Temperature Dependence of PV-modules Performance

Shule Wang, Adnan Zaman, Tanuj Nagentra Ramachandran, Ancy Sijo Kureekal & Axelina Lindgren

Lunds Tekniska Högskola

AEBF30 - Photovoltaic Systems

Deep Assignment

2025-03-05

Contents

1 Introduction

1.1 Objective

In recent years, the growing popularity of photovoltaics (PVs) as a renewable energy source is evident from the dark blue panels frequently seen on rooftops. A curious person might wonder how well a panel can perform. Much research has been done on this topic, and one factor often mentioned is temperature. The study aims to investigate how temperature affects the performance of polycrystalline and thin-film panels in a laboratory set-up mimicking a solar panel installed on a roof. Does the temperature affect panel performance, and if it does, are high or low temperatures the most beneficial?

1.2 Background

1.2.1 The Physics of a Solar Panel

To better understand the experiment, it is essential to understand the physics behind PVs. PV cells are generally made of silicon – a naturally occurring semiconductor. When exposed to a light source, this material allows the photons to be absorbed, resulting in electron movement over the band gap. For the electrons to be excited over the band gap, they must absorb the energy from photons with equal or higher energy than the bandgap energy. Therefore, the bandgap sets the maximum energy of an electron, i.e. the PV potential (Bernardo 2025a).

In a solar cell, the Silicon is doped, creating a PN-junction. When light hits the cell, its photons with enough energy excite some of the electrons in the material. This creates electron-hole pairs, separated by the electric field created by the PN-junction. If the two sides are connected with an external circuit, a current will flow through the circuit because the electrons flow to the p-side to recombine. The maximum current, i.e. the short circuit current (I_{sc}), is achieved if there is no load placed over the circuit (no voltage). The maximum voltage, i.e. the open circuit voltage (U_{oc}), is achieved when there is no connection between the two sides (no current). The total power of a cell is given by:

$$P = I \cdot U \tag{1}$$

where P is the power, I the current and U the voltage (Bernardo 2025a), and the efficiency formula yields:

$$\eta_{max} = \frac{MPP}{E \cdot A_p} \cdot 100\% \tag{2}$$

where η_{max} is the maximum panel efficiency, MPP the maximum power point, E the irradiance and A_p the panel area (Bernardo 2025b).

Increasing a semiconductor's temperature lowers its bandgap's energy, implying that more electrons can jump from the valence to the conduction band. Since the bandgap determines the cell's potential, a decrease in bandgap energy would also mean a reduction in potential. The opposite will happen with I_{sc} since more electrons can recombine with holes. The total power of the cell will decrease because the gain in current is smaller than the decrease in voltage. (Honsberg and Bowden 2019).

1.2.2 Previous Research

A PV module's temperature significantly affects its electrical performance. Research shows that solar radiation, short-circuit current, output power, and conversion efficiency (The efficiency of PV cells in converting solar energy into electrical energy) are linearly correlated to the PV module temperature, which means the module output can be boosted within the normal operating temperature range. The conversion efficiency will decrease when the temperature exceeds the range (Ale, Rotipin, and Makanju 2022). Hishikawa et al. studied the current-voltage (I-V) characteristics of crystalline silicon solar cells (c-Si), copper indium gallium selenide (CIGS) cells, dye-sensitized solar cells (DSC), and organic photovoltaic cells (OPV) under different temperatures. Thin film solar cells could be composed of either of the following - CIGS, DSC and OPV. The results showed that as the temperature increased, the short-circuit current slightly increased with the CIGS remaining almost unchanged, and the open-circuit voltage generally decreased, with the OPV cells experiencing the smallest decline, remaining nearly stable. (Hishikawa, Tobita, Sasaki, et al. 2013). Therefore, PV module temperature optimisation is highly related to power generation performance.

PV module temperature is related to solar radiation, ambient temperature, wind speed, and encapsulating materials. R. Muhfidin et al. analysed the relationship between the temperature of the PV module and solar radiation, the temperature of the environment and wind speed (Muhfidin and Yu 2019). Modules get more energy with increased solar radiation, causing an increase in temperature and a reduction in the open circuit voltage, output power, and conversion efficiency. In addition, thermal losses are directly proportional to solar radiation incidence in which the radiation intensity is higher, the rate of temperature increase is higher, and the energy loss is more significant. Increasing temperature in the surrounding environment raises the module temperature, impacting conversion efficiency. A growth in wind speed decreases the module temperature through convective heat transfer, increasing the conversion efficiency. And the materials used for the encapsulation of photovoltaic modules also contribute to the heat control. As a study showed, Glass-glass and glass-Tedlar PV modules are tested, with the latter exhibiting higher temperature differential between layers, which may affect efficiency in thermal conduction (Tofighi 2013). As the energy conversion efficiency of PV modules is about 13-20% (Armstrong and Hurley 2010), the rest of the energy transforms to heat and increases module temperature. Therefore, the thermal conduction properties of different encapsulation materials need to be investigated for the thermal optimisation of PV modules.

Thus, the conversion efficiency is associated with solar radiation, the temperature of the environment, and wind speed, so the temperature should be well-controlled. Suitable control of the temperature, such as modifying encapsulant materials, deploying cooling measures, and optimising the installation method, can contribute a lot to raising the efficiency of PV modules in improving long-term stability and system power generation efficiency.

1.3 Limitations

In the experiment, we were limited to two different types of panels. Other types might yield different results. The range of temperatures tested was limited to the available equipment. The study was done for a single irradiance as similar IV-curve trends at varied panel temperatures are expected when subjected to a different irradiance. Lastly, the panel temperature was recorded on the back of the panel, which might differ from the front temperature.

2 Method

The experiment was conducted in the Energy and Building Design Laboratory. The study aimed to investigate the effect of temperature on a PV panel. A halogen floodlight was used as the primary source of light. The PV panel was connected to a circuit, as shown in Figure 1. A voltmeter was connected parallel to the panel to measure the output voltage, and an ammeter was connected in series to measure the current. Furthermore, as shown in Figure 1, a variable resistor was connected to control the load. A thermostat was attached to the back of the PV module to measure and monitor the panel temperature.

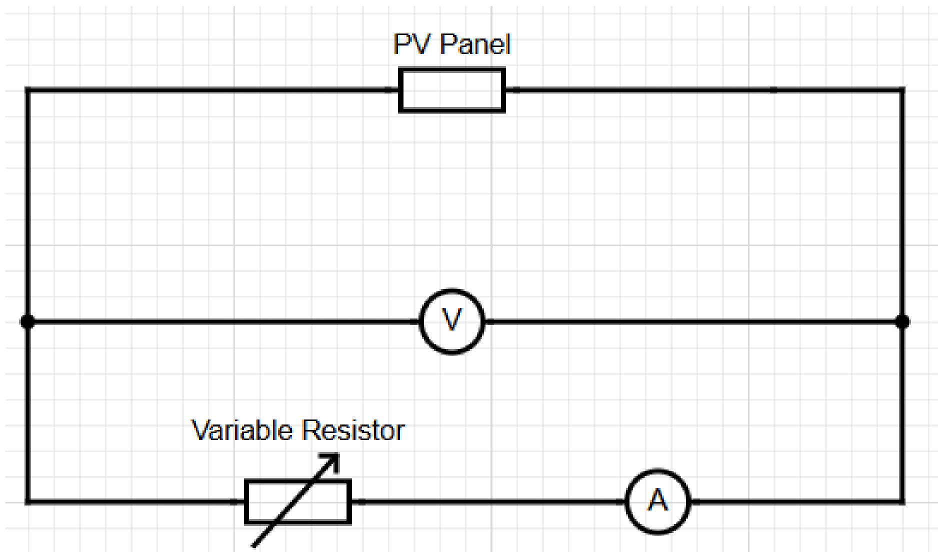

Figure 1: Circuit diagram of the set-up.

For this study, the irradiance was set to 500 W/m^2 using a pyranometer. The resistance was gradually increased, and the corresponding changes in voltage and current were recorded by a data logger at varied panel temperatures. After exporting data from the data logger, IV curves were plotted in Excel. These steps are performed for both the polycrystalline panel and the thin-film panel.

3 Results

Multiple temperature readings are taken for each panel, and the IV curves at varied panel temperatures are plotted to understand the effect of temperature on each panel. The maximum power point is identified to understand the panel efficiency at each temperature. The panel efficiency at each temperature is then calculated using Equation 2.

3.1 Polycrystalline Panel

In Figure 2, for the case of a polycrystalline panel, it is seen that there is a voltage drop accompanied by a drop in current as the temperature increases.

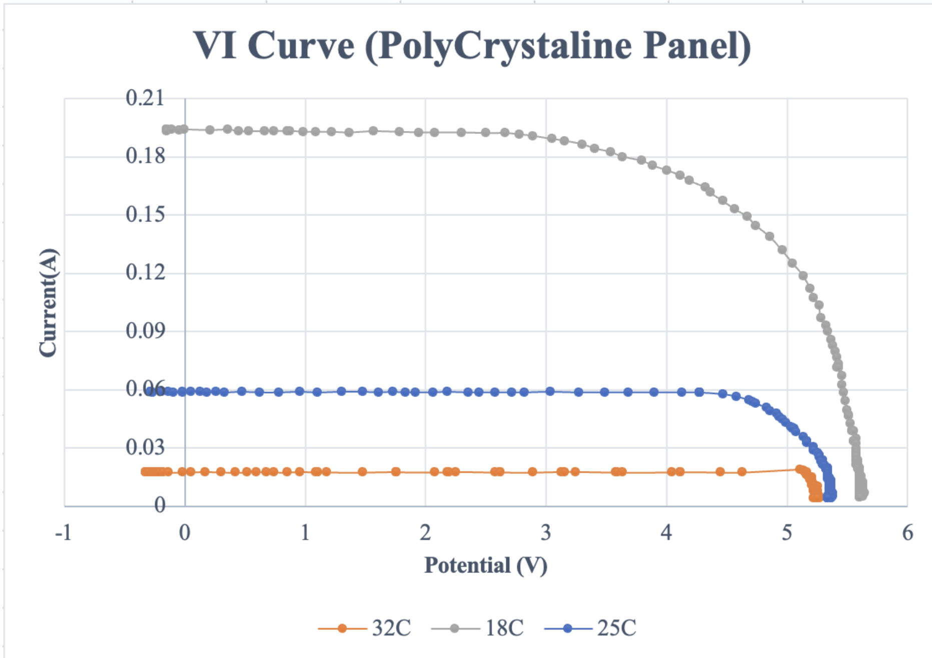

Figure 2: IV-curve for a Polycrystalline Panel.

Table 1: Panel Performance at varying temperatures – Polycrystalline Panel

Temperature (°C)	MPP (W)	η_{max} (%)
18	0.7069	11.35
25	0.2593	4.18
32	0.0968	1.55

As per the literature and as stated previously, the panel efficiency must decrease with an increase in surface temperature. This trend is noticed for the entirety of the dataset, as depicted in Table 1. Although there should be a slight efficiency drop with temperature, the drop noticed for this study is more significant, and the power output from the panel is almost obsolete at higher temperatures with a recorded efficiency of about 1.55%.

3.2 Thin Film Panel

In Figure 3, for the case of a thin film panel, it is seen that there is a voltage drop accompanied by an increase in current as the temperature increases.

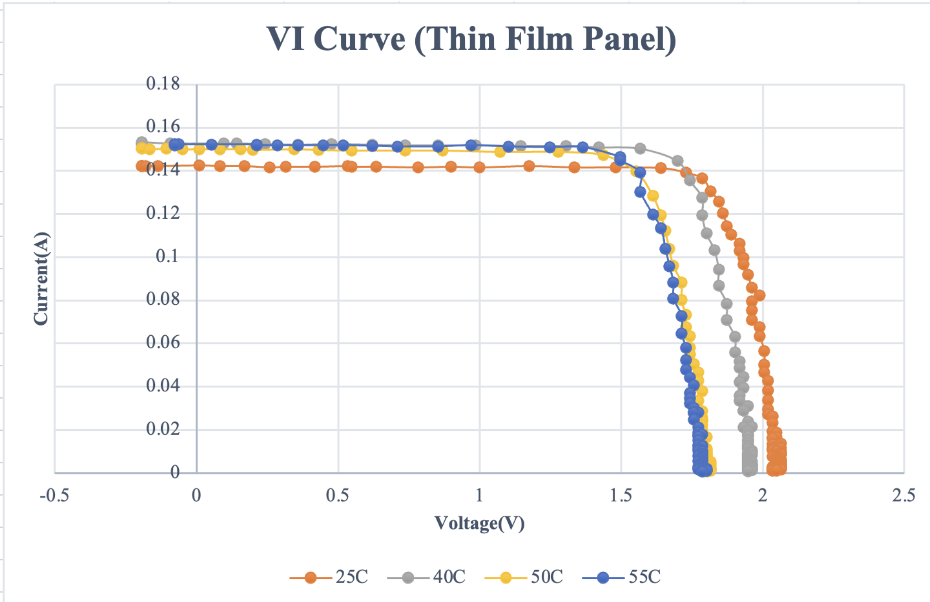

Figure 3: IV-curve for a Thin Film Panel.

Table 2: Panel Performance at varying temperatures – Thin Film Panel

Temperature (°C)	MPP (W)	η_{max} (%)
25	0.2436	9.74
40	0.2455	9.82
50	0.2169	8.68
55	0.2187	8.75

As per the literature and as stated previously, the panel efficiency must decrease with an increase in surface temperature. Although that trend is noticed, it is not consistent for the entirety of the dataset, as depicted in Table 2. The efficiency is almost consistent or even slightly increases as the surface temperature is increased from 25°C to 40°C. The efficiency then decreases when the temperature rises from 40°C to 50°C, which is expected. Then, it stays almost consistent or slightly increases as the temperature rises from 40°C to 55°C.

4 Discussion

The results obtained from the experiment depict how the electrical output and panel performance are heavily dependent on thermal conditions. This is common for both of the tested panels. As per theory, the current increase must be accompanied by a voltage drop with an increase in temperature. This section aims to explain trends and compare them with existing research.

4.1 Polycrystalline Panel

In the case of polycrystalline panels. An unexpected decrease in current is observed with increasing temperatures, as seen in Figure A. A possible explanation for this irregularity could be a culmination of the various factors listed below:

1. Grain Boundary Recombination: Polycrystalline solar cells are made of multiple crystal grains. This leads to the formation of grain boundaries, which act as recombination centres. The probability of carrier recombination is high at higher temperatures at these boundaries, which restricts the expected rise in I_{sc}.

2. Increased Series Resistance: In elevated thermal conditions, the resistance of metallic contacts increases, thereby acting as an impedance to the flow of charge carriers, resulting in decreased output current.

3. Trap-Assisted Recombination: The fusion of multiple grains in polycrystalline panels causes defects in the silicon lattice. These defects become more active at higher temperatures and trap the carriers before contributing to the current flow.

Furthermore, as the temperature increases, the panel efficiency significantly decreases. Although panel efficiency is expected to decrease with rising temperatures, such a sharp decline is not expected, as seen in Table 1. However, this efficiency drop and the unexpected IV curves signify that the panel experiences losses in at least one of the three forms stated above.

Therefore, as per the study, it can be concluded that the tested polycrystalline panel must be maintained at a temperature close to 18°C for an ideal electrical output. Moreover, if a polycrystalline panel is to be considered for real-world application, the above conditions must be carefully accounted for during the design and testing stages of the panel to ensure panel reliability in varied real-world weather conditions.

4.2 Thin Film Panel

As per theory, a temperature increase decreases the semiconductor's band gap energy, which causes a reduction in the energy required for the electrons to be excited from the valence band to the conduction band. Furthermore, it increases the amount of thermally excited carriers; as a result, the current rises significantly with temperature, accompanied by a voltage drop. The trend, as seen in Figure B, concludes that the experiment is in conjunction with theory.

Furthermore, the IV curve irregularity experienced with a polycrystalline panel is avoided as the thin film panel has fewer grain boundaries and a uniform structure of thin film cells, which minimizes grain boundary recombination losses. Moreover, the bandgap energy in a thin film panel might behave more consistently with temperature changes, reducing thermal degradation effects. Additionally, as they have no metal contacts exposed to the light source, they avoid any unwanted series resistance. Therefore, a more consistent I_{sc} is ensured, and the electrical output from the panel follows the expected trend as the temperature increases. A slight inconsistency noticed for panel efficiency as a function of temperature (as elaborated upon in Section 3.2) is most likely a result of experimental/measurement error – Not increasing the load through the variable resistor in the same manner as with the other temperature readings. Despite this, it can be understood that the panel efficiency decreases with temperature if values at 25°C to 50°C are compared. Furthermore, the maximum efficiency is achieved at 25°C. Therefore, the surface temperature for the tested thin-film panel is recommended to be maintained at 25°C for optimal electrical output. However, even if the panel were to be operated at a higher temperature, the performance loss is not as significant.

5 Conclusion

As per the experiment, the general trend is that the panel efficiency drops with temperature. There is a sharper efficiency drop for the polycrystalline panel and a more minimal efficiency drop for the thin film panel. It is further noted that the polycrystalline panel yields a higher maximum efficiency (11.35% at 18°C) than the thin film panel at lower temperatures, making them ideal for installation in regions experiencing colder climates. Moreover, the extreme drop in output with temperature is unwarranted but is mainly due to the design constraints of the tested panel. In contrast, even though thin film panels are less efficient at ideal temperatures, they yield a higher maximum efficiency (8.75% at 55°C) at higher temperatures, as their efficiency only marginally drops with an increase in temperature. This makes them ideal for installation in regions experiencing warmer climates. These arguments are not entirely conclusive, as the panel choice could be contingent on various other factors such as cost, expected lifespan, installation surface (curved or flat) or area availability. However, these conclusions are in conjunction with PV literature, as polycrystalline panels are expected to outperform thin film panels in terms of maximum efficiency when observed under ideal temperatures (around 25°C), and thin film panels are expected to retain electrical output with an increase in temperature.

References

Ale, T. O., K. J. Rotipin, and T. D. Makanju (2022). "Temperature Effects on Optimal Performance of PV Module". In: *Journal of Engineering Advancements* 3.04, pp. 162–165. DOI: 10.38032/jea.2022.04.004.

Armstrong, S. and W. G. Hurley (2010). "A thermal model for photovoltaic panels under varying atmospheric conditions". In: *Applied Thermal Engineering* 30.11, pp. 1488–1495. DOI: 10.1016/j.applthermaleng.2010.03.012.

Bernardo, R (2025a). *Compendium of Solar Cell Physics*. Based on PVeducation.org and other reading material. Course: Solar Photovoltaic Systems Basic Course (AEBF30). Lunds Tekniska Högskola.

— (2025b). *PV syst & components*. PowerPoint presentation, [Lecture], Lunds Tekniska Högskola. URL: https://canvas.education.lu.se/courses/34390/files/6055078?module_item_id=1440816.

Hishikawa, Y., H. Tobita, A. Sasaki, et al. (June 2013). "Current-voltage characteristics of novel PV devices under various irradiance and temperature conditions". In: *2013 IEEE 39th Photovoltaic Specialists Conference (PVSC)*, pp. 1417–1422. DOI: 10.1109/PVSC.2013.6744409.

Honsberg, C. B. and S. G. Bowden (2019). *Effect of Temperature - Photovoltaics Education Website*. Accessed: 27 Feb. 2025. URL: https://www.pveducation.org/pvcdrom/solar-cell-operation/effect-of-temperature.

Muhfidin, R. and I.-S. Yu (Oct. 2019). "Thermal Analysis of PV Module and the Effect on its Efficiency". In: *2019 International Conference on Technologies and Policies in Electric Power Energy*, pp. 1–4. DOI: 10.1109/IEEECONF48524.2019.9102515.

Tofighi, A. (May 2013). "Performance Evaluation of PV Module by Dynamic Thermal Model". In: *Journal of Power Technologies* 93.2. Accessed: 27 Feb. 2025, pp. 111–121. ISSN: 2083-4195. URL: https://papers.itc.pw.edu.pl/index.php/JPT/article/view/329.