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# Investigation of Panel Efficiency in Photovoltaic Systems Under Partial Shading and Different Pollution Conditions: An Experimental Study

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**ABSTRACT**

PV systems are very important to ensure the efficient operation of electricity generation. However, environmental conditions or the structure of the panels affect the efficiency of this production. In this study, which is carried out on one day in summer, it is aimed to investigate the factors affecting productivity. For this purpose, the surface temperature under full irradiation and partial shading conditions is measured with a thermal camera, and analysis is carried out. According to pollution levels, the panels are classified as defective and healthy in two different conditions, and characteristic curves of PV panels are generated. According to the experimental results, it is observed that the clean panel washed with water produced more power than the other panels under both full irradiation and partial shading conditions. Surface temperatures are observed to be at optimum levels in clean panels. This study shows that regular cleaning of PV panels and detection of panel defects by a thermal imaging camera are beneficial to increase efficiency.

## Kısmi Gölgeleme ve Farklı Kirlilik Koşulları Altında Fotovoltaik Sistemlerde Panel Verimliliğinin Araştırılması: Deneysel Çalışması

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**ÖZ**

Fotovoltaik (PV) sistemlerin elektrik üretiminde verimli çalışmasını sağlamak çok önemlidir. Ancak çevresel koşullar veya panellerin yapısı bu üretimin verimini etkilemektedir. Yaz aylarında bir günde gerçekleştirilen bu çalışmada, verimliliği etkileyen faktörlerin araştırılması amaçlanmıştır. Bu amaçla tam ışınım ve kısmi gölgelenme koşullarında yüzey sıcaklığı termal kamera ile ölçülmüş ve analizler yapılmıştır. Kirlilik seviyelerine göre paneller iki farklı koşulda arızalı ve sağlıklı olarak sınıflandırılmış ve PV panellerin karakteristik eğrileri oluşturulmuştur. Deneysel sonuçlara göre hem tam ışınım hem de kısmi gölgeleme koşullarında su ile yıkanan temiz panelin diğer panellere göre daha fazla güç ürettiği görülmüştür. Temiz panellerde yüzey sıcaklıklarının optimum seviyede olduğu gözlemlenmiştir. Bu çalışma, PV panellerin düzenli olarak temizlenmesinin ve panel kusurlarının termal kamera ile tespit edilmesinin verimliliği artırmak için faydalı olduğunu göstermektedir.

## 1. INTRODUCTION

The production, transmission, and distribution of electrical energy have become very important with the intensive demand for its use in the modern day. The impact and importance of sustainability and efficiency are increasing in parallel with energy production. Therefore, the tendency towards renewable energy sources is increasing day by day. Solar energy is one of the most prominent renewable energy sources. It is preferred in regions with extreme dust, snowfall, extreme humidity, or high wind speed, thanks to its ease of installation in open land or roof applications [1]. However, the efficiency of PV panels installed in these regions is affected. This situation causes fluctuations in energy production. To solve these fluctuations, research has focused on the efficiency of PV panels under different environmental conditions. It is concluded in a study that there are changes in efficiency as a result of the increase in panel temperature. Experimental researches are carried out with active and passive methods to prevent this efficiency loss and to prevent the thermal structure of the panel from deteriorating [2,3]. In another study, analyses related to the operating temperature of the cells of PV panels are carried out. Increases in operating temperature lead to a decrease in open circuit voltage ($V_{OC}$), fill factor, and power output [4]. In [5], the effect of temperature variation in monocrystalline and polycrystalline PV cells is observed. A small increase in short-circuit current ($I_{SC}$) causes a loss of conversion efficiency and permanent damage to PV cell materials.

Dusting is another factor affecting the efficiency of PV panels. Dust accumulation occurs on PV panels with the effect of wind. Accumulated dust dries with the effect of wind speed and sticks on the panel. In addition to dusting, bird waste or chemicals from smokestacks also cause pollution. Pollution decreases the efficiency as it causes both a decrease in the solar irradiation on the panel and an increase in the panel temperature. Excessive dusting is observed especially in panels that are mounted on the ground for agricultural irrigation and energy generation [6-8]. Dust mixed with rainfall turns into mud and adversely affects panel efficiency [9].

One of the factors affecting the performance of PV panels is hot spot failures. Hot spot failure occurs when one or more of the cells connected in series on the PV panel are exposed to heat and as a result, they lose their properties and cannot produce [10]. In a study, a focus on the efficiency of hot spots at the point of energy generation and the prevention of heating of hot spot PV panels is carried out [11]. In another study, thermal images taken from PV panels are analyzed and a study is carried out on the detection and analysis of hot spots with the YOLO algorithm [12]. Hot spot failures also occur as a result of partial shading. In the study in [13], partial shading, one of the factors causing hot spots, is analyzed. The effects on PV panel efficiency are examined as a result of measurements taken using a thermal camera. In another study, a different method is developed to detect hot spots in advance. The data obtained by using the K-means clustering method is made more computationally efficient [14].

PV panels are activated by taking into account the angle of solar irradiation in the area during installation, the geometric structure of the place to be installed, and the shading situation. In this case, shading is seen in places that we call blind spots. In addition, PV panels in the region are exposed to shading factors such as trees, poles, solar collectors on the roof, satellites, antennas, and smokestacks. This shading affects the energy production efficiency of the cells. This effect affects the efficiency of the entire PV panel series and causes a decrease in the generated power [15-17]. In another study on efficiency, the effect of PV panel installation direction, angle, shading, irradiation, and temperature factors on battery health is investigated [18]. The effects of humidity, shading, orientation, and climate changes on PV panels are investigated in another study [19]. According to the results obtained in the structure created in Matlab/Simulink, it is concluded that these environmental factors negatively affect the performance of PV panels [20,21].

In this paper, environmental and production factors related to the efficiency performance of PV systems are analyzed. Initially, an overview of the technical structure of PV panels is presented. Then, under the same conditions, the pollution, shading, and hot spot conditions of identical PV panels are measured with a thermal camera and a PV analyzer. The analysis is performed by setting the panels as dirty, cleaned by a wiped with a cloth, and cleaned by water washed, with and without shading. In the results obtained, suggestions are presented on how to make the most efficient production in electrical energy production points with PV panels.

## 2. EXPERIMENTAL SETUP

PV panels are affected by environmental factors during energy generation. These factors adversely affect panel efficiency, thus causing the power plant to fail to provide the desired performance and causing the panels to fail. The factors affecting the efficiency are sunlight, direction and angle of irradiation, panel temperature, humidity, panel cleanliness (dusting, contamination, bird waste, snow, etc.), shading, and hot spot failures. Two different scenarios are created to examine the factors affecting the PV panels. Firstly, PV panels are divided into healthy panels and panels with hot spots. In the first case, the effects of pollution on panel efficiency are analyzed when the PV panels are at full irradiation. The dust accumulation on the panel is left dirty on one panel, cleaned by a wiped with a cloth on one panel, and cleaned by water washed on the other panel. In the second case, these analyses are repeated for the case of partial shading of the PV panels. Analyses are performed for both the intact panels and the panel with hot spot failure.

Figure 1 shows the general schematic of the panels for full irradiation and partial shading cases. Irradiance measurements, current-voltage (I-V) and power-voltage (P-V) characteristic curves of PV panels, and thermal measurements of PV panels are carried out within the scope of the experiment.

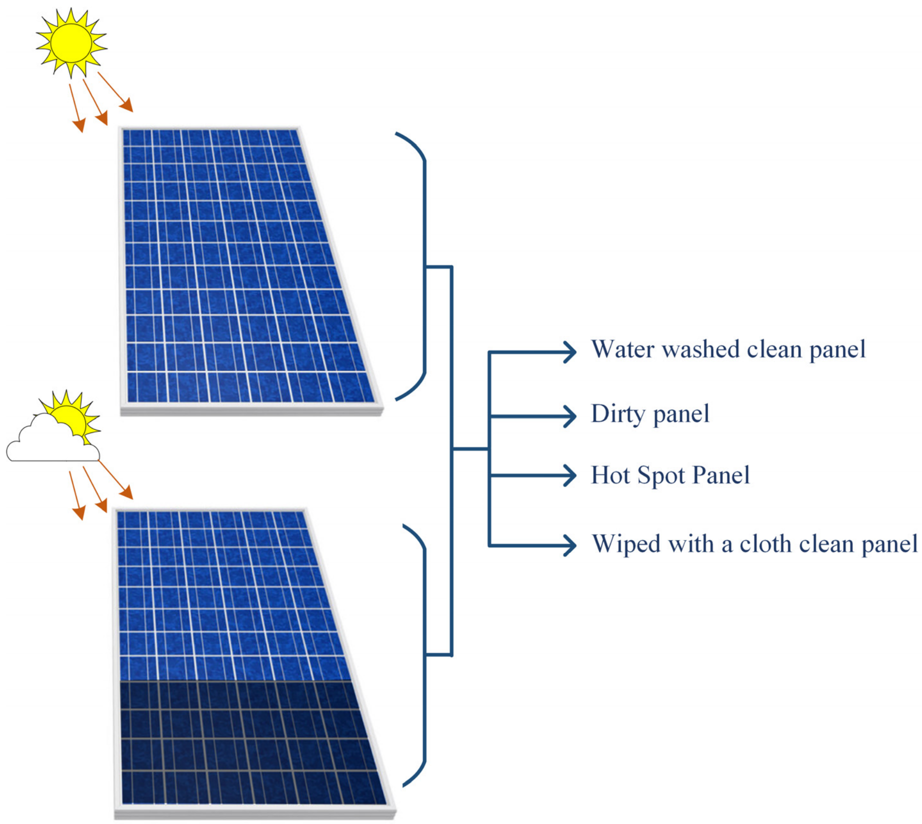


**Figure 1.** PV panel system

Figure 2(a) (PCE-PVA 100, PCE Instruments, Germany) shows the connection of the device used to plot the I-V and P-V characteristic curves of the panels. This instrument can be used to measure PV panels at 60 V and 12 A. The I-V and P-V characteristic curves of the panels under different conditions are obtained by connecting the panel ends to the poles of the device. The irradiance values during the experiment are recorded using a pyranometer (MS410, EKO, Japan) and a data logger (LR5041, Hioki, Japan). The MS410 pyranometer measures with a sensitivity of 11.51 µV/Wm-2. Figure 2(b) shows the general structure of the pyranometer and data logger connection. The connection of the thermal measurements of the PV panels is given in Figure 2(c). Sensitive temperature measurement of the panels with a thermal imager (875-2i, Testo, Germany) and heat mapping of the measured surface temperatures are analyzed with Testo IRSoft software. Table 1 gives the technical specifications of the PV panel used during the experiment.

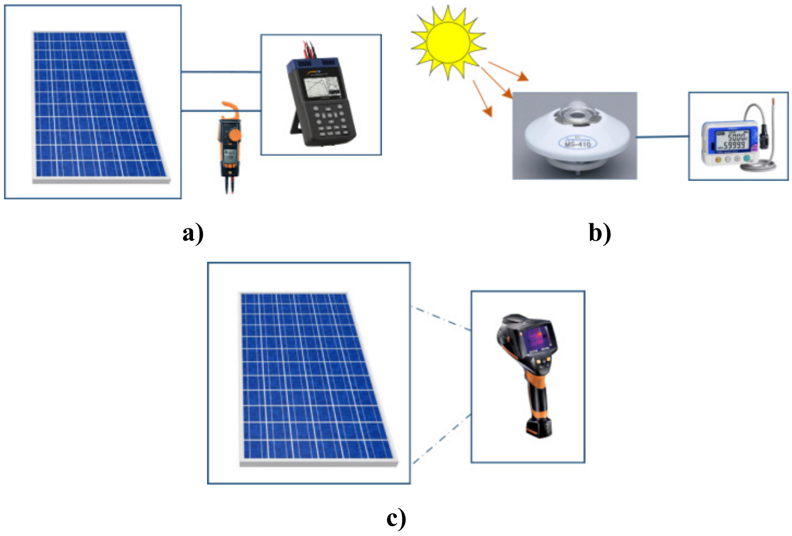


**Figure 2. (a)** Solar module analyzer, **(b)** Pyranometer and datalogger, and **(c)** Thermal camera

**Table 1.** The characteristics of the PV panel (CSUN270-60P) used in this experimental study

| **Parameter** | **Value** |
|---|---|
| Maximum power ($P_{MPP}$) | 270 W |
| Open circuit voltage ($V_{OC}$) | 37.9 V |
| Short circuit current ($I_{SC}$) | 9.07 A |
| Maximum power voltage ($V_{MPP}$) | 30.7 V |
| Maximum power current ($I_{MPP}$) | 8.8 A |

## 3. EXPERIMENTAL RESULTS AND DISCUSSION

In this paper, two scenarios are created and analyses are performed on these scenarios. The first scenario is under full irradiation, and the second scenario is under partial shading conditions. On 15 July 2024, experimental measurements are carried out between 13:30 and 15:05 at a temperature of 37℃. Irradiation measurements are taken from the pyranometer between the hours of the experiment. The irradiance value taken from the pyranometer during the experiment is approximately 900 W/m². The experimental set required for measuring and analyzing the factors affecting energy production efficiency was established on the roof of the Mersin University Electrical and Electronics Engineering Department.

### 3.1. Scenario 1

In this scenario, PV panels are at full irradiation. The PV panels are determined as healthy panels and panels with hot spots. Six different conditions are created on these equivalent panels dirty, cleaned by wiped with a cloth, and cleaned with water washed. Figures 3 and 4 show the P-V and I-V curves obtained under full irradiation. The power value is measured as 226 W when the healthy panel is clean in the measurements made under full irradiation. The power values obtained on the wiped with a cloth and dirty panels are 185.1 W and 183.1 W, respectively. These procedures performed on the healthy panel are repeated on the panel with the hot spot. During these measurements, the power value obtained from the panel with the hot spot is measured as 210.2 W when clean, 198.1 W when wiped with a cloth, and 195 W when dirty.

It is observed that the panel cleaned by washed with water for the healthy panel produces 40.9 W, i.e., 18.09% more power than the panel wiped with a cloth. It produces 42.9 W, i.e., 18.98% more power than the dirty panel. The clean panel, which is healthy and washed with water, operates 15.8 W, i.e., 6.9% more efficiently than the panel with a hot spot and washed with water. It produces 27.9 W more power than the wiped panel with a hot spot and 31 W more power than the dirty panel with a hot spot. It is observed that it works 12.35% and 13.71% more efficiently, respectively. Table 2 shows the maximum power points, open circuit voltage, and short circuit current values obtained from six different cases under full irradiation.

**Table 2.** Results obtained from scenario 1 under full irradiation

| Panel cleanliness state | $V_{OC}$ (V) | $I_{SC}$ (A) | $V_{MPP}$(V) | $I_{MPP}$ (A) | $P_{LOSS}$ (W) |
|---|---|---|---|---|---|
| Dirty panel | 32.94 | 7.82 | 26.32 | 6.957 | 32.18% |
| Water washed clean panel | 36.02 | 8.55 | 28.74 | 7.865 | 16.28% |
| Wiped with a cloth clean panel | 33.97 | 7.511 | 26.62 | 6.955 | 31.42% |
| Water washed clean hot spot panel | 35.91 | 7.85 | 28.91 | 7.273 | 22.12% |
| Dirty hot spot panel | 34.49 | 7.812 | 27.4 | 7.134 | 27.60% |
| Wiped with a cloth clean hot spot panel | 34.7 | 7.792 | 27.35 | 7.242 | 26.64% |

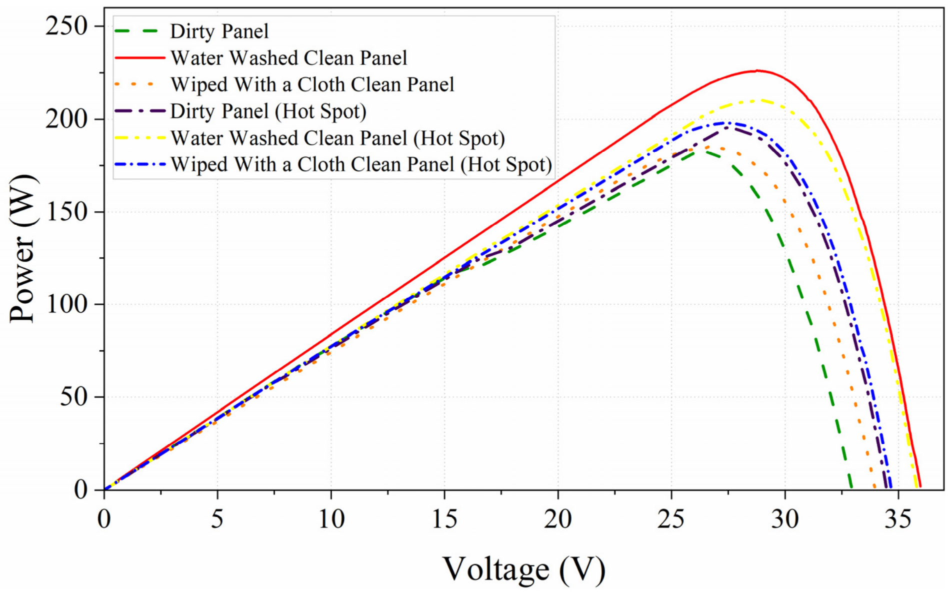


**Figure 3.** P-V characteristic curves obtained from scenario 1 under full irradiation

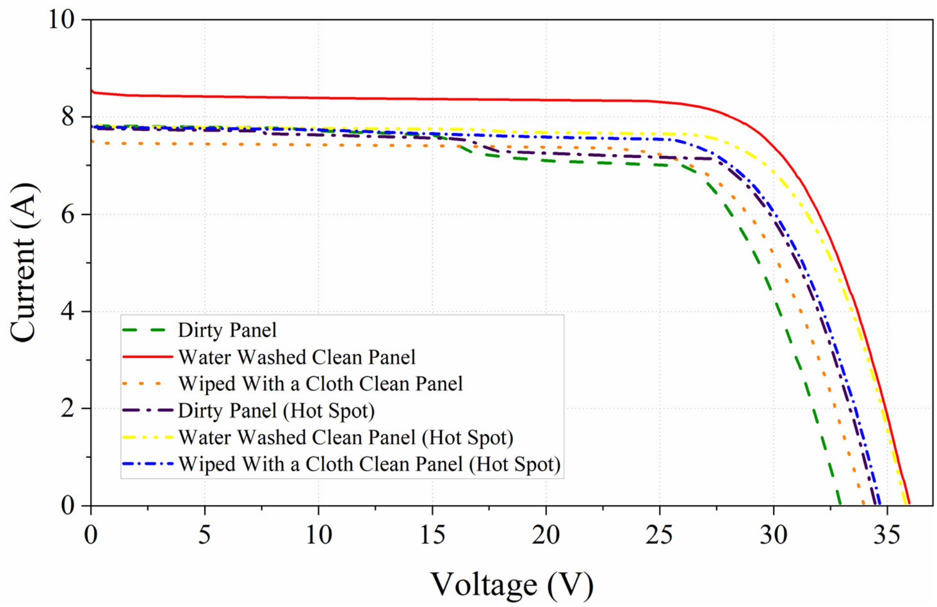


**Figure 4.** I-V characteristic curves obtained from scenario 1 under full irradiation

Figure 5 shows the panel pictures under full irradiation and their thermal camera images. The first measurement is taken when the healthy and hot spot panels are clean and washed with water. On the healthy panel, the lowest surface temperature is 34°C and the highest temperature is 36.5°C. On the panel with a hot spot, the lowest temperature is 42°C and the highest temperature is 44.5°C.

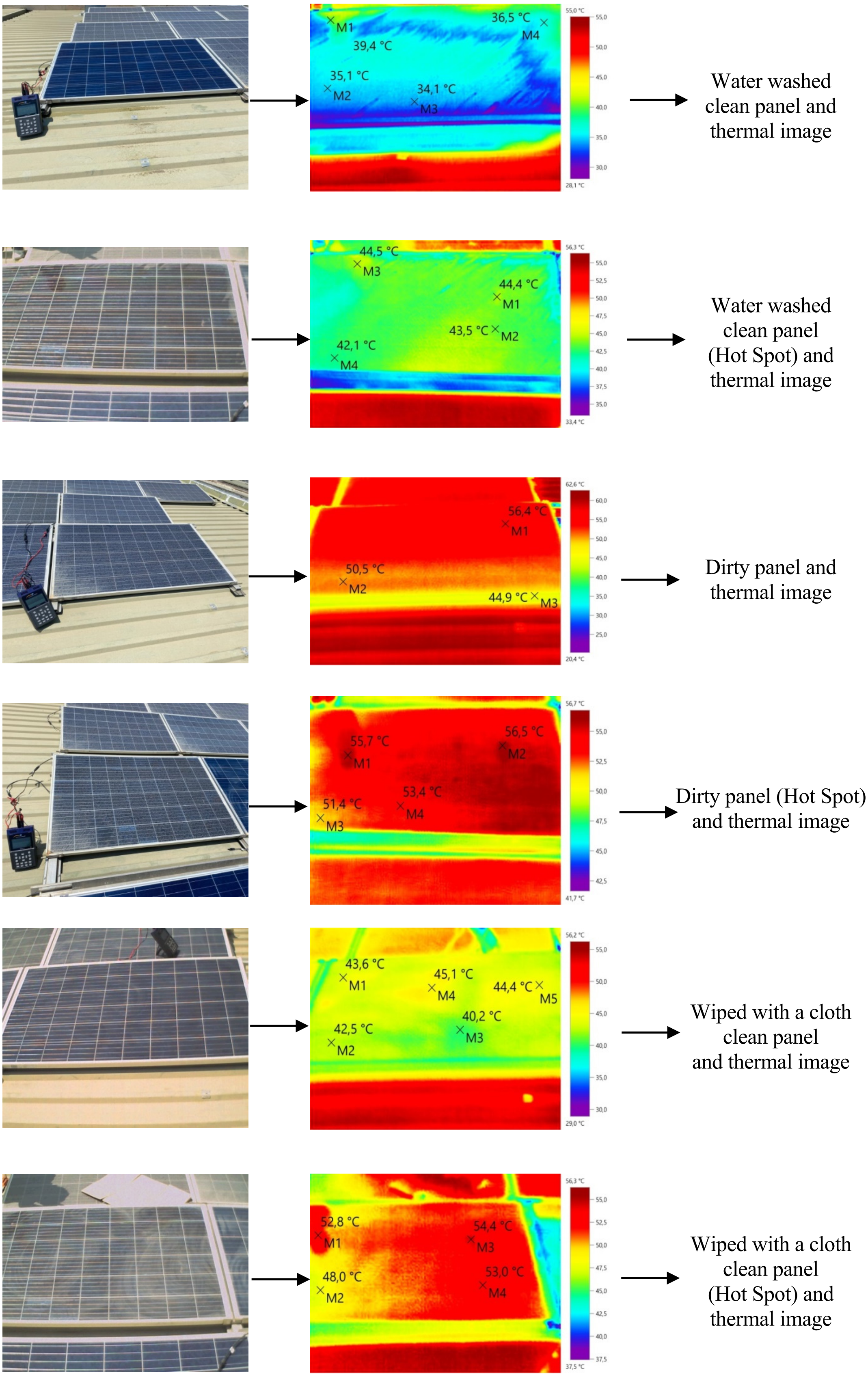


**Figure 5.** Temperature distribution in the IR images and panel photographs from scenario 1

The second measurement is taken when the healthy and hot spot panels are dirty. The lowest temperature point on the intact panel is 44.9°C and the highest point is 56.4°C. On the panel with a hot spot, the lowest temperature is 51 °C and the highest point is 56.5°C. The last measurement is taken on the panels with healthy and hot spot panels cleaned by wiped with a cloth. The lowest surface temperature is 40°C and the highest is 45.1°C on the healthy panel cleaned by wiped with a cloth. The lowest temperature is 48°C and the highest temperature is 54.4°C on the panel with the hot spot cleaned by wiped with a cloth.

It is observed that the power generated by the PV panels is directly proportional to the panel cleanliness when the measurements taken are analyzed at full irradiation. The cleaner the PV panels are, the higher the power generated; thus, more efficient production is provided. In addition, the continuous high surface temperature increases the hot spot formation in the PV panel. Hot spot formation causes a loss of efficiency, as seen from the measurements.

### 3.2. Scenario 2

Partial shading is created on the PV panels in this scenario. The procedures in the first scenario are repeated for the partial shading condition. Figures 6 and 7 show the P-V and I-V curves obtained under partial shading. In the measurements made under partial shading condition, the power value is measured as 12.6 W for the healthy panel cleaned by washed with water. The power values obtained for the cleaned by wiped with a cloth and dirty panel are 10.51 W and 9.686 W, respectively. These procedures performed on the healthy panel are repeated on the panel with a hot spot. The power value obtained from the panel with a hot spot during these measurements is 11.82 W when washed with water, 11.95 W when wiped with a cloth, and 11.05 W when dirty. According to the measurements taken, it is observed that the panel cleaned by washed with water for the intact panel produces 2.09 W, i.e., 16.58% more power than the panel cleaned by wiped with a cloth. It produces 2.91 W, i.e., 23.12% more power than the dirty panel, and 0.78 W, i.e., 6.19% more power than the hot spot panel washed with water. In the panel where the experimental work is carried out, since the partial shading causes the serial cells of the panel to close, the power generated is 94% lower on average compared to the measurements made under full irradiation. Partial shading in PV panels directly affects the efficiency of the panel.

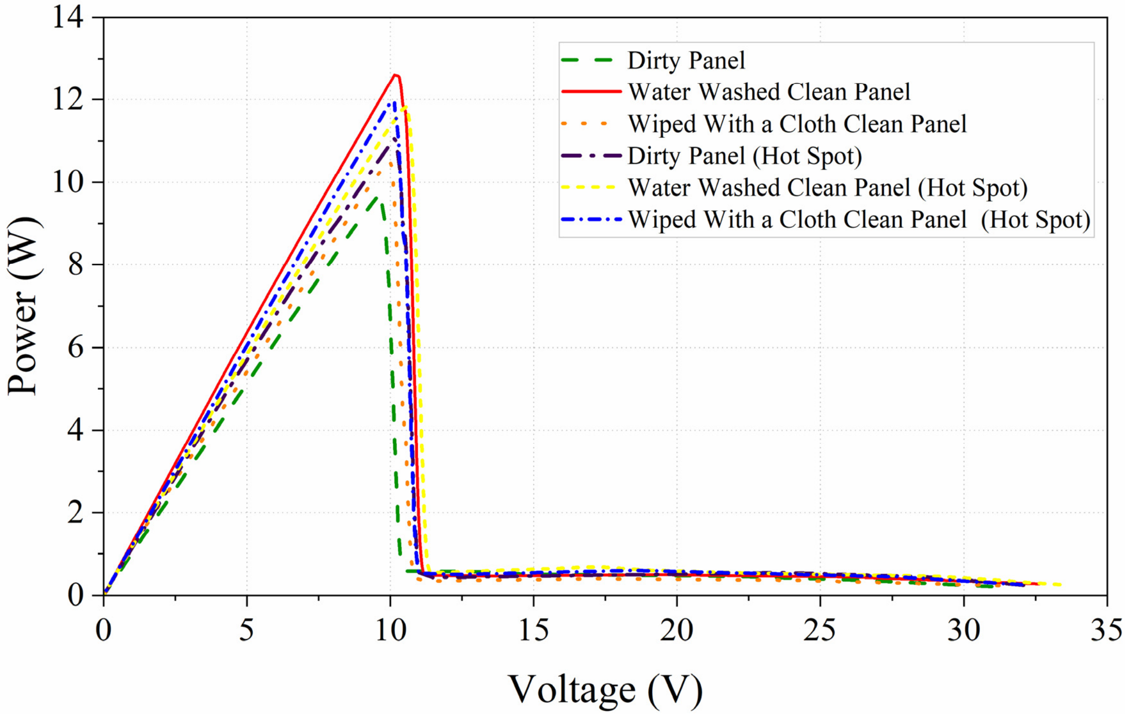


**Figure 6.** P-V characteristic curves obtained from scenario 2 under partial shading

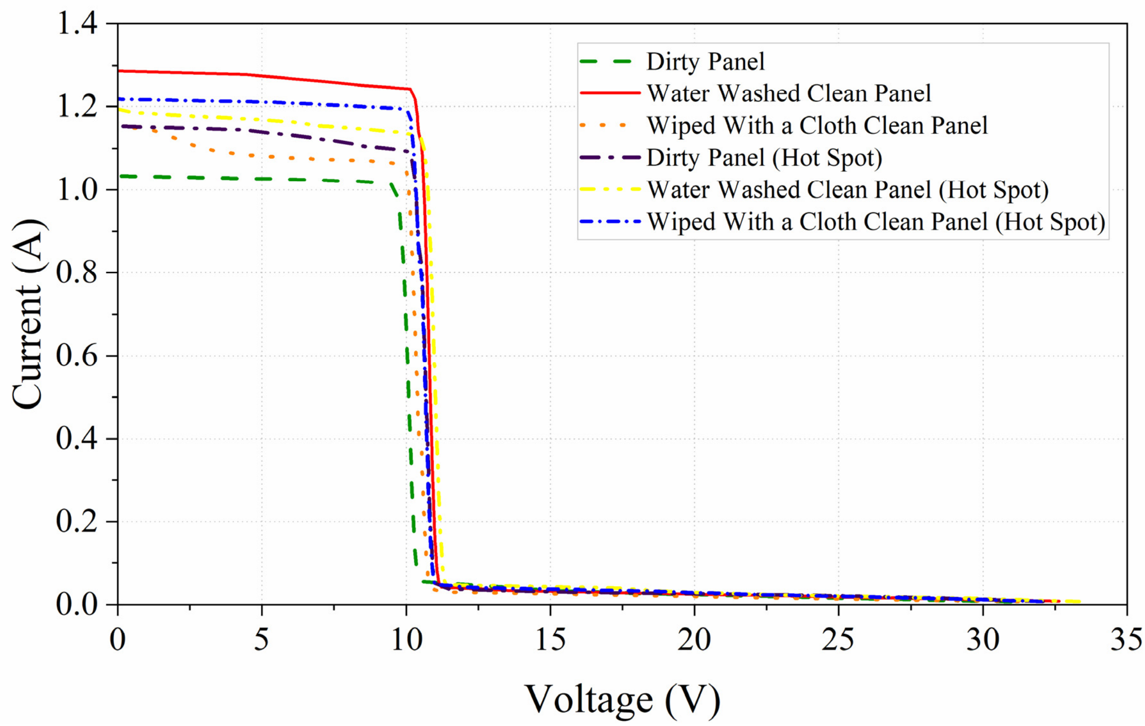


**Figure 7.** I-V characteristic curves obtained from scenario 2 under partial shading

Table 3 shows the maximum power points, open circuit voltage, and short circuit current values obtained from six different cases under partial shading condition.

**Table 3.** Results obtained from scenario 2 under partial shading

| Panel Cleanliness State | $V_{OC}$ (V) | $I_{SC}$ (A) | $V_{MPP}$ (V) | $I_{MPP}$ (A) | $P_{LOSS}$ (W) |
|---|---|---|---|---|---|
| Dirty panel | 30.97 | 1.033 | 9.621 | 1.006 | 96.4% |
| Water washed clean panel | 32.62 | 1.286 | 10.14 | 1.242 | 95.33% |
| Wiped with a cloth clean panel | 31.2 | 1.153 | 9.937 | 1.058 | 96.11% |
| Water washed clean hot spot panel | 33.35 | 1.194 | 10.53 | 1.122 | 95.62% |
| Dirty hot spot panel | 32.07 | 1.152 | 10.13 | 1.091 | 95.90% |
| Wiped with a cloth clean hot spot panel | 32.02 | 1.218 | 10.08 | 1.185 | 95.57% |

Figure 8 shows the pictures of the panels in partial shading and their thermal camera images. The first measurement is taken when the healthy and hot spot panels are cleaned by washed with water. The lowest surface temperature on the intact panel is 35.7°C at the point where there is partial shading, and the highest temperature is 41.9°C. The lowest temperature on the panel with a hot spot is 37°C, and the highest temperature is 44°C. The second measurement is taken when the healthy and hot spot panels are dirty. The lowest temperature point on the healthy panel is 41.1°C, and the highest point is 55.3°C. The lowest temperature on the panel with a hot spot is 38.7°C, and the highest point is 54.4°C. The last measurement is taken over the panels with healthy and hot spot panels cleaned by wiped with a cloth. The lowest temperature is 33.5°C, and the highest temperature is 44.2°C on the healthy panel cleaned by wiped with a cloth. The lowest temperature is 41.5°C, and the highest temperature is 54.4°C in the panel with a hot spot. As mentioned in scenario 1, the cleanliness of the panels is directly proportional to the power generated from the panels. In this scenario, it is noted that the degree to which partial shading affects the production of the generated power is significantly reduced.

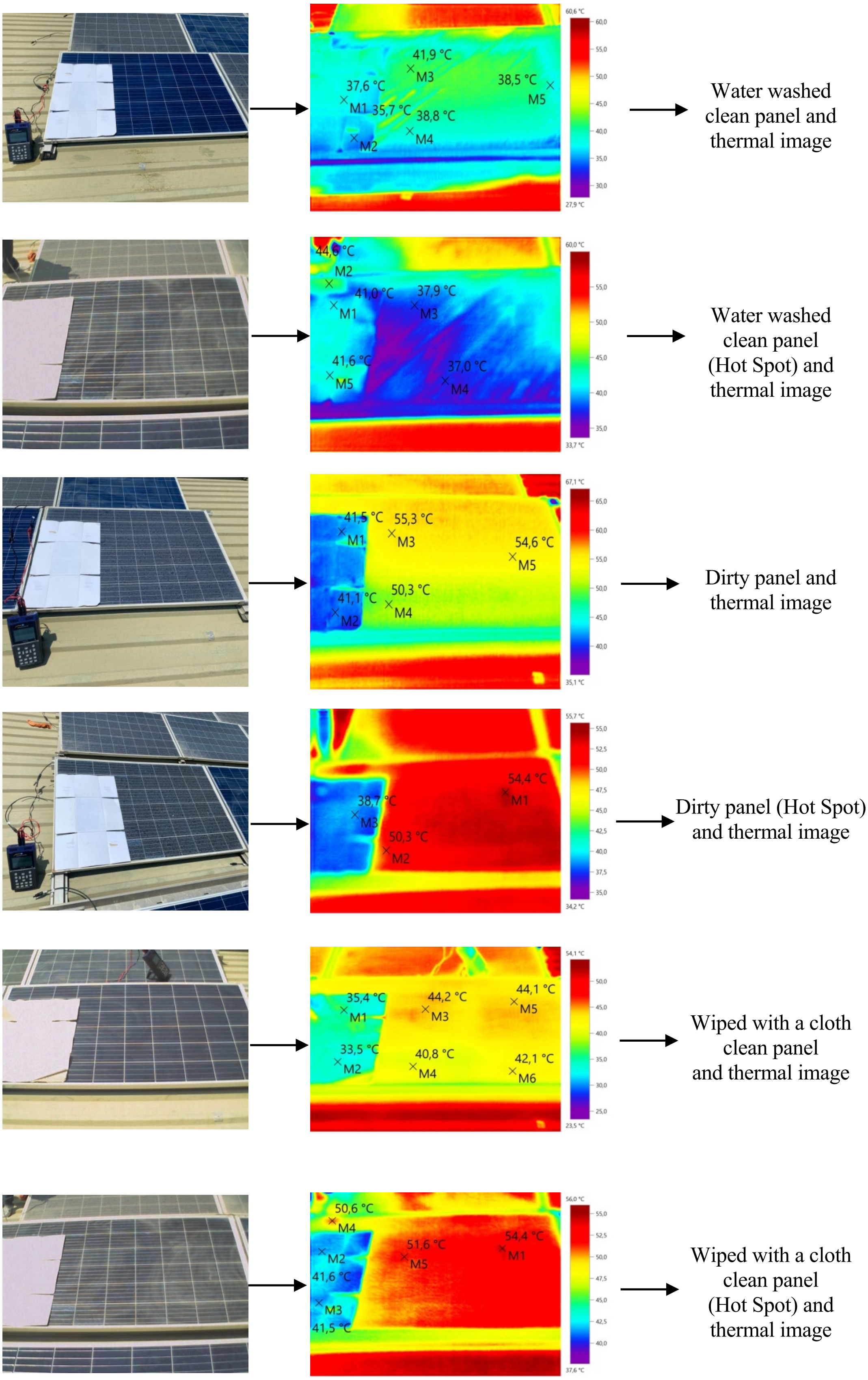


**Figure 8.** Temperature distribution in the IR images and panel photographs from scenario 2

## 4. CONCLUSION

The responses of PV panels to environmental factors in terms of efficiency are analyzed, and conclusions are drawn within the scope of the study conducted in this article. As a result of the experimental studies, the effect of pollution and shading on both the panel surface temperature and the production efficiency is observed. The power obtained in case of pollution is 183.11 W, while this value is 226.1 W in the panel washed with water. In the panel wiped with a cloth, it is 185.15 W. It is seen that the same situation is also the same for hot spot panels. According to the results obtained on identical panels, pollution reduces power generation by 18.98% and a temperature difference of 19.9℃ is observed in temperature measurements made with a thermal camera. This situation shows that the pollution negatively affects both the surface temperature and the power generation by preventing the irradiation from reaching the panel in a healthy way. This situation emphasises that the way of cleaning the panel is also important.

In partial shading conditions, it is seen that the dirty panel produces the lowest power with 9.6 W. In the panel cleaned by washing with water, the highest power value of 12.6 W was obtained. According to the results obtained in the case of partial shading for general evaluation, power generation decreases by approximately 94% for all cases. Therefore, the panels should be placed by considering the shading situation when placing the panels. In addition, when constant shading occurs, the panel structure deteriorates due to the inoperability of the production points on the panel and the imbalances on the panel. It may even cause hot spot failures. Both shading and high surface temperature accelerate the deterioration of the structure of PV panels. In this article, hot spot failure panels, another important condition affecting panel efficiency, are also analyzed. As a result of the analyses performed on the panel with hot spot failure detected by the thermal camera, it is observed that the power generation decreased by 6.9%. Especially when large power PV systems are considered, this rate is an emergency situation to be solved as it reduces efficiency by negatively affecting the entire power generation. According to the results of the study, it is concluded that to prevent this situation, the PV panels are checked with a thermal camera, the defective panels are removed from the system, and the pollution is periodically washed to minimize energy losses.

## 5. ACKNOWLEDGMENTS

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