IoT-Based Monitoring System for Solar Photovoltaics' Parameter Analysis and Prediction

Muhammad Afifuddin Pozi, Heng Siong Lim, Boon Kian Lim(✉), and Kia Wai Liew

Faculty of Engineering and Technology, Multimedia University, Melaka, Malaysia
bklim@mmu.edu.my

Abstract. A popular alternative to using fossil fuels to generate power is to use a photovoltaic (PV) system. However, the efficiency of PV system is very sensitive to the environmental conditions and frequent maintenance is needed to achieve the best performance. In practice, data of both the surrounding environment and the PV system need to be collected simultaneously to monitor the status and also to characterize the performance of the system. But this cannot be done manually as the PV system is commonly placed at remote or hard-to-reach places. To address this problem, an IoT based solar photovoltaic monitoring system is designed and developed in this project. ESP32 is used as the core processing unit. Several sensors such as temperature, solar irradiation, current and voltage sensors are used for data collection. An IoT cloud server is used to store and display the data. The measurement results show satisfactory accuracy and reliability of the system. Further data analysis of the collected high temporal resolution sensor data reveals substantially different correlations of the parameters in three different weather conditions during non-rainy days, namely cool and cloudy, moderately hot and sunny, and very hot and sunny. A support vector machine (SVM) regression is proposed to predict the PV panel temperature and the result is compared to the conventional least square regression. Improved prediction performance is observed especially for the very hot and sunny scenario.

Keywords: Solar PV monitoring system · Internet of Things (IoT) · PV panel temperature · Support vector machine regression

1 Introduction

The over dependency on fossil fuels may cause the depletion of electricity generation resources for the use of our future generation. This makes the renewable energy resources such as solar energy, wind energy and hydroelectric energy become the crucial part of the efforts to lower down the dependency on fossil fuels as they can be produced in a sustainable manner. Solar energy is one of the most important renewable energies used around the world. Solar photovoltaic (PV) system is used to generate energy from the sunlight. The performance of the PV panel used is very sensitive to the environmental conditions and it determines the power that can be generated from the panel. So, optimization and

M. Y. bin Alias (Ed.): MECON 2022, AER 214, pp. 401–412, 2023.
https://doi.org/10.2991/978-94-6463-082-4_35

maintenance of the PV system are crucial to get the best out of the installed PV system. Solar PV systems are normally installed in hard-to-access areas. Manual collection of data for monitoring and analyzing the condition and performance of the PV cells can be costly and time consuming. To overcome this challenge, an Internet-of-things (IoT) based monitoring system is a promising solution.

The output power or efficiency of a solar PV system is mostly governed by environmental factors such as solar intensity, operating temperature of the solar cells, and sunlight direction [1]. Aside from climatic and operating factors, various technological factors can also influence the amount of electricity generated by a PV system such as the type of solar cell employed. Monitoring the parameters of a solar PV system is important for measuring the system's performance and efficiency, promptly identifying possible issues, and troubleshooting problems before the system suffers loss. Output current and voltage, operating temperature of the PV panel, soiling on PV panel and weather conditions are some of the commonly measured and monitored parameters [2].

1.1 Previous Work

In the literature, there are many low-cost IoT-based monitoring system developed for measuring and logging the parameters of solar PV system and also the environmental conditions such as those reported in [3–7]. These systems mainly consist of 4 components: Sensors, microcontroller and interfacing, wireless connectivity, as well as cloud server. The data collected are normally used for PV system condition monitoring, performance optimization, and for characterizing the correlation between the different parameters [8].

PV panel temperature is one of the most important factors affecting the performance of the PV system under real operating conditions. However, long-term and large-scale accurate measurement of the PV panel temperature could be challenging because of the high-cost sensor and the requirement of good thermal coupling. Hence, there is a need to predict the instantaneous value of solar PV panel temperature. For IoT applications, due to the limited computing and storage resources, low complexity approach is preferred. Various theoretical and empirical models had been proposed for this purpose but they are mostly rigid physics-based models or linear regression models based on small datasets with time resolution of days, hours, or even minutes [9–11].

In this work, a support vector machine (SVM) regression is proposed to predict solar PV panel temperature based on high temporal resolution real measurements of ambient temperature, solar irradiance, and output power.

2 System Development

In this work, the developed solar PV monitoring system has two parts: the power system and data collection part. The power system part consists of a solar panel, a pulse width modulation (PWM) solar charge controller and a rechargeable battery. An 18 V 30 W polycrystalline solar panel with dimensions 600 × 350 × 17 mm is used. The output power from the solar panel charges the battery and power the whole system. The solar charge controller acts as controller and switches the power source between solar panel and battery depending on the battery's current capacity. A 12 V sealed lead acid battery with capacity of 7.2 AH is used. Figure 1 shows the hardware components of the monitoring system.

The data collection part of the system consists of the sensors and the controller. The sensors used are voltage sensor, current sensor, surrounding temperature sensor, solar panel temperature sensor and solar irradiation sensor. The solar irradiation sensor has a spectral range of 0.3–3 μm. It is capable of measuring in the range 0–800 W/m^2 with a resolution of 1 W/m^2. A waterproof digital temperature sensor capable of measuring −55 to 125 °C with a precision of ±0.5 °C is used for measuring the temperature of the solar panel. An ambient temperature sensor mounted in a ventilated shield is used for measuring the surrounding temperature.

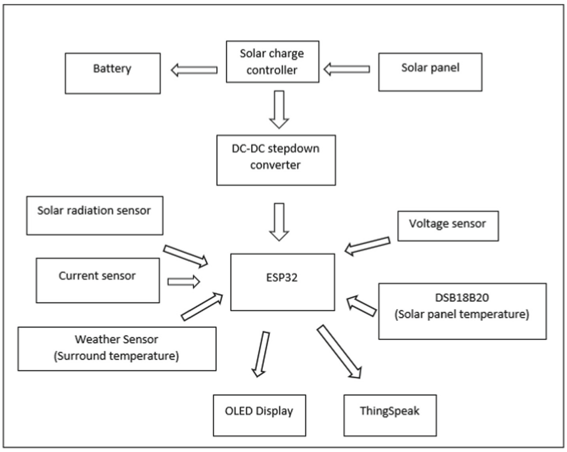

Fig. 1. Hardware Components

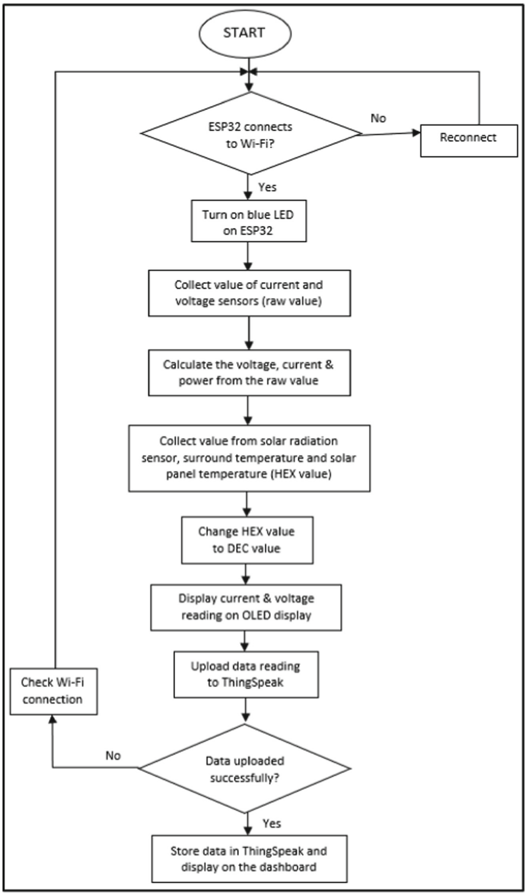

Fig. 2. Flowchart of Data Collection

A NodeMCU Esp32 module is used as the controller of the system. It has the capability of connecting to the Wi-Fi network for uploading data to the internet. The controller collects data from all the sensors in the system, performs the required data conversion and calculation, and uploads the data to a cloud server (ThingSpeak) for storing and display. Figure 2 shows the flowchart of the data collection process.

Figure 3 shows the developed solar PV monitoring system. To ensure that the system is able to operate under all weather conditions, those non waterproof components are placed in and protected with a weatherproof enclosure (see Fig. 4).

Fig. 3. Developed System

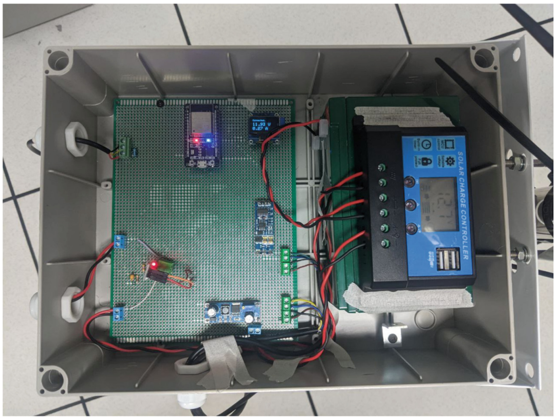

Fig. 4. Components in the Weatherproof Box

3 Result and Discussion

3.1 Accuracy of Measured Current, Voltage and Temperature Values

The accuracy of the sensor reading is important to make sure the performance and reliability of the solar PV monitoring system are verified before the data collection is started. The data received by ThingSpeak are compared to the values of the reading on a measurement instrument. The output current and voltage are measured using a multimeter. Ten sets of data have been taken and recorded for both voltage and current. The mean squared error of the voltage reading is 0.04874 and the average accuracy is around 94.23%. The error may be due to the heat loss at the resistor of the voltage sensor. The mean squared error for the current reading is quite low at around 0.000428 and the average accuracy is around 94.23%. The small error may be caused by the disturbance at the sensor by other electromagnetic force exist around the connection as the ACS712 current sensor is a linear sensor based on the Hall-effect. Temperature detected is also compared with a measurement instrument to assess the accuracy of the data. An infrared thermometer is used to compare the reading of the solar PV panel's temperature with that of the DS18B20 temperature sensor. Ten sets of data have been recorded and compared with the temperature data uploaded. The mean squared error for temperature is 0.69. This shows the value read from the temperature sensor is reliable with average accuracy of 97.84%.

3.2 Analysis of Data

The developed IoT-based solar PV monitoring system was set up in an open area for data collection. The collection of the data started from around 9:00 am to 5:00 pm with the system connected to the Wi-Fi network. The data were uploaded to the ThingSpeak platform for every 15 s interval throughout the day and then downloaded for analysis. Some collected data are presented and analysed in this section to gain insight about the relationship between the environmental conditions and the power generated by the solar PV panel.

Table 1 shows the summary of the data collection work done for 14 days during the non-rainy days. The minimum and maximum measured panel temperatures are also given. Figure 5 shows the data collected during a typically cool and cloudy day.

Table 1. Data collection during clear days

Data	Date	Weather Condition	Temp (°C) Min-Max
1	20/2/2022	Moderately hot & sunny	33.0–52.3
2	22/2/2022	Moderately hot & sunny	30.6–39.4
3	26/2/2022	Cool & cloudy	28.3–31.5
4	27/2/2022	Cool & cloudy	30.0–39.5
5	28/2/2022	Moderately hot & sunny	29.9–42.4
6	04/3/2022	Cool & cloudy	28.7–34.6
7	06/3/2022	Cool & cloudy	26.1–44.9
8	07/3/2022	Cool & cloudy	30.4–38.2
9	08/3/2022	Moderately hot & sunny	31.8–46.4
10	11/3/2022	Moderately hot & sunny	30.5–52.4
11	12/3/2022	Moderately hot & sunny	30.0–50.0
12	13/3/2022	Moderately hot & sunny	32.0–53.6
13	17/3/2022	Moderately hot & sunny	30.7–52.8
14	19/3/2022	Very hot & sunny	28.4–60.1

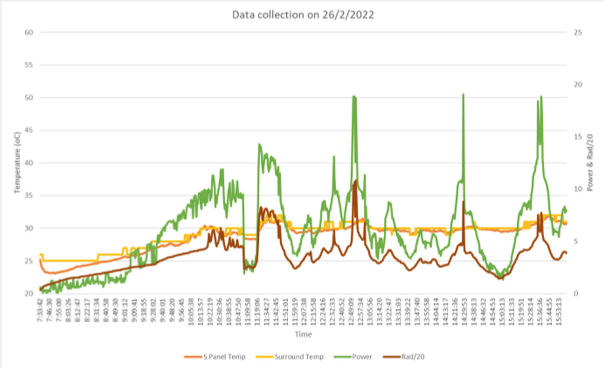

Fig. 5. Typical data during a cool and cloudy day

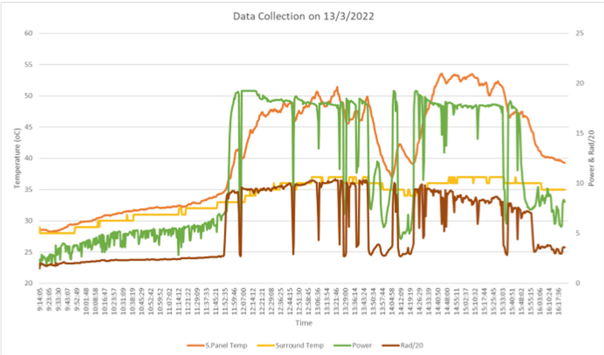

Fig. 6. Typical data during a moderately hot and sunny day

The ambient temperature of the day was relatively low which shows that day was not really sunny and hot. The maximum ambient temperature was around 32 °C. The solar irradiation also seems to be fluctuating due to the occasional sunny intervals. The relationship between the generated power and the solar irradiation can be clearly seen as the output power follows closely the trend of the solar irradiation value.

The data for a moderately hot and sunny is shown in Fig. 6. The solar irradiation value was quite consistently at the high value during the time 12.00 pm to 1.40 pm and 2.30 pm to 4.00 pm. The recorded solar panel temperature is quite high with the maximum at around 55 °C. The maximum ambient temperature was about 37 °C. The maximum solar irradiation value of the day was around 208 W/m^2. The fluctuation in the solar irradiation happened because of the shade made by the clouds that sometimes blocked the sunlight. The data collected shows the clear relationship between the solar irradiation and power generated.

Figure 7 shows the data collected during a very hot and sunny day.

The ambient temperature of the day shows the day during data collection was very hot with maximum ambient temperature of 38 °C at around 12.40 am. The solar irradiation

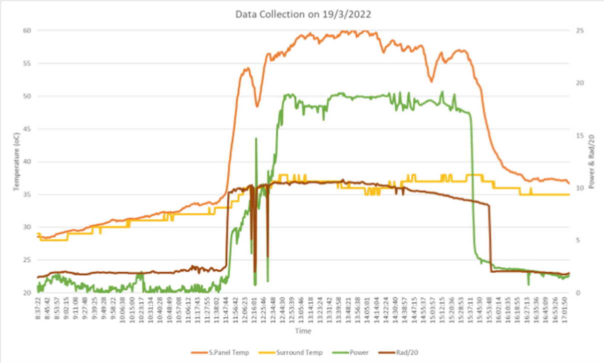

Fig. 7. Typical data during a very hot and sunny day

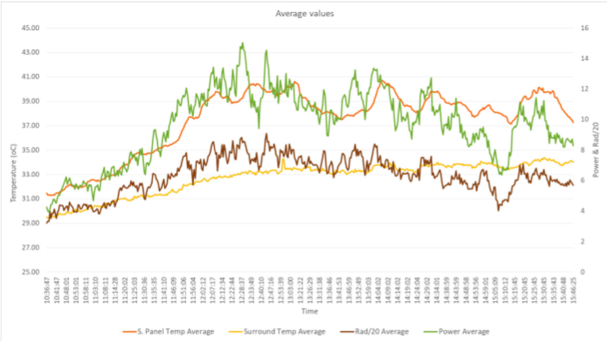

Fig. 8. Average values of the measured data

was very high and consistent from around 11.30 am to 3.50 pm. The long duration of sunlight exposure during the hot day heated up the solar panel substantially. It can be seen the solar PV panel achieved maximum temperature of 60.1 °C.

The average values of the data collected during the 14 days are calculated and plotted in Fig. 8.

3.3 Prediction of PV Panel Temperature

The data collected during the different weather conditions shows that the characteristics and correlations between the parameters are weather dependent and may not be linearly proportional to each other. Figures 9, 10 and 11 characterize the relationships between the panel temperature versus ambient temperature, solar irradiance, and output power respectively for three different types of weather conditions, namely cool and cloudy (cool), moderately hot (moderate) and sunny and very hot and sunny (hot).

Positive correlations are observed between the PV panel temperature and the other three parameters. This confirms that the data of ambient temperature, solar irradiance and output power are useful for predicting the PV panel temperature value. Nevertheless, the

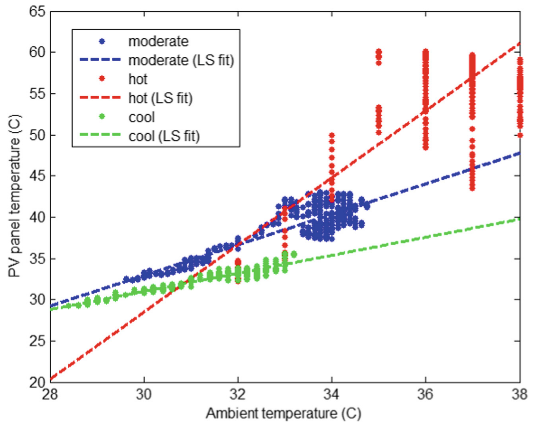

Fig. 9. PV panel temperature versus ambient temperature

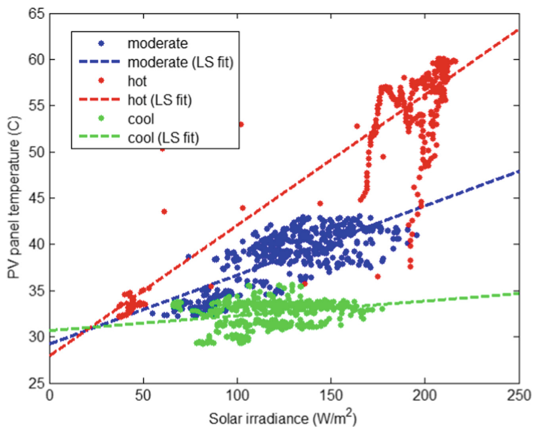

Fig. 10. PV panel temperature versus solar irradiance

correlations are dependent on weather condition and may not be properly characterized by linear regression.

In this work, a low-complexity SVM regression approach using a Gaussian kernel function is proposed to predict the temperature of PV panel using the ambient temperature, solar irradiance and output power. Figure 12 compares the measurement data for 4 days and the predicted temperature values using linear least squares (LS) regression and the proposed SVM regression.

The linear regression works well for low to moderate temperature scenarios but performs poorly for very hot and sunny weather condition. This may be due to the relationship between PV panel temperature and the other three parameters in high temperature are no longer linear. The prediction mean squared errors (MSE) of the proposed method and the LS method are 10.09 and 22.87 respectively.

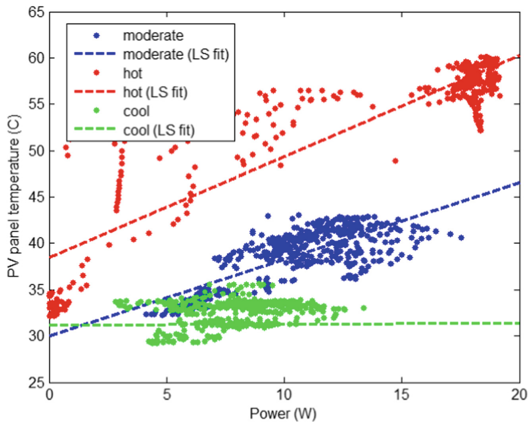

Fig. 11. PV panel temperature versus output power

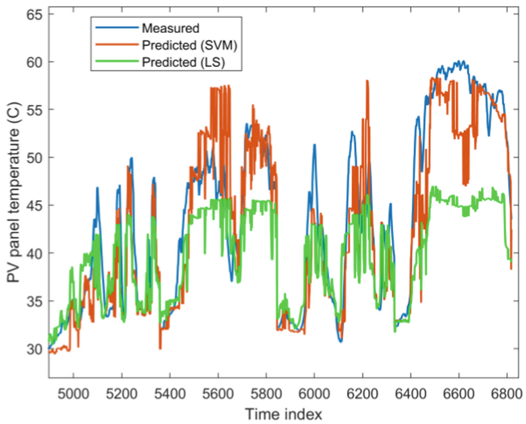

Fig. 12. Prediction of solar PV panel temperature

4 Conclusion

An IoT-based monitoring system has been developed for solar PV system in this work. The measured sensor data are validated using standard measurement instruments with low mean square error. The readings from the voltage and current sensor have average accuracy of 98.53% and 94.23% respectively. The data from the temperature sensor used for measuring the PV panel temperature is found to have 97.39% average accuracy. A data collection campaign had been conducted from around 9:00 am to 5:00 pm for 14 non-rainy days. The data were uploaded to a cloud server for every 15 s interval throughout the day and then downloaded for analysis. The collected datasets are categorized according to three weather conditions – cool and cloudy, moderately hot and sunny, and very hot and sunny. Detailed data analysis of the measured parameter data reveals substantially different correlations of the parameters in the three different weather conditions. Due to this, the conventional LS regression based PV temperature prediction method works well for low to moderate temperature scenarios but performs poorly for very hot and sunny weather condition. A low-complexity SVM regression approach using a Gaussian kernel function is therefore proposed to predict the temperature of PV panel using the ambient temperature, solar irradiance and output power. Improved prediction performance is observed especially for the very hot and sunny scenario. For future work, other environmental sensors such as air humidity and wind sensors can be added to the current system and more datasets can be gathered for better analysis and modelling.

Acknowledgement. This work was supported by Multimedia University through the Internal Research Fund MMUI/210116.

References

1. K. Hasan, SB. Yousuf, MSHK. Tushar, BK. Das, P. Das, MS. Islam, "Effects of different environmental and operational factors on the PV performance: A comprehensive review." Energy Sci Eng. 10: 656–675, 2022 https://doi.org/10.1002/ese3.1043
2. R.J. Mustafa, M.R. Gomaa, M. Al-Dhaifallah, H. Rezk, "Environmental Impacts on the Performance of Solar Photovoltaic Systems," Sustainability, 12, 608, 2020. https://doi.org/10.3390/su12020608
3. M. Gopal, T. Chandra Prakash, N. Venkata Ramakrishna, and B. P. Yadav, "IoT Based Solar Power Monitoring System," in IOP Conference Series: Materials Science and Engineering, Dec. 2020, vol. 981, no. 3. https://doi.org/10.1088/1757-899X/981/3/032037.
4. R. F. Gusa, W. Sunanda, I. Dinata, and T. P. Handayani, "Monitoring System for Solar Panel Using Smartphone Based on Microcontroller," in Proceedings - 2018 2nd International Conference on Green Energy and Applications, ICGEA 2018, May 2018, pp. 79–82. https://doi.org/10.1109/ICGEA.2018.8356281.
5. S. Adhya, D. Saha, A. Das, J. Jana, and H. Saha, "An IoT based smart solar photovoltaic remote monitoring and control unit," in 2016 2nd International Conference on Control, Instrumentation, Energy and Communication, CIEC 2016, Jul. 2016, pp. 432–436. https://doi.org/10.1109/CIEC.2016.7513793.
6. K. Tamilselvi, E. Jananandhini, and N. Vijayakumar, "Design and Implementation of IoT Enabled Smart Solar Power Monitoring System," International Journal of Advanced Research Trends in Engineering and Technology (IJARTET), vol. 6, 2019,
7. N. A. Anang Othman et al., "The Development of IoT-based Solar Battery Monitoring System," in Proceedings - 2021 IEEE Regional Symposium on Micro and Nanoelectronics, RSM 2021, Aug. 2021, pp. 34–37. https://doi.org/10.1109/RSM52397.2021.9511610.
8. Louwen, A., de Waal, A. C., Schropp, R. E. I., Faaij, A. P. C., and van Sark, W. G. J. H. M. (2017) Comprehensive characterisation and analysis of PV module performance under real operating conditions. Prog. Photovolt: Res. Appl., 25: 218–232. https://doi.org/10.1002/pip.2848.
9. G. Ciulla, V. L. Brano, V. Franzitta, M. Trapanese, "Assessment of the Operating Temperature of Crystalline PV Modules Based on Real Use Conditions", International Journal of Photoenergy, vol. 2014, Article ID 718315, 11 pages, 2014. https://doi.org/10.1155/2014/718315

10. S. Kaplanis, and E. Kaplani, “A New Dynamic Model to Predict Transient and Steady State PV Temperatures Taking into Account the Environmental Conditions.” Energies, 12, 2. 2019 https://doi.org/10.3390/en12010002
11. H. Akdemir, M. Böcu and I. Nakir, “The Experimental Assessment of Different PV Cell Temperature Models Under The Actual Climatic Conditions for Cd-Te PV Modules,” 2021 IEEE PES Innovative Smart Grid Technologies - Asia (ISGT Asia), 2021, pp. 1–5, https://doi.org/10.1109/ISGTAsia49270.2021.9715678.