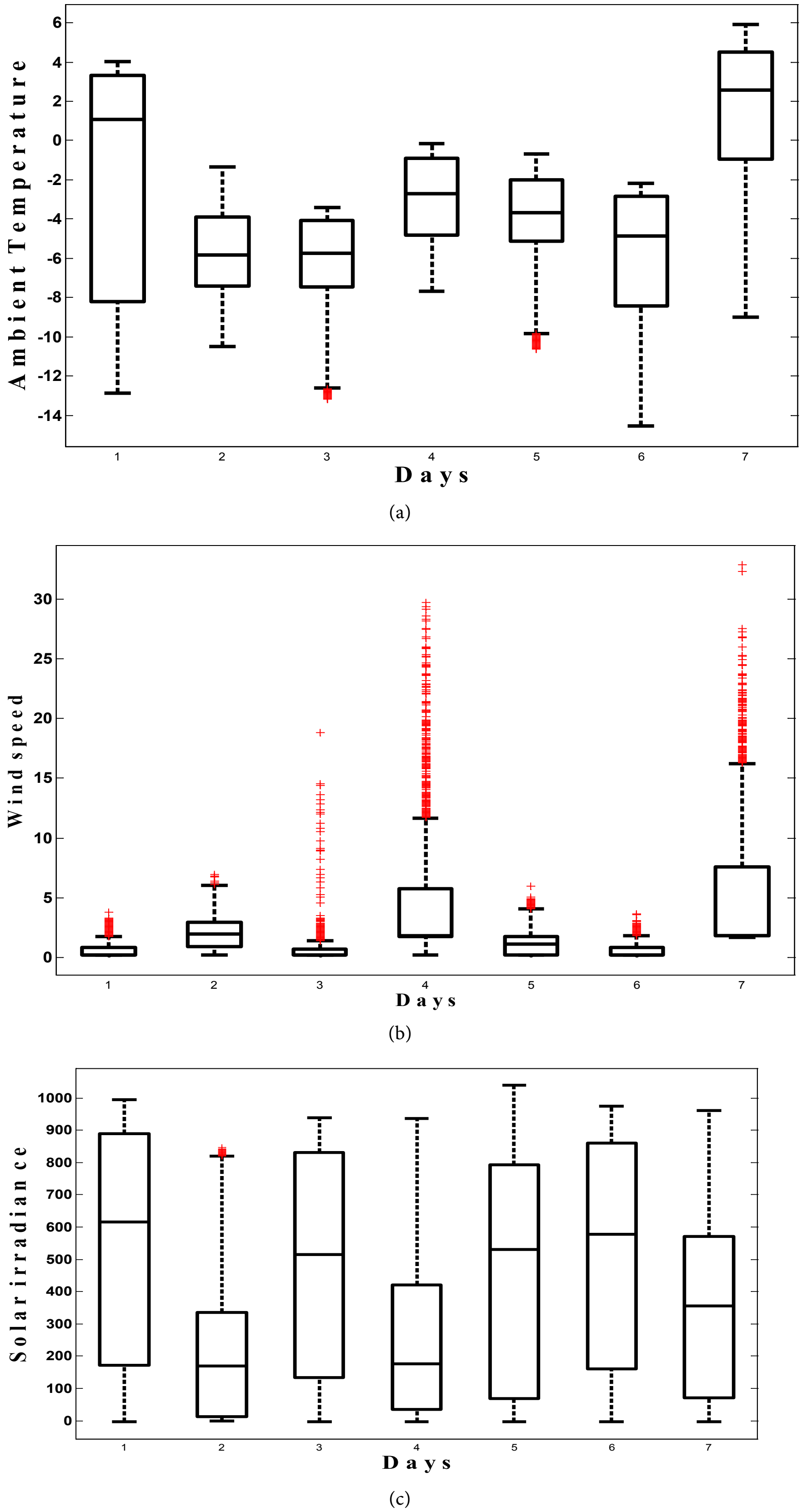


Figure 2. Statistical plots of the experimental measurements of (9 Feb. 2015-15 Feb. 2015). (a) Ambient temperature; (b) Wind speed; (c) Solar irradiance.

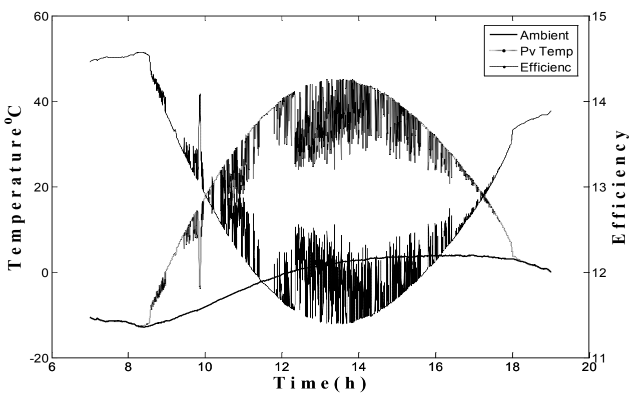
Figure 2(a) reveals that the minimum ambient temperature is −14.6˚C detected on the 6th day, the maximum temperature is 5.9˚C detected in the 7th, while the maximum mean is 1.31˚C detected in the 7th. The outliers only detected in the 3rd and 5th days where the temperature falls below −13.2˚C and −10.7˚C respectively. According to the measurements the temperature is less than 16˚C a day. Figure 2(b) shows the record of the wind speed data per day for the same week. A significant variation is shown by the wind speed and described by several outliers. The minimum wind speed is 0.18 m/s detected on the 3rd day, the maximum wind speed is 32.97 m/s is detected on the 7th day, and the maximum mean is 4.99 m/s detected on the 7th day. Generally, the wind variation is lower than 33 m/s. The solar irradiance measurements are shown in Figure 2(c) for the same period. The outliers are only detected on the 2nd day when the solar radiation is exceeding 800 W/m^2. The minimum solar irradiance is −3.8 W/m^2 witnessed on the 1st day, the maximum solar irradiance is 1040 measured on the 5th day, and the maximum mean is 536.3 W/m^2 recorded on the 1st day. The variation of solar irradiance during the experiment is more than 800 W/m^2 per day.

In Figure 3 the (T_{pv}) and (T_a) are depicted as a function of the day hours for all measurements of the week. These figures reveal the dependence of PV surface temperature on the solar irradiance.

What is interesting about the data in Table 3 is that at 0800 and 1900 0'clock in some days the (T_{pv}) measurements are lower than (T_a). This is mainly due to the influence of wind.

Based on the experimental results, as shown in Figure 4 the minimum efficiency is 11.52% achieved during the 5th day where the wind speed is ranged between 1.19 m/s and 5.97 m/s; the minimum and maximum ambient temperature is −10.7˚C and −0.67˚C respectively; the mean of ambient temperature is −4.2˚C; the solar irradiance is ranged (−2.80 - 408.4) W/m^2.

The maximum efficiency being 14.75% is detected during the 1st day where the wind speed is ranged between (0.2 - 3.75) m/s; the ambient temperature is ranged between (−12.9 - 4.03); the solar irradiance is ranged between (−3.84 - 994) W/m^2. Generally, when the solar irradiance witnesses a significant increase, the instantaneous value of the efficiency is reduced, particularly, when the solar



(a)

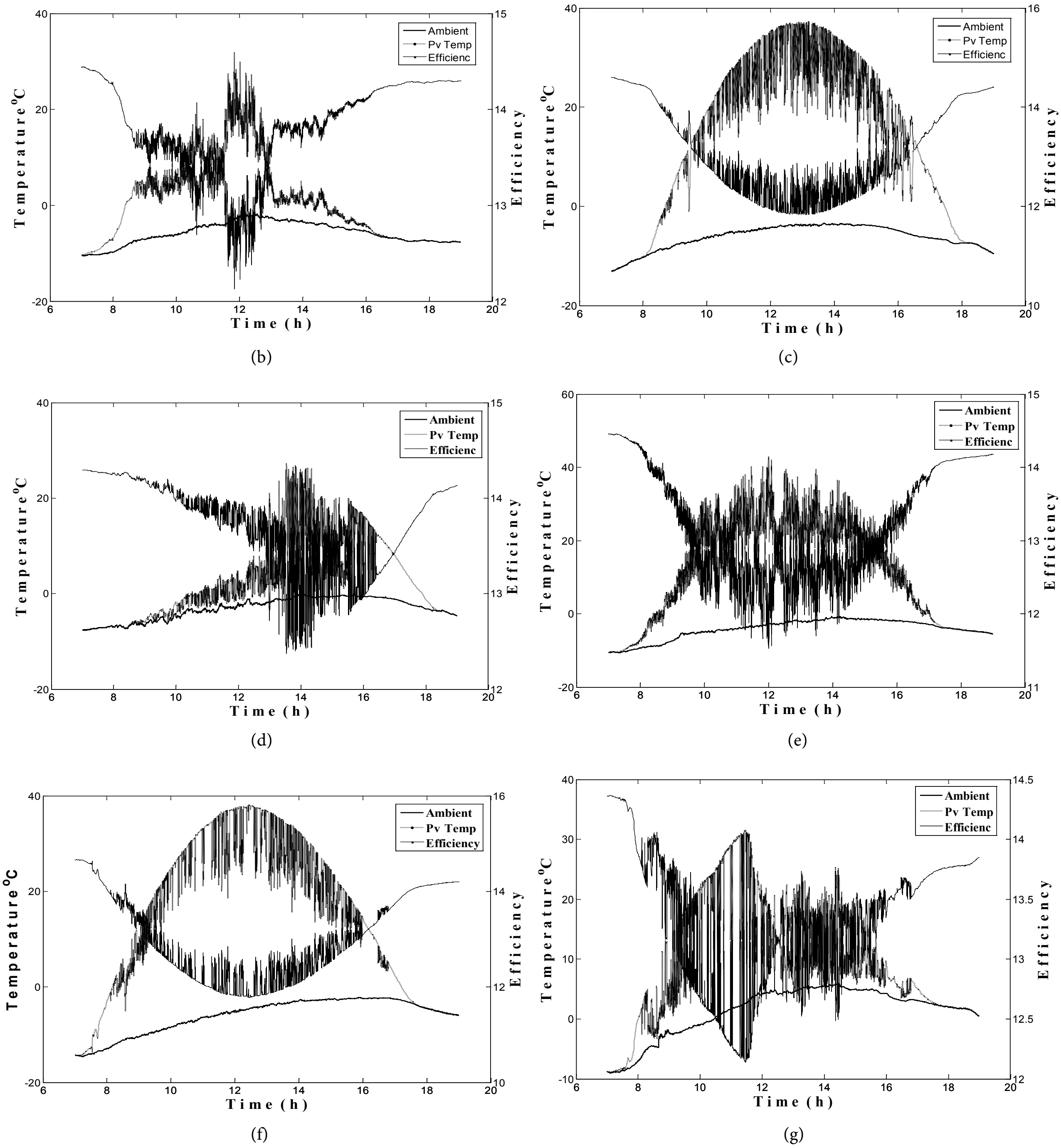


Figure 3. Ambient temperature, PV surface temperature, and the efficiency as a function of day hours for the entire week. (a) 1st day; (b) 2nd day; (c) 3rd day; (d) 4th day; (e) 5th day; (f) 6th day.

irradiance exceeds 800 W/m^2, this due to the considerable increase of the photovoltaic surface temperature as shown in **Figure 5**.

6. Conclusions

In this paper the influences of the environmental factors such as solar radiation, wind speed, and ambient temperature on the house-hold PV panel efficiency are

Table 3. Statistical values of ambient temperature and PV surface temperature.

Ambient temperature			PV temperature			Days
min	max	mean	min	max	mean	
−12.9	4.03	−1.93	−12.7	45.16	19.11	1^{th}
−10.5	−1.36	−5.77	−10.4	31.80	0.99	2^{th}
−13.2	−3.41	−6.22	−13.2	37.28	12.95	3^{th}
−7.68	−0.13	−3.11	−7.68	27.38	2.57	4^{th}
−10.7	−0.67	−4.21	−10.6	42.73	11.19	5^{th}
−14.6	−2.18	−6.01	−14.4	38.13	14.62	6^{th}
−9.02	5.93	1.31	−8.97	31.58	9.62	7^{th}

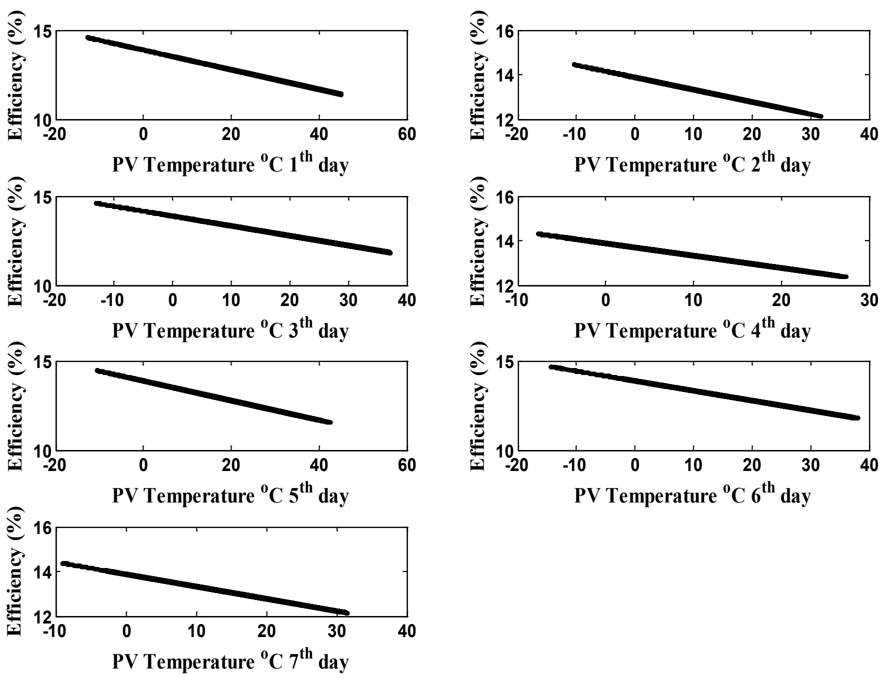


Figure 4. The plots of the efficiency as a function of PV surface temperature of (9 Feb. 2015-15 Feb. 2015).

investigated and quantified. Based on the experimental results, the house-hold PV panel performance is considerably varied. This deviation is ranged between 11.39% - 14.75%.

The house-hold PV panel performance is basically affected by the PV surface temperature, therefore, multilevel of energy is detected. Approximately, 3% efficiency variation is detected.

This investigation is exclusively considered solar radiation, wind speed, and ambient temperature as an environmental factor, and future work should associate other factors such as humidity, rainfall, seasonal variation.

Investigating and analyzing the influence of the environmental factors on the

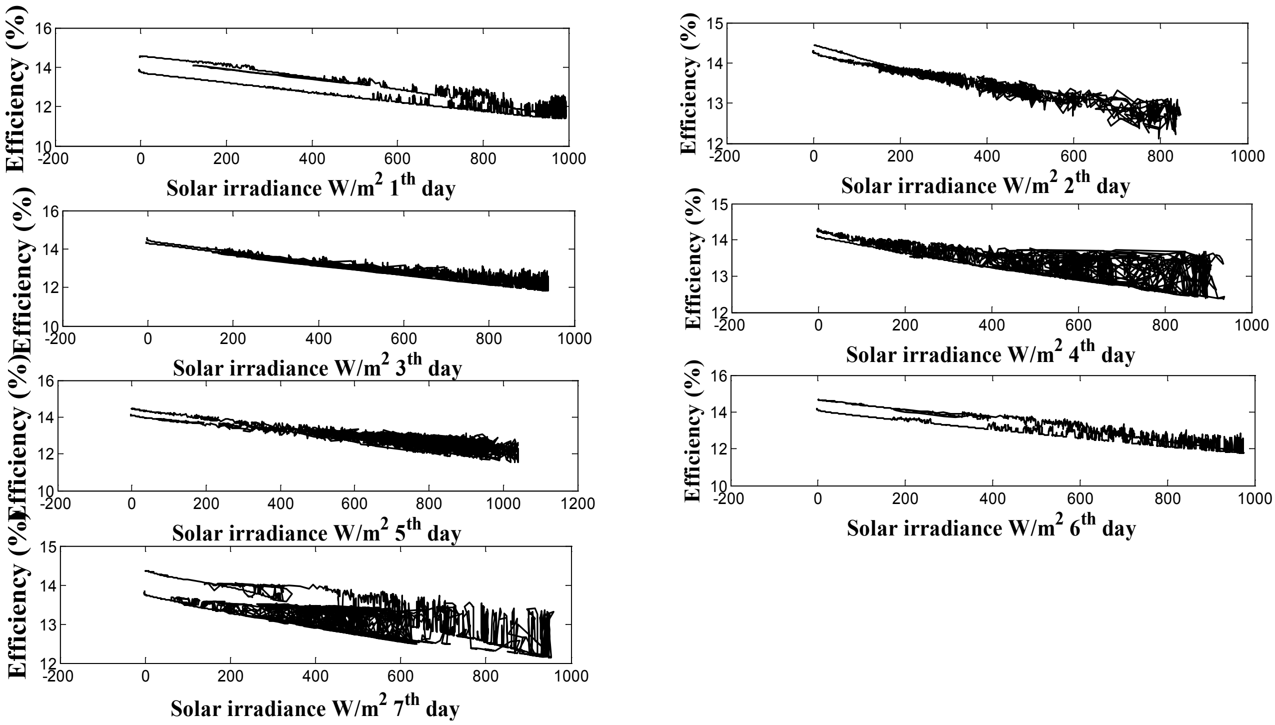


Figure 5. The plots of the efficiency as a function of solar radiation of (9 Feb. 2015-15 Feb. 2015).

house-hold PV panel facilitate the process of assessment and prediction of performance and the harvested power and thus accurately size the PV plants.

Conflicts of Interest

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

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