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Araştırma Makalesi / Research Article

Evaluation of Photovoltaic Panel Power Generation Based on Instant Solar Radiation and Meteorological Parameters

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Keywords
Instant solar radiation; Meteorological Parameters; PV Output Power; Efficiency; Photovoltaic

Abstract

The solar radiation incident on the surface of photovoltaic (PV) panels, dependent on the inclination angle, and the temperature of the panels are the most significant parameters affecting power generation. These two parameters are necessary to accurately evaluate the electrical performance by enabling the calculation of cell and module temperatures. In this study, the efficiencies and electrical power behaviors of PV panels positioned towards the sun at a 37° inclination angle in Hakkari province were examined under real solar radiation and ambient temperature values. In addition, the effect of wind speed parameters was also considered, and the impact on panel efficiency and PV panel output power was evaluated. When the results were evaluated, it was confirmed that the effect of wind increases the efficiency of PV panels, resulting in an increasing in PV output power.

Anlık Güneş Işınımı ve Meteorolojik Parametrelere Bağlı Olarak Fotovoltaik Panel Güç Üretiminin Değerlendirilmesi

Anahtar kelimeler
Anlık güneş ışınımı; Meteorolojik parametreler; FV çıkış gücü; Verim; Fotovoltaik

Öz

Fotovoltaik (PV) panel yüzeyine eğim açısına bağlı olarak düşen güneş ışınımı ve panellerin sıcaklığı güç üretimini etkileyen en önemli parametrelerdir. Bu iki parametre hücre ve modül sıcaklık hesaplamalarının yapılmasını sağlayarak elektrik performansını doğru bir şekilde değerlendirmek için gereklidir. Bu çalışmada, Hakkâri ilinde 37° eğim açısı ile güneşe doğru konumlandırılmış PV panellerin gerçek güneş ışınımı ve ortam sıcaklığı değerleri altındaki verimleri ve elektriksel güç davranışları incelenmiştir. Bunun yanı sıra, rüzgâr hızı parametresinin etkisi de dikkate alınarak panel verimleri ve PV panel çıkış gücü üzerindeki etkisi değerlendirilmiştir. Sonuçlar değerlendirildiğinde, rüzgârın etkisinin PV panellerin verimlerini yükselttiği ve buna bağlı olarak PV çıkış gücünün arttığı doğrulanmıştır.

1. Introduction

Solar energy is a renewable energy source that is environmentally friendly and considered the most fundamental energy source on Earth. PV panels, which are widely used today to convert solar radiation into electrical energy, are expected to play a significant role in the future development of sustainable energy. Furthermore, the rapid rise in the installation of PV systems has generated increased research interest in efficiency improvements in recent years.

Solar radiation and temperature are two important parameters that directly affect the power output of PV panels. It is observed that the best performance is achieved when the temperature on the surface of the PV panel is minimal and solar radiation is at its highest level (Al-Ghezi *et al*. 2023, Aoun 2022, Khatib *et al*. 2012). Most of the panels today convert approximately 20% of the incident sunlight into electrical energy. The remaining 80% is converted into heat energy, which causes an increase in the temperature of the PV cells. It is well known that this temperature increase in PV cells plays a crucial role in determining the power conversion efficiency, as it affects the current and voltage values. Even the slightest increase in the level of incident sunlight on the surface of the PV panel significantly increases the current output. However, due to the heat it carries, it also significantly reduces the voltage to a large extent (Aly *et al*. 2019, Ibrahim and Anani 2017, Kazem *et al*. 2020, Skoplaki and Palyvos 2009). The efficiency of a system is measured in terms of its impact on the environment (Malik and Chandel 2021). PV module manufacturers use standard test conditions to measure cell temperature and solar radiation components. These conditions vary and often affect the power output of the modules. (Mustafa *et al*. 2020). Thus, they determine the specifications of their products under standard test conditions (STC) with 1000 W/m^2 solar radiation and a module temperature of 25 °C. In this context, under real operating conditions, the current-voltage characteristics of PV modules can significantly vary depending on solar radiation, ambient temperature, and wind speed (Gokmen *et al*. 2016, Deutsche Gesellschaft für Sonnenenergie 2013). In the literature, studies have been conducted to examine the operational efficiency of PV panels and consequently, the PV panel output power using not only fundamental meteorological parameters such as solar radiation and ambient temperature but also the parameter of wind speed (Skoplaki *et al*. 2008, Koehl *et al*. 2011, Kaplani and Kaplanis 2014, Kaldellis *et al*. 2014, Barroso *et al*. 2016, Obiwulu *et al*. 2020, Aoun 2021, Sun *et al*. 2022, Yolcan and Kose 2023).

In this study, the efficiency and output power of PV panels were calculated using the most commonly used mathematical formulas in the literature, utilizing the measured parameters of solar radiation, ambient temperature, and wind speed in real-world conditions. First, calculations were made using the parameters of solar radiation and ambient temperature, and then the effect of the wind speed parameter on the efficiency and output power of PV panels was examined. The main contributions of this study are as follows:

- ✓ Determining the accuracy of mathematical formulas used in PV power calculation in solar system applications with regional data.
- ✓ Determining the effects of meteorological parameters obtained in real environment on PV panel cell/module temperature, efficiency, and power values.
- ✓ Determining the variation of PV panel cell/module temperature in windy and calm conditions, and assessing the impact of wind-induced temperature changes on efficiency and power generation of PV panels.
- ✓ Examining the seasonal variation of meteorological data and its impact on seasonal power generation of PV panels in the selected region.

In the current article, the effects of varying wind speed conditions on the overall performance of a monocrystalline solar panel were analyzed, considering the parameters of actual solar irradiance and ambient temperature. This study is organized as follows: The mathematical calculation model equations, based on the obtained data, are presented in Section 2. The cell and module temperatures derived from these equations, along with the corresponding PV panel efficiency and power values, are discussed in Section 3. In the final section, the results of the study are presented.

2. Materials and Methods

Throughout the study, meteorological data obtained from the meteorological station of Hakkari University (N:37.571799, E: 43.724936), located in Hakkari province, were used. General methodology of this study is given in Figure 1.

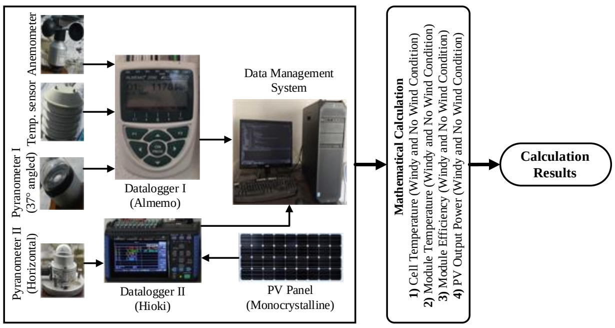

Figure 1. Data management and measurement system.

The experimental setup consists of two pyranometers, placed horizontally and at an inclination of 37°, for measuring solar irradiance. Additionally, there is one temperature sensor for measuring ambient temperature, one anemometer for measuring wind speed, and two dataloggers to record the data from these sensors. The power of the PV panel, which is of monocrystalline technology, is measured through a load resistance connected to its terminals. The experimental setup, measurement sensors, and the specifications of the PV panel for this study are illustrated in Figure 2.

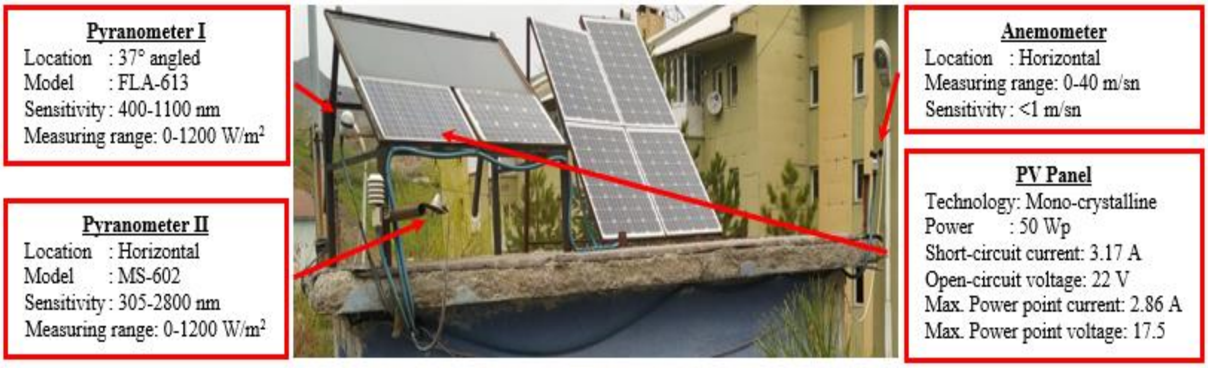

Figure 2. Experimental setup and measurement equipment of Hakkari University meteorological station.

In the meteorological data station, data from the pyranometers, anemometer, and temperature sensor were collected at 1-minute intervals for a one-year period from January 1, 2020, to December 31, 2020. The acquired data was transferred from the datalogger to a computer and stored for further analysis.

2.1 Mathematical Calculation Model

In this section, the most commonly used mathematical models in the literature are provided for calculating the PV panel cell temperature (T_c) and, consequently, the module temperature (T_m)using the measured total solar radiation (I), ambient temperature (T_a) and wind speed (ω_s) data on the surface of a 37° inclined PV panel installed in Hakkari province (latitude 37.57° north). Subsequently, using the calculated parameters, the PV panel efficiency (η_{PV}) and PV panel output power (P_{output}) were determined using mathematical models.

Temperature is an important parameter that directly affects the power output of a PV system. It is dependent on multiple factors, but primarily it is influenced by solar radiation (I), ambient temperature (T_a), and wind speed (ω_s) values (Alsayed *et al*. 2013). The PV module raises the cell temperature above the operational safety limits due to the absorbed direct solar irradiance and ambient temperature. This high temperature leads to a decrease in the electrical efficiency of cell surfaces, resulting in a shortened operational lifespan of PV panels (Ebhota and Tabakov 2023). Equation (1), represents the mathematical model for calculating cell temperature without considering the effect of wind, while Equation (2), represents the mathematical model that takes into account the effect of wind in calculating the cell temperature.

$$T_c = 30 + 0{,}0175 \times (I - 300) + 1{,}14 \times (T_a - 25) \quad (1)$$

$$T_c = 30 + 0{,}0175 \times (I - 300) + 1{,}14 \times (T_a - 25) - k_r \times \omega_s \quad (2)$$

Here, (T_c); represents the PV panel cell temperature (°C), (I); represents the instantaneous solar radiation (W/m^2), and (T_a); represents the ambient temperature (°C). Additionally, (ω_s); represents the wind speed (m/s), and (k_r); is a coefficient that varies for each PV technology. In this study, this coefficient was assumed to be 1.509 for monocrystalline PV technology (Ayaz 2012). The mathematical equation for calculating the module temperature of a solar panel, generated by solar cells, is given in Equation (3) (King *et al*. 2004).

$$T_m = T_c + \left(\frac{I}{I_0}\right) \times \Delta_T \quad (3)$$

In this equation, (I_0); represents the reference solar radiation value, which is assumed to be 1000 W/m^2. (Δ_T); represents the temperature difference between the cell and the back surface of the module under the reference solar radiation. This temperature difference is approximately 2 to 3 °C. In this study, this value was assumed to be 3 (King *et al*. 2004). The most well-known PV panel efficiency, which is dependent on the module temperature, can be calculated as shown in Equation (4).

$$\eta_{PV} = \eta_{STC} \times \left[1 + \beta_{PMP} \times \left(T_m - T_{ref}\right)\right] \times \left[1 + \gamma_{pmp} \times ln\left(\frac{I}{I_0}\right)\right] \quad (4)$$

In Equation (4), (η_{PV}); represents the PV module efficiency (%), (η_{STC}); represents the efficiency determined by the manufacturer under standard test conditions (18.1%), (β_{PMP}); represents the temperature coefficient, and (T_{ref}); represents the reference temperature (25 °C). The (β_{PMP}); coefficient is generally not measured and, according to the IEC 60891 standard, it falls within the range of 0.52% to -0.37% per degree Celsius. In this study, it was selected as -0.39% (Akhsassi *et al*. 2018). (γ_{pmp}); is a coefficient that varies between 3% and 12%, and in this study, it was selected as 4% (Yigit and Arslanoğlu 2021).

A typical PV panel is made up of the combination of different layers. Therefore, there are various losses in each layer. This reduces the amount of incoming sunlight reaching the PV cells. For this reason, it is recommended to take into account the effects of the layers of the PV panel when determining the temperature of the PV cells (Barroso *et al*. 2016). There are also losses referred to as other components that affect system efficiency, such as cables, connections, etc. These losses are represented by the coefficient (η_{other}) in Equation (5), which is assumed to be 93% (Durusu 2016). The output power of a PV panel can be formulated as follows, considering the panel efficiency and solar irradiance intensity:

$$P_{output} = \eta_{PV} \times \eta_{diğer} \times I \quad (5)$$

Here, (P_{output}); represents the PV output power (kW), (η_{PV}); represents the PV module efficiency obtained from Equation (4) (%), (η_{other}); represents the assumed loss efficiency of 0.93, and (I) represents the solar irradiance measured by the pyranometer with a tilt angle of 37 degrees (W/m^2).

3. Results and Discussion

Many PV systems, temperature measurement of PV modules is not available. Therefore, modeling the physical relationships between PV module temperature, solar radiation, ambient temperature, and, where possible, wind speed is desired (Akhsassi *et al*. 2018). In this context, although the effect of low-speed winds is small, it is necessary to investigate the impact of wind data on PV module temperatures due to its influence on both ambient temperature and temperature-dependent PV output power. Figure 3 and Figure 4 show the effects of temperature changes on the environment, cell, and module in windy and no wind conditions, respectively.

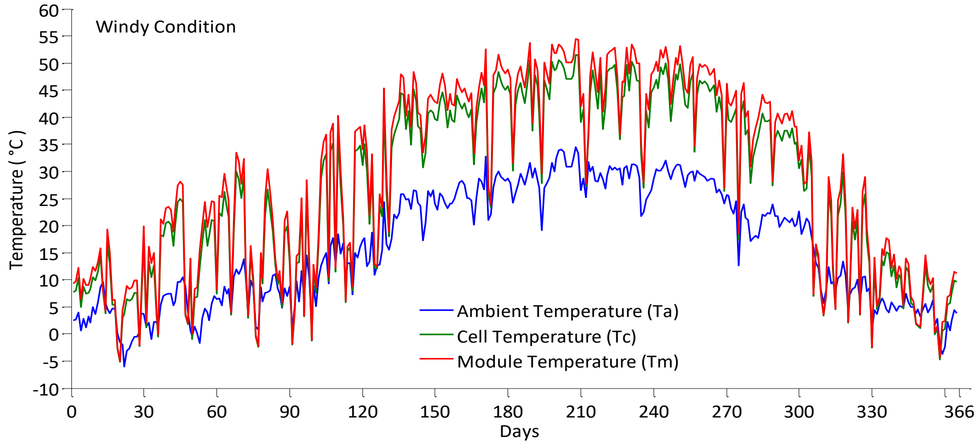

Figure 3. Temperature variations for windy conditions.

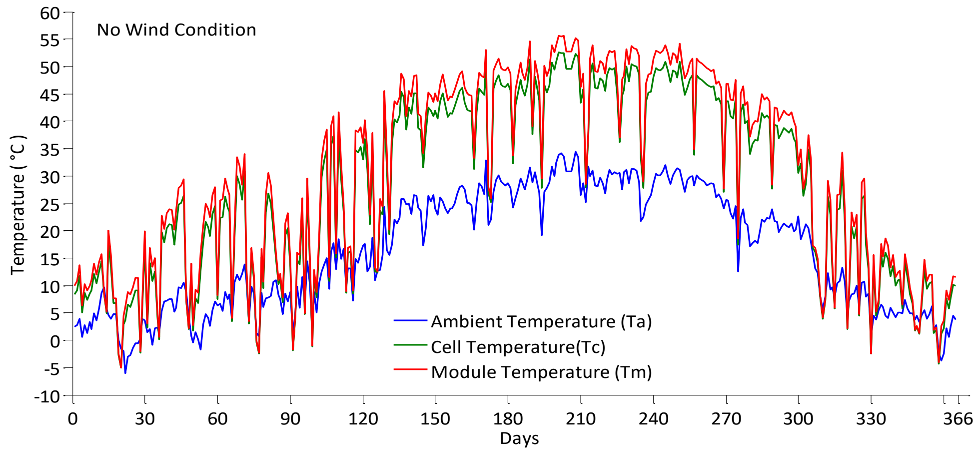

Figure 4. Temperature variations for no wind conditions.

The temperature information of the PV panel is an important parameter for determining its efficiency. This requires the accurate determination of the operating temperatures of the panel at any given time and environmental conditions. When considering irradiance, temperature, and wind speed, it is necessary to include the effect of wind speed on cell temperature in the calculation of PV efficiency in the PV system energy production model. In this context, PV module efficiency has been calculated based on external ambient temperature, solar irradiance, and wind speed. Figure 5, shows the variation in PV module efficiency for windy and windless conditions.

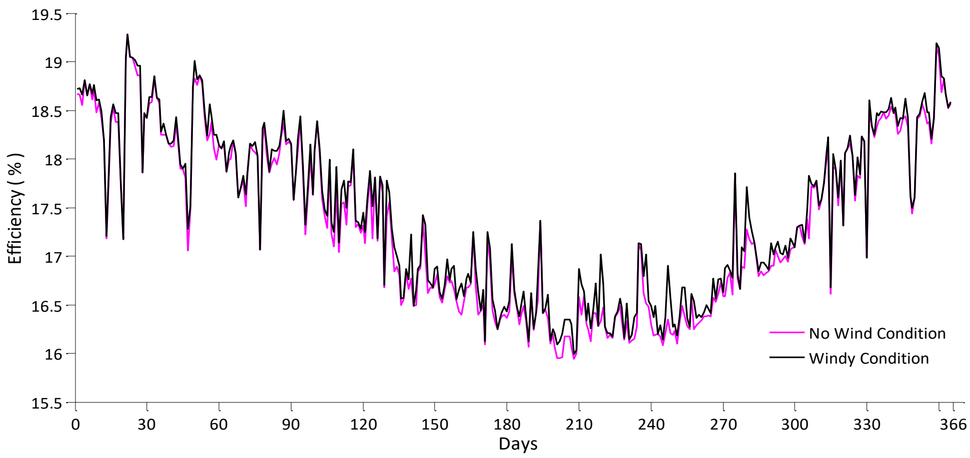

Figure 5. PV Efficiency for windy and no wind conditions

To determine the energy output of a PV panel, it is necessary to calculate the PV cell/module temperature and efficiency. The calculations were performed using instantaneous data for a yearly time period of 366 days. The output power of the PV panel was calculated, taking into account the instantaneous data of solar irradiance and ambient conditions. Figure 6, shows the variation of PV panel output power for windy and windless conditions.

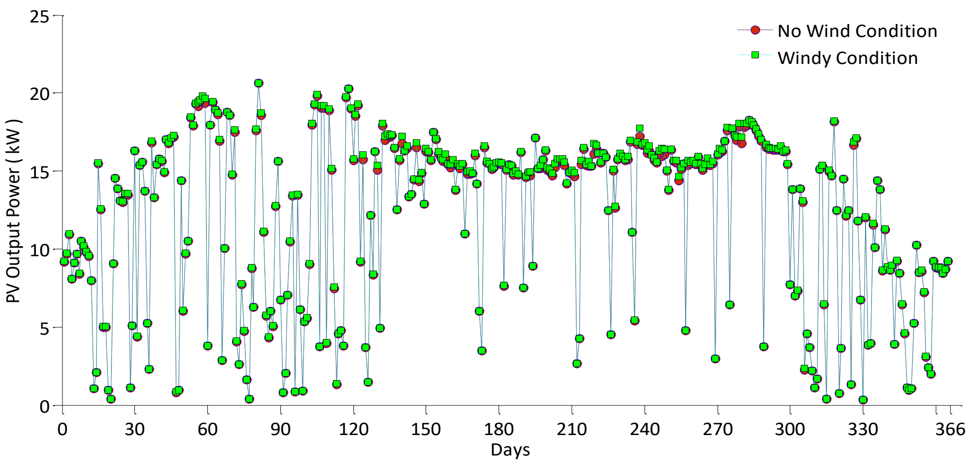

Figure 6. PV output power for windy and no wind conditions

The meteorological parameters obtained in 2020 from the measurement devices positioned on the PV panel inclined at 37° and facing south in Hakkari province are shown in Table 1. The incident radiation values on the PV panel surface placed at the specified angle, along with the calculated panel efficiencies based on wind speed and ambient temperature values, are also provided in this table, along with the generated electrical power values from the panel.

Table 1. Monthly average meteorological data and calculation results

MONTHS	Solar Radiation (I) (W/m²)	Ambient Temp. (T_a) (°C)	Wind Speed (ω_s)	Case Where Wind is Not Considered: Cell Temp. (T_c) (°C)	Module Temp. (T_m) (°C)	Panel Efficiency (η_{PV}) (%)	PV Output Power (P_{output}) (kW)	Case Where Wind is Considered: Cell Temp. (T_c) (°C)	Module Temp. (T_m) (°C)	Panel Efficiency (η_{PV}) (%)	PV Output Power (P_{output}) (kW)
January	506,87	2,15	0,40	7,58	9,10	18,49	8,80	6,97	8,49	18,53	8,82
February	813,10	4,36	0,70	15,45	17,89	18,28	13,84	14,39	16,83	18,35	13,90
March	653,61	7,93	0,47	16,72	18,68	17,99	10,92	16,01	17,97	18,04	10,95
April	631,20	11,45	0,80	20,35	22,25	17,64	10,28	19,14	21,04	17,72	10,33
May	896,39	20,70	1,04	35,54	38,23	17,01	14,12	33,98	36,67	17,12	14,22
June	950,50	26,35	0,90	42,92	45,77	16,57	14,62	41,56	44,41	16,67	14,71
July	931,35	29,39	1,05	46,05	48,84	16,33	14,11	44,47	47,27	16,44	14,21
August	958,52	28,94	1,26	46,01	48,89	16,35	14,55	44,11	46,99	16,48	14,68
September	971,00	28,31	1,20	45,52	48,43	16,39	14,79	43,71	46,62	16,52	14,91
October	957,16	20,63	0,90	36,52	39,39	17,01	15,11	35,16	38,03	17,10	15,20
November	509,67	8,93	0,67	15,35	16,88	17,81	8,50	14,34	15,87	17,87	8,53
December	429,77	3,67	0,56	7,96	9,25	18,41	7,40	7,11	8,40	18,47	7,42

In this table, in cases where the radiation values are low, the electrical generation capacity of PV panels is at a high level due to the low ambient temperature. In this context, it is observed that efficiency is significantly affected during the winter months in Hakkari province. On the other hand, during the summer months, despite the high cell/module temperature due to high solar radiation values and ambient temperatures, an increase in PV panel electrical power production was observed. In cases where wind speed has an effect, this leads to a decrease in cell/module temperature, resulting in an increase in efficiency and PV panel output power. The PV panels electrical power generated remains approximately constant during the summer months.

In this study, the effect of wind on the PV panel output power level has also been investigated. The amounts of electrical power generated by the PV panel at different wind speeds at the measurement point throughout the year 2020 are shown in Table 1. The calculation was performed with an inclination angle of 37°. The monthly PV panel powers obtained using the calculated efficiency values based on daily temperature values are presented in this table. In this table, when the wind speed is taken into account, the power generated by the PV panel varies only slightly. However, in cases where the wind speed is high, albeit to a small extent, the PV panel cell/module temperature decreases, resulting in an increase in the PV output power. In these regions, it is considered more favorable to prefer windier areas for the installation of PV power plants.

4. Conclusion

This study involves evaluations for the calculation of cell/module temperature, efficiency, and output power of a monocrystalline PV panel installed at 37° inclination angle in Hakkari province, characterized by harsh winters and mild summers. The calculation models utilize meteorological data parameters such as solar radiation and ambient temperature. In addition to these parameters, the effect of wind speed parameters has been included in the mathematical calculations and investigated.

The electrical performance of a PV panel varies inversely with operating temperature. Therefore, in this study, the calculation of the PV panel's cell/module temperature and its impact on the power performance under different meteorological conditions were examined. In this case, for every increase in ambient temperature, the temperature of PV cells also increases approximately at the same rate. At the same time, an increase in solar radiation also leads to a significant increase in cell temperature. Each increase of 50 W/m^2 in solar radiation causes a temperature change of approximately 5 °C in the cell. Changes in wind speed do affect the cell/module temperature of the PV panel, but the rate at which temperature decreases with wind speed is not balanced. However, especially in windy areas such as hills and mountains, the contribution of wind speed should not be overlooked. In addition, this study is important in terms of providing fundamental data that can serve as a comprehensive roadmap for future solar energy projects. Considering the findings of this study can be beneficial for companies planning to invest in systems based on electricity generation from solar energy.

5. References

Akhsassi, M., El Fathi, A., Erraissi, N., Aarich, N., Bennouna, A., Raoufi, M. and Outzourhit, A., 2018. Experimental investigation and modeling of the thermal behavior of a solar PV module. *Solar Energy Materials and Solar Cells*, **180**, 271-279.

Al-Ghezi, M. K., Ahmed, R. T., Chaichan, M. T., 2022. The Influence of Temperature and Irradiance on Performance of the photovoltaic panel in the Middle of Iraq. *International Journal of Renewable Energy Development*, **11(2)**, 501.

Alsayed, M., Cacciato, M., Scarcella, G. and Scelba, G., 2013. Multicriteria optimal sizing of photovoltaic-wind turbine grid connected systems. *IEEE Transactions on energy conversion*, **28(2)**, 370-379.

Aly, S. P., Ahzi, S. and Barth, N., 2019. Effect of physical and environmental factors on the performance of a photovoltaic panel. *Solar Energy Materials and Solar Cells,* **200**, 109948.

Aoun, N., 2021. Outdoor testing of free standing PV module temperature under desert climate: a comparative study. *International Journal of Ambient Energy*, **42(13)**, 1484-1491.

Aoun, N., 2022. Methodology for predicting the PV module temperature based on actual and estimated weather data. *Energy Conversion and Management: X*, **14**, 100182.

Ayaz, R., 2012. Modeling of the different PV technologies using real environmental datum and determination of optimum tilt angles for Istanbul. MSc. Thesis, Yildiz Technical University Graduate School Of Natural And Applied Science, Istanbul, 72.

Barroso, J. S., Barth, N., Correia, J. P. M., Ahzi, S. and Khaleel, M. A., 2016. A computational analysis of coupled thermal and electrical behavior of PV panels. *Solar Energy Materials and Solar Cells*, **148**, 73-86.

Deutsche Gesellschaft für Sonnenenergie (DGS), 2013. Planning and installing photovoltaic systems: a guide for installers, architects and engineers. *Routledge*.

Durusu, A., 2016. A new approach for photovoltaic solar plant design and site optimization. PhD. Thesis, Yildiz Technical University Graduate School Of Natural And Applied Science, Istanbul, 136.

Ebhota, W. S., & Tabakov, P. Y., 2023. Influence of photovoltaic cell technologies and elevated temperature on photovoltaic system performance. *Ain Shams Engineering Journal*, **14(7)**, 101984.

Gokmen, N., Hu, W., Hou, P., Chen, Z., Sera, D. and Spataru, S., 2016. Investigation of wind speed cooling effect on PV panels in windy locations. *Renewable Energy*, **90**, 283-290.

Ibrahim, H. and Anani, N., 2017. Variations of PV module parameters with irradiance and temperature. *Energy Procedia*, **134**, 276-285.

Kaldellis, J. K., Kapsali, M. and Kavadias, K. A., 2014. Temperature and wind speed impact on the efficiency of PV installations. Experience obtained from outdoor measurements in Greece. *Renewable Energy*, **66**, 612-624.

Kaplani, E. and Kaplanis, S., 2014. Thermal modelling and experimental assessment of the dependence of PV module temperature on wind velocity and direction, module orientation and inclination. *Solar Energy*, **107**, 443-460.

Kazem, H. A., Al-Waeli, A. H., Chaichan, M. T., Al-Waeli, K. H., Al-Aasam, A. B., & Sopian, K., 2020. Evaluation and comparison of different flow configurations PVT systems in Oman: A numerical and experimental investigation. *Solar Energy*, **208**, 58-88.

Khatib, T., Mohamed, A. and Sopian, K., 2012. A review of solar energy modeling techniques. *Renewable and Sustainable Energy Reviews*, **16(5)**, 2864-2869.

King, D. L., Kratochvil, J. A. and Boyson, W. E., 2004. Photovoltaic array performance model. *United States Department of Energy*, **8**, 1-19.

Koehl, M., Heck, M., Wiesmeier, S. and Wirth, J., 2011. Modeling of the nominal operating cell temperature based on outdoor weathering. *Solar Energy Materials and Solar Cells*, **95(7)**, 1638-1646.

Malik, P., Chandel, S. S., 2021. A new integrated single-diode solar cell model for photovoltaic power prediction with experimental validation under real outdoor conditions. *International Journal of Energy Research*, **45(1)**, 759-771.

Mustafa, R. J., Gomaa, M. R., Al-Dhaifallah, M., Rezk, H., 2020. Environmental impacts on the performance of solar photovoltaic systems. *Sustainability*, **12(2)**, 608.

Obiwulu, A. U., Erusiafe, N., Olopade, M. A. and Nwokolo, S. C., 2020. Modeling and optimization of back temperature models of mono-crystalline silicon modules with special focus on the effect of meteorological and geographical parameters on PV performance. *Renewable Energy*, **154**, 404-431.

Skoplaki, E., Boudouvis, A. G.and Palyvos, J. A., 2008. A simple correlation for the operating temperature of photovoltaic modules of arbitrary mounting. *Solar energy materials and solar cells*, **92(11)**, 1393-1402.

Skoplaki, E. and Palyvos, J. A., 2009. On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations. *Solar energy*, **83(5)**, 614-624.

Sun, C., Zou, Y., Qin, C., Zhang, B., Wu, X., 2022. Temperature effect of photovoltaic cells: a review. *Advanced Composites and Hybrid Materials*, **5(4)**, 2675-2699.

Yigit and Arslanoğlu, N., 2021. Anlık işinim şiddeti ve çevresel faktörlere bağlı optimum PV panel açısı, verim, güç üretiminin incelenmesi. *Uludağ Üniversitesi Mühendislik Fakültesi Dergisi*, **26(1)**, 301-314.

Yolcan, O. O., Kose, R., 2023. Photovoltaic module cell temperature estimation: Developing a novel expression. *Solar Energy*, **249**, 1-11.