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Research Article

Performance Investigation of Tempered Glass-Based Monocrystalline and Polycrystalline Solar Photovoltaic Panels

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Solar photovoltaic (PV) converts sunlight into electricity and is an appropriate alternative to overcome the depletion of conventional fuels and global warming issues. The performance of a PV panel may vary with respect to PV cell technology, fabrication methods, and operating conditions. This research aims at performing an experimental study to investigate the electrical performance of novel tempered glass-based PV panels using two different types of solar cells: monocrystalline and polycrystalline. Tempered glass-based panels are modified forms of commercial PV panels, in which ethylene-vinyl acetate (EVA) and Tedlar are not utilized. This new fabrication method was carried out in this research. Real-time data recordings regarding the PV electrical characteristics (I-V curve) and solar irradiance were conducted under Malaysian weather conditions on clear sunny days. Results indicated that, at solar irradiance of 900 W/m^2, the outputs from the fabricated polycrystalline and monocrystalline PV panels were 67.4 W and 75.67 W, respectively. However, at the highest average solar irradiance (634.61 W/m^2), which was obtained at 12:30 PM, the outputs from both panels were 47.87 W and 54.89 W. An I-V curve was obtained for the real-time weather. The electrical efficiencies of the two PV panels were analyzed to be 10.54% and 12.23%.

1. Introduction

Global warming is currently one of the most concerning issues caused by greenhouse gas (GHG) in the atmosphere. Generally, there exists a direct relationship between global warming and energy consumption. As stated by the U.S. Energy Information Administration 2017, world energy consumption would escalate by 5% between 2016 and 2040 [1]. Energy can be produced from different means, yet the most compromising ones are renewable energies. Renewable energies are considered clean and sustainable energy sources that are utilized to minimize both secondary waste and environmental impacts by providing an excellent opportunity for GHG mitigation via substituting conventional fossil-burning energy [2].

The adoption of clean, alternative, and sustainable energy sources is being driven by energy demand and environmental concerns in the globe [3]. Solar energy is one of the examples where energy is free and direct and that both sunlight and heat are absorbed and employed by humans and the environment. Solar energy can be applied with various benefits. In solar thermal collector (STC) systems, the energy from the sunbeam is right transformed into heat or thermal energy, one form of which can be applied as industrial process heat [4, 5]. In solar photovoltaic (PV) systems, moreover, solar energy is generated to electricity via solar PV cells, which are the minimal part of solar PV panels. Solar PV module or panel produces direct current (DC) electricity when the solar rays strike the surface of the panel.

The photovoltaic cell, which is the fundamental component of PV panels, may be categorized as crystalline silicon, thin-film, organic and polymer, hybrid PV cell, dye-sensitized, and new technologies including carbon nanotubes (CNT), quantum dots, and hot carrier solar cells. In the crystalline silicon group, cell technologies include

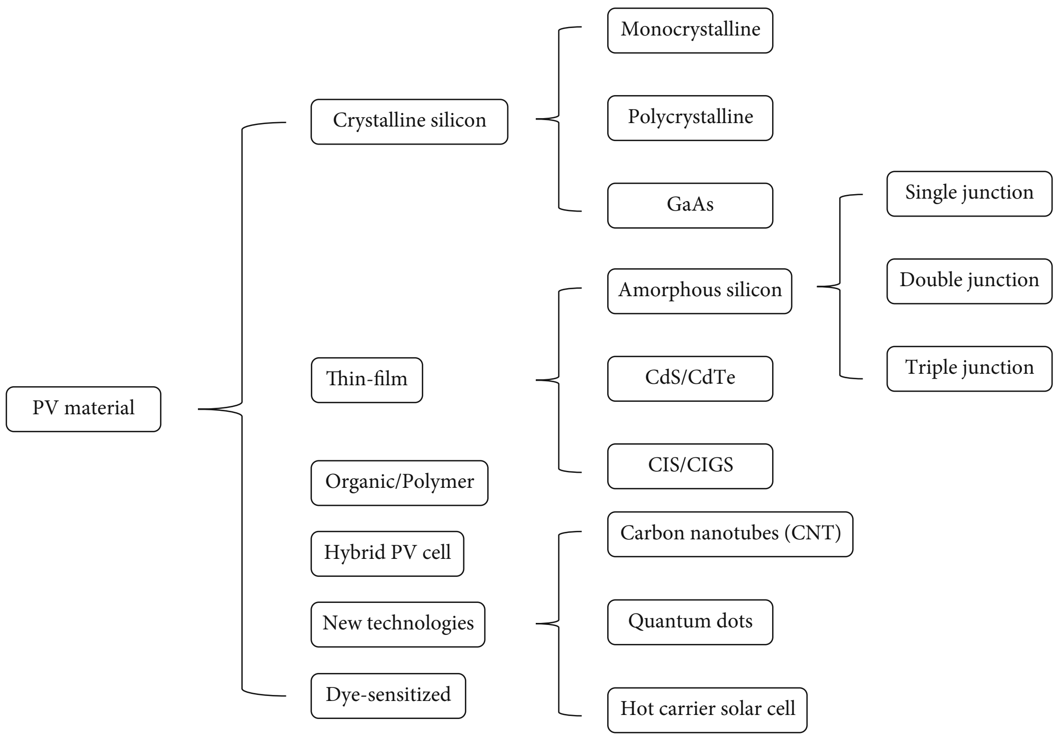

Figure 1: Different PV cell technologies [6].

monocrystalline, polycrystalline, and gallium arsenide (GaAs). In the amorphous silicon group, however, the cell technologies consist of single, double, and triple junction types. Figure 1 shows the chart of different PV cell technologies.

At the time of their review, Tyagi et al. [6] concluded that monocrystalline and polycrystalline PV technologies were the most popular, having more than 40% share of the market with an efficiency range of 15%-17%. In terms of cost, polymer solar cells were considered as a predominant challenger in production compared to crystalline-based solar cells. Not only it has a lower cost but it could also be produced at a massive rate [7]. Besides the cell technologies, operating temperature (cell temperature), solar irradiance, humidity, and dust accumulation also significantly impact the performance of the PV panels [8, 9]. A review of polymer materials for PV in which epoxy was considered was also studied by Gorter and Reinders [10]. In their research work, Gorter and Reinders mentioned that epoxy and glass fiber-reinforced polymer (GFR) epoxies were great alternatives for reducing the weight and cost of PV panels. These polymers offer a high strength to the panel fabrication when the thickness is lower than 4 mm. In a recent research, Suman et al. [11] have grouped the PV cell technology into four generations such as first-, second-, third-, and fourth-generation PV cells. They have illustrated the best research cell efficiencies based on solar companies and solar cell technologies represented by the National Renewable Energy Laboratory (NREL). To date, the efficiencies of the solar cells just before the year 2020 and the major recordings are as follows:

(i) The highest efficiency obtained from multijunction cells was 46.0% by Fraunhofer

(ii) Efficiencies obtained from single-junction GaAs were in the range between 27.5 and 29.1% by LG Electronics, Alta Devices, and FhG-ISE

(iii) Efficiencies obtained from crystalline Si were between 21.2 and 27.6%

(iv) Efficiencies of the thin-film technology were in the range of 13.6 to 23.3%

(v) Efficiencies of emerging PV cells were recorded between 10.6 and 22.1%. The perovskite cell made by KRICT/UNIST is the most outstanding in this cell type with an efficiency of 22.1%

Solar PV modules are the combination of solar cells connected in series. The module of a PV system is a box-like component that is packaged, protected, and assembled by multiple solar cells in series to deliver a specific electrical output power. Figure 2 illustrates the components and layers of a PV module.

The conventional PV module glass-to-Tedlar fabrication method suffers many problems that affect the PV electrical performance. These drawbacks include electrical power reduction because EVA becomes yellow after years of usage (reducing the amount of solar irradiance striking onto the PV cells) and moisture gain inside the module through EVA and Tedlar sheets. A study was carried out to identify the impact of encapsulating materials, processing, and testing of the PV panel [13]. It was observed that different types of encapsulating materials provide different PV

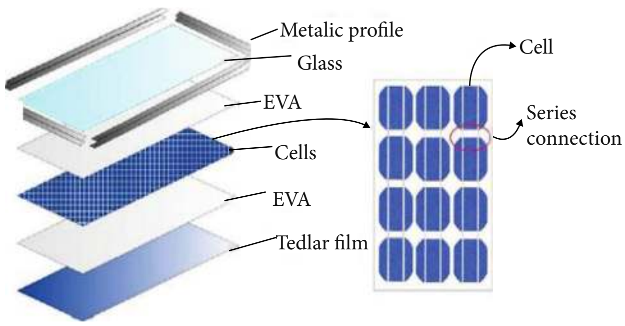

Figure 2: Components and layers of a PV module [12].

performances. The encapsulation failures including encapsulation breakdown, delamination, corrosion, and discoloration and the impact of these problems on the electrical performance reduction have been studied [14–16]. The discoloration is normally reported as an EVA color change (to yellow or sometimes brown) between the glass and the cells. Owing to the reduction of optical propagation and sunlight hitting the cells, this phenomenon causes a depletion of the power produced by reducing the photogenerated current of the panel [17]. To overcome these issues, the glass-to-glass PV module was proposed [18].

The literature review reveals that, despite extensive research on the electrical efficiency of PV panels, accomplishment on the performance investigations to overcome the drawbacks of EVA and Tedlar is yet to achieve. EVA and Tedlar sheet traps the heat and reduces the efficiency of the PV panels. Therefore, this study aims at investigating the electrical performance analysis of tempered glass-based solar PV panels that are modified forms of PV panels where EVA and Tedlar are not utilized like commercial PV panels. The tempered glass-based panels are of the same concept with the glass-to-glass PV panels.

2. Methodology

2.1. Onsite Experimental Setup. The experimental setup was performed using the main components as illustrated in Figure 3. In this whole setup, newly fabricated polycrystalline PV (Poly-PV) and monocrystalline PV (Mono-PV) panels have been introduced. All panels were supported by supporting structures made of aluminum profiles. One pyranometer was attached to the top of one of them to measure the intensity of solar irradiance. The slope of the supporting frames was set to 15° following the recommended installation slope in Malaysia [19]. All temperature and solar irradiance data were real-time recorded by DataTakers (DT80), which are located inside a sealed box below the panels. Moreover, an IV tracer was used to show the electrical output of each panel. At the end of the day (at 17:00), all recordings were retrieved using a PC provided by the laboratory. Figure 3 shows the experimental setup with the data acquisition facility. The instruments have been calibrated following standard procedures. Table 1 shows the model and range of measurements of different instruments used in the experimental study. Table 2 shows the specifications of the tempered glass-based PV panels.

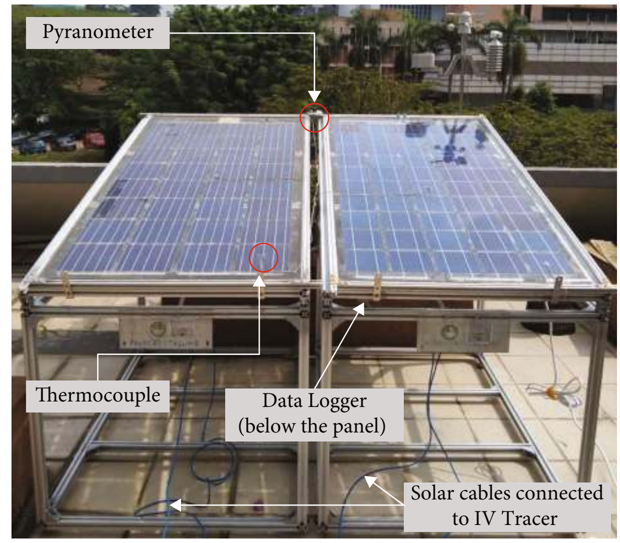

Figure 3: Experimental setup of the polycrystalline and monocrystalline PV panels.

Table 1: Details of the components.

Description	Specification
Pyranometer	LI 200R, 0-2000 W/m^2
Thermocouple	Type K, -200 to 1000°C
Data logger	DataTaker DT80
IV tracer	30-channel IV tracer

Table 2: Specification of the panels.

Descriptions	Poly-PV	Mono-PV
Cell type	pc-Si	mc-Si
Cell efficiency	18.4%	19%
Cell I_{sc}	9.0 A	NA
Cell V_{oc}	0.56 V	0.5 V
Cell P_{max}	4.5 W	2.8 W
Cell number	8 × 4 = 32	10 × 5 = 50
Cell size	156 × 156 mm	125 × 125 mm
Panel size	155 × 79 cm	155 × 79 cm
Panel weight	17.5 kg	17.5 kg

The layout of the tempered glass-based PV panels is indicated in Figure 4, where the solar cells were placed beneath the tempered glass having a thickness of 3 mm and sealed by encapsulation tape and an epoxy layer of 4 mm.

2.2. Data Acquisition Procedure. An experimental study was carried out in the Solar Garden of UM Power Energy Dedicated Advanced Centre (UMPEDAC), University of Malaya, Kuala Lumpur, Malaysia. Data collection was conducted every day for two weeks between December and January. An IV tracer traced the readings of the electrical characteristics (current and voltage) of the panels. The temperature and

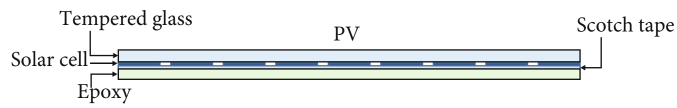

Figure 4: Layout of the tempered glass-based PV panel.

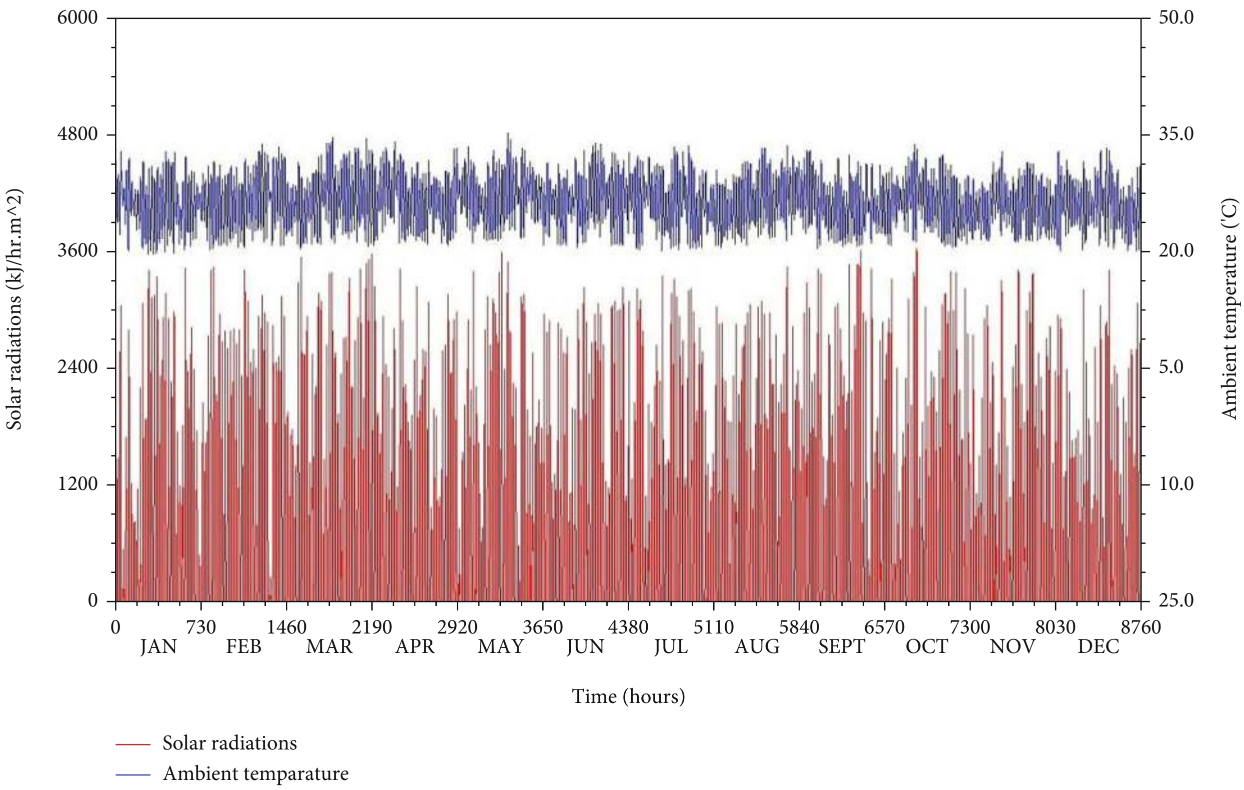

Figure 5: Annual variations of average solar radiations and ambient temperature across Malaysia.

solar irradiance readings were recorded by DataTakers modeled DT80. All data was collected from 8:30 in the morning until 17:00, before being retrieved into a PC for data analysis purposes.

2.3. Mathematical Formulation. To understand the performance of a system and how much it differs from another, efficiency calculation and comparison are the most crucial identification. Malaysia is situated in the slightly northern hemisphere of the globe. Therefore, solar modules have been installed facing south. The angle of the PV and modules can be calculated using

$$\delta = 23.45 \ \sin\left[\left(\frac{360}{365}\right)(d+284)\right], \quad \beta = (\varphi - \delta), \tag{1}$$

where δ is the solar declination, d is the day of the year, φ is the latitude of the experimental site, and β is the angle of the module towards the equator.

The electrical efficiency of the system is given by

$$\eta_e = \frac{P_{\max}}{A \times G}, \tag{2}$$

where the maximum electrical power output is calculated as follows:

$$P_{\max} = I_{sc} \times V_{oc} \times \mathrm{FF} = V_{mp} \times I_{mp}. \tag{3}$$

3. Results and Discussion

3.1. Malaysian Weather Conditions. The annual variation of maximum and minimum solar radiations and ambient temperatures across Malaysia is shown in Figure 5. Malaysia is situated at the equatorial region, and it observes two monsoon seasons annually. Average solar radiation increases from November to March, and it decreases from May to September. In Figure 5, average solar radiation is about 3420 kJ/hr·m^2 which is around 950 W/m^2 from January to March, and then, average solar radiation reduces to 3060 kJ/hr·m^2 which is around 850 W/m^2 from May to

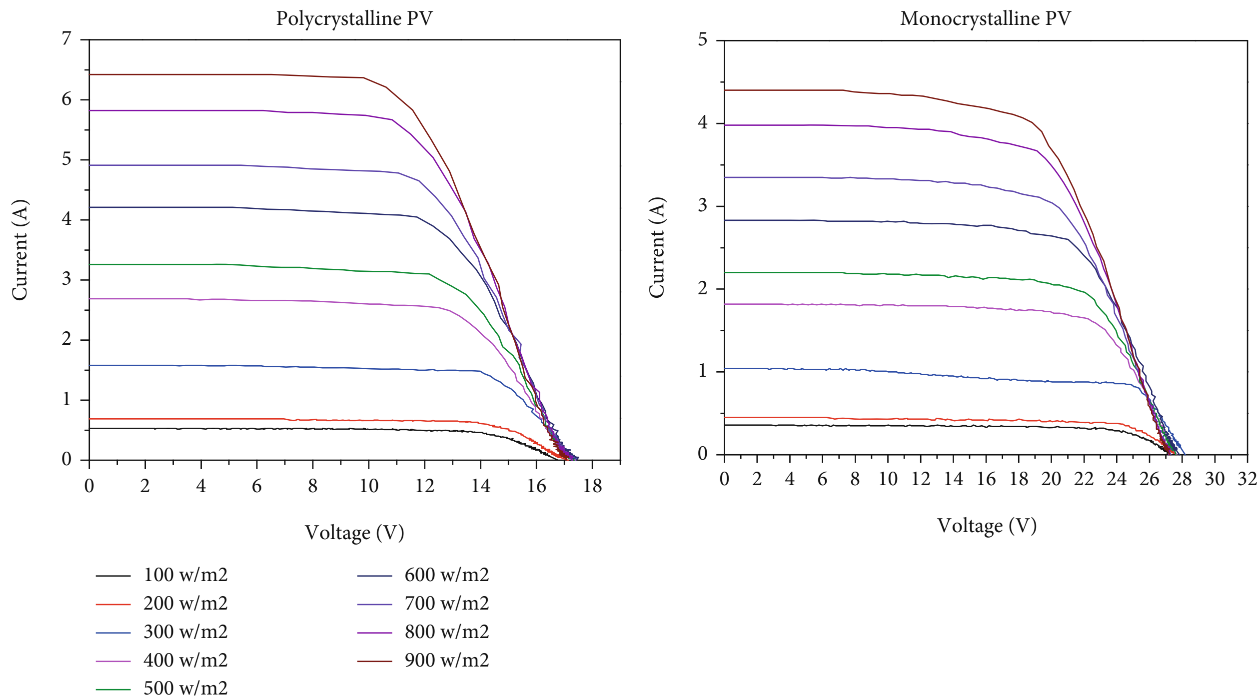

Figure 6: I-V curve of the panels.

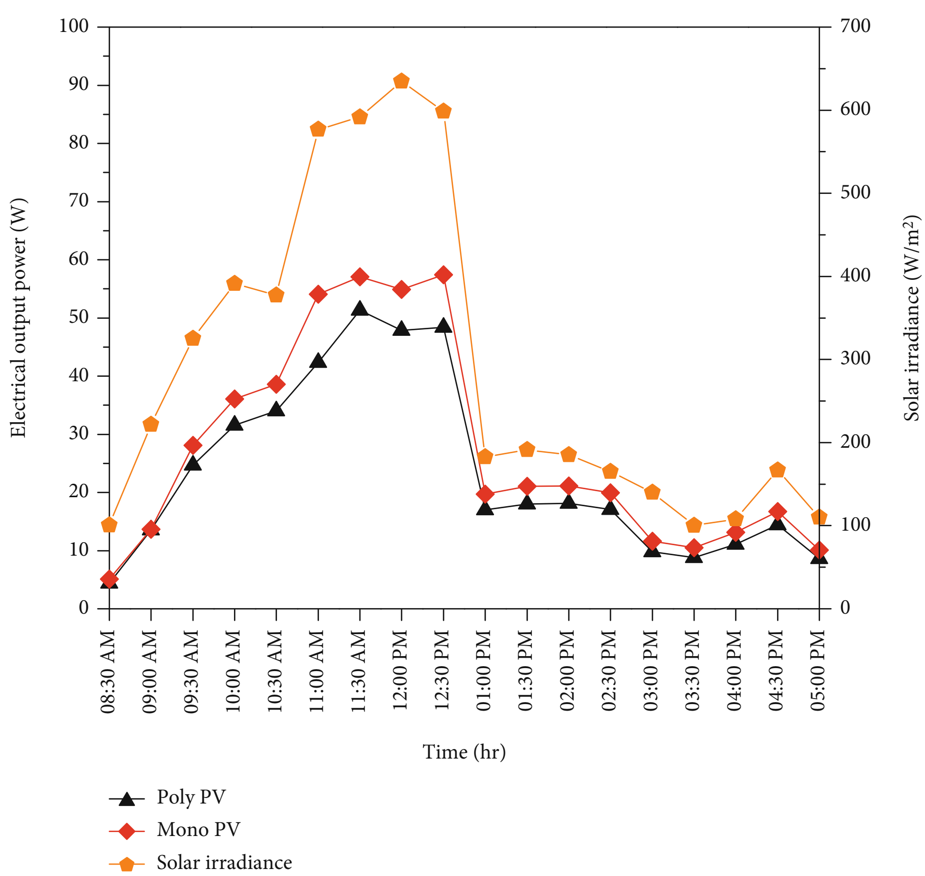

Figure 7: Electrical output power with respect to time and solar irradiance.

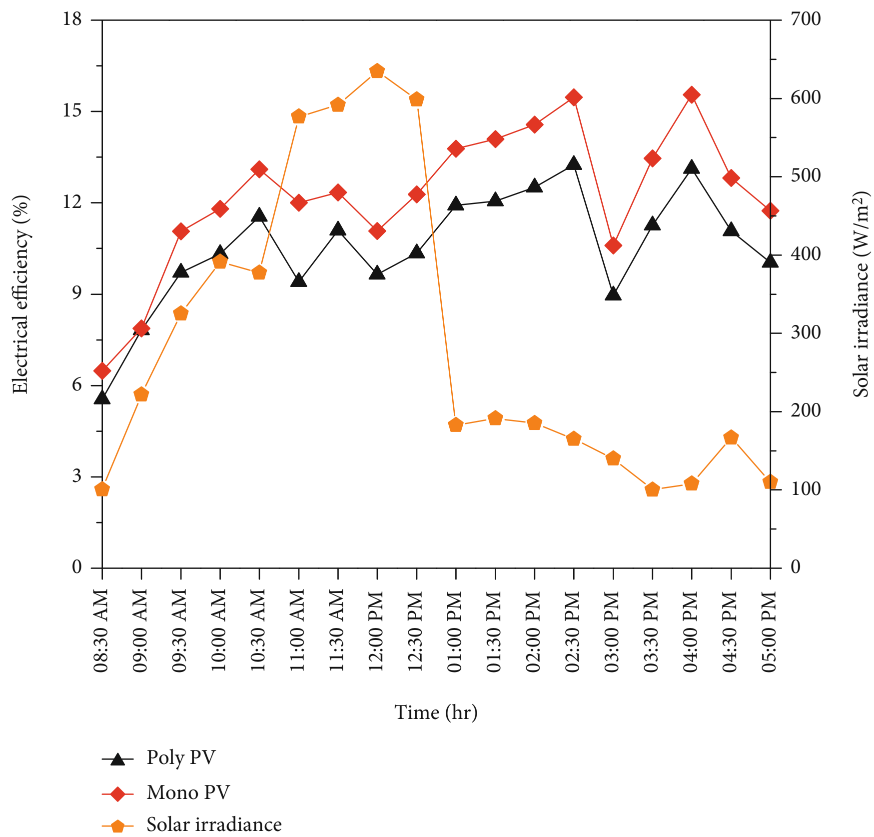

FIGURE 8: Electrical efficiency with respect to time and solar irradiance.

August; afterwards, it again rises to 3240 kJ/hr·m^2 which is around 900 W/m^2 from September to December [20].

3.2. Electrical Characteristics. Voltage and current are the key electrical properties of PV panels. The intensity of the solar irradiance entering the cell regulates the current, while its voltage is decreased by the elevation of cell temperature. The I-V curves in Figure 6 represent the electrical characteristics of the PV panels experimented within this research work. According to the graph, the short-circuit current (I_{sc}) obtained from the maximum solar irradiance (900 W/m^2) of the panels was 6.42 A and 4.4 A, respectively, for polycrystalline and monocrystalline PV, while the current at maximum power (I_{mpp}) was 5.83 A and 3.9 A, respectively. The voltages at maximum power obtained from the same irradiance were 11.57 V and 19.41 V, while the open-circuit voltages (V_{oc}) were 17.06 V and 27.24 V. Moreover, the maximum power (P_{max}) obtained from these panels at 900 W/m^2 was 67.4 W and 75.67 W, respectively.

3.3. Electrical Output Power. Solar photovoltaic is the concept of converting sunlight into electricity. Therefore, the amount of solar irradiance received by the PV panels is the key and an impactful parameter to determine the output. From the graph in Figure 7, the electrical output power of both panels followed the trend of solar irradiance. As the solar irradiance increased to the maximum averaged value of 634 W/m^2 between 12:00 PM and 12:30 PM, the output power of the panels also increased to their peaks. The electrical output powers obtained in this period were 67.4 W and 75.67 W, respectively, for the polycrystalline and monocrystalline PV. The monocrystalline PV offered a higher output than the polycrystalline PV. At the beginning of the day (at 8:30 AM), the solar irradiance was only 100.75 W/m^2, while the output power of the polycrystalline and monocrystalline PV was only 4.37 W and 5.10 W. All values increased to their peaks between 12:00 PM and 12:30 PM before experiencing a dramatic decrease. A substantial drop in solar irradiance occurred after 12:30 PM, as the values of the output power of the panels also followed accordingly. The trend experienced a significant drop after this time due to the shading from the building near which the experimental setup was located.

3.4. Electrical Efficiency. Electrical efficiency is the main characteristic to determine the electrical performance of the systems installed in this experimental study. In electrical efficiency analysis, the current and voltage at maximum power, area of the PV panel, and the amount of solar irradiance are the major parameters to be considered. Generally, more solar irradiance would increase the current of the cells in the PV system. However, the higher the solar irradiance, the warmer the PV cells would become. The increase in cell temperature would result in a reduction of the voltage of the cell as well as the panel as a whole, therefore affecting the performance of the system. Figure 8 illustrates the changes in electrical efficiency of the polycrystalline and monocrystalline PV panels in this experimental study, with respect to time and solar irradiance. In this graph, it could be seen that, despite sudden changes in solar irradiance, the efficiencies of the panels followed the same trends. The efficiency of the panels fluctuated quite significantly, but the overall trends show increasing efficiency from the morning at 8:30 AM until the afternoon before experiencing a sudden drop at 3:30 PM. The maximum obtainable efficiency for the polycrystalline and monocrystalline PV was 13.25% and 15.55%, respectively. The average electrical efficiencies of the four panels are 10.54% and 12.23%.

4. Conclusion and Future Work

The purpose of this study was to investigate the electrical performance of the tempered glass-based polycrystalline and monocrystalline PV panels under typical Malaysian weather. The real-time outdoor experiment was successfully achieved. The electrical performance analysis was conducted to compare the two fabricated panels. An *I-V* curve was also obtained to identify the electrical characteristics of the monocrystalline and polycrystalline panels. For such, it is concluded that the polycrystalline PV provided a higher current compared to the monocrystalline PV. In contrast, the monocrystalline PV produced a much higher voltage compared to the polycrystalline PV. At solar irradiance of 900 W/m^2, the electrical power produced by the polycrystalline PV and monocrystalline PV was 67.4 W and 75.67 W, respectively. The electrical output is affected by the amount of solar irradiance. The higher the solar irradiance, the more the electrical output power is obtained from the PV panels. At an average solar irradiance of 634.61 W/m^2, the electrical output from the polycrystalline and monocrystalline PV was 47.85 W and 54.89 W. The average electrical efficiency of the polycrystalline and monocrystalline PV was 10.54% and 12.23%, respectively.

Furthermore, in solar photovoltaic (PV) systems, the performance or electrical efficiency of solar PV panels is affected by their surface temperature. The excessive temperature in solar PV panels can cause severe degradation to the solar cell material and reduce the lifespan of the panel itself. Alternatively, a possible performance improvement by employing cooling technologies to reduce the surface temperature of the panel should be studied [21, 22]. In this regard, solar thermal collectors with the solar PV panel can play a significant role in both producing thermal energy and in cooling down the PV panel surface temperature. The combination of STC and solar PV is called a solar photovoltaic-thermal (PVT) system. For future work, the authors would like to continue this work and compare these results with tempered glass-based PV/T systems using novel flat-plate absorber designs.

Data Availability

Data are available upon request to the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] U S Energy Information Administration, *Assumptions to the annual energy outlook 2017*, U.S Energy Information Administration, 2017.

[2] N. L. Panwar, S. C. Kaushik, and S. Kothari, “Role of renewable energy sources in environmental protection: a review,” *Renewable and Sustainable Energy Reviews*, vol. 15, no. 3, pp. 1513–1524, 2011.

[3] M. Hosenuzzaman, N. A. Rahim, J. Selvaraj, M. Hasanuzzaman, A. B. M. A. Malek, and A. Nahar, “Global prospects, progress, policies, and environmental impact of solar photovoltaic power generation,” *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 284–297, 2015.

[4] L. Kumar, M. Hasanuzzaman, and N. A. Rahim, “Global advancement of solar thermal energy technologies for industrial process heat and its future prospects: a review,” *Energy Conversion and Management*, vol. 195, pp. 885–908, 2019.

[5] A. Ahmadi, M. A. Ehyaei, A. Doustgani et al., “Recent progress in thermal and optical enhancement of low temperature solar collector,” Energy Systems, 2021.

[6] V. V. Tyagi, N. A. A. Rahim, N. A. Rahim, and J. A. L. Selvaraj, “Progress in solar PV technology: research and achievement,” *Renewable and Sustainable Energy Reviews*, vol. 20, pp. 443–461, 2013.

[7] F. C. Krebs, “Fabrication and processing of polymer solar cells: a review of printing and coating techniques,” *Solar Energy Materials & Solar Cells*, vol. 93, no. 4, pp. 394–412, 2009.

[8] M. M. Rahman, M. Hasanuzzaman, and N. A. Rahim, “Effects of various parameters on PV-module power and efficiency,” *Energy Conversion and Management*, vol. 103, pp. 348–358, 2015.

[9] A. Maleki, A. Haghighi, M. El Haj Assad, I. Mahariq, and M. Alhuyi Nazari, “A review on the approaches employed for cooling PV cells,” *Solar Energy*, vol. 209, pp. 170–185, 2020.

[10] T. Gorter and A. H. M. E. Reinders, “A comparison of 15 polymers for application in photovoltaic modules in PV- powered boats,” *Applied Energy*, vol. 92, pp. 286–297, 2012.

[11] P. S. Suman, P. Sharma, and P. Goyal, “Evolution of PV technology from conventional to nano-materials,” *Materials Today: Proceedings*, vol. 28, pp. 1593–1597, 2020.

[12] C. T. Machado and F. S. Miranda, “Photovoltaic solar energy: a briefly review,” *Revista Virtual de Química*, vol. 7, no. 1, pp. 126–143, 2015.

[13] J. Pern, “Module encapsulation materials, processing and testing (presentation),” in *APP International PV Reliability Workshop*, pp. 1–33, Shanghai, China, 2008, http://www.nrel.gov/docs/fy09osti/44666.pdf.

[14] A. Bouaichi, A. A. Merrouni, A. el Hassani et al., "Experimental evaluation of the discoloration effect on PV-modules performance drop," *Energy Procedia*, vol. 119, pp. 818–827, 2017.

[15] M. C. C. de Oliveira, A. S. A. Diniz Cardoso, M. M. Viana, and V. . F. C. Lins, "The causes and effects of degradation of encapsulant ethylene vinyl acetate copolymer (EVA) in crystalline silicon photovoltaic modules: a review," *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 2299–2317, 2018.

[16] M. C. C. de Oliveira, D. A. Cassini, A. S. A. C. Diniz et al., "Comparison and analysis of performance and degradation differences of crystalline-Si photovoltaic modules after 15-years of field operation," *Solar Energy*, vol. 191, pp. 235–250, 2019.

[17] P. Rajput, G. N. Tiwari, O. S. Sastry, B. Bora, and V. Sharma, "Degradation of mono-crystalline photovoltaic modules after 22 years of outdoor exposure in the composite climate of India," *Solar Energy*, vol. 135, pp. 786–795, 2016.

[18] A. A. Jadallah, A. O. Hanfesh, and T. H. Jebur, "Design, fabrication, testing and simulation of a modern glass to glass photovoltaic module in Iraq," *Journal of Engineering Science and Technology*, vol. 13, no. 9, pp. 2750–2764, 2018.

[19] J. Selvaraj, "Impact of tilt angle on the performance of photovoltaic modules in Malaysia: a review," in *4th IET Clean Energy and Technology Conference*, Kuala Lumpur, Malaysia, January 2016.

[20] L. Kumar, M. Hasanuzzaman, N. A. Rahim, and M. M. Islam, "Modeling, simulation and outdoor experimental performance analysis of a solar- assisted process heating system for industrial process heat," *Renewable Energy*, vol. 164, pp. 656–673, 2021.

[21] M. Hasanuzzaman, A. B. M. A. Malek, M. M. Islam, A. K. Pandey, and N. A. Rahim, "Global advancement of cooling technologies for PV systems: a review," *Solar Energy*, vol. 137, pp. 25–45, 2016.

[22] M. M. Islam, M. Hasanuzzaman, N. A. Rahim, A. K. Pandey, M. Rawa, and L. Kumar, "Real time experimental performance investigation of a NePCM based photovoltaic thermal system: an energetic and exergetic approach," *Renewable Energy*, vol. 172, pp. 71–87, 2021.