

# **MAXIMIZING PV MODULE'S POWER OUTPUT THROUGH COOLING BY THERMOELECTRIC DEVICE**

By

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# DECLARATION

I, GAUTA TSHEPO VALENTINE MOOKO, with student number \_\_\_\_\_, hereby affirm that the research project I have presented, for the degree of Master of Engineering in Electrical Engineering at the Central University of Technology, Free State, is entirely my own work. It adheres to the principles outlined in the Academic Integrity Code and all other applicable policies, procedures, rules and regulations of the Central University of Technology, Free State. Furthermore, this research project has not been previously submitted by any individual to fulfil or partially fulfil the requirements for any qualification.

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Date: **12<sup>th</sup> November 2023**

# DEDICATION

To my late mother, Morongoenyana Lucy Mooko.

## ACKNOWLEDGMENTS

I would like to thank my esteemed supervisors, Prof. K. Kusakana and Dr. P. Hohne. Their unwavering support, invaluable guidance, constant encouragement, and remarkable patience has been instrumental throughout this arduous journey.

I would like to express my gratitude to the Central University of Technology (CUT), Free State, for their generous financial support and invaluable assistance, which has been instrumental in the accomplishment of this endeavour.



# LIST OF ABBREVIATIONS

|        |                                      |
|--------|--------------------------------------|
| SCIP   | Solving Constrained Integer Programs |
| PV     | Photovoltaic                         |
| STC    | Standard Test Conditions             |
| TE     | Thermoelectric                       |
| TEM    | Thermoelectric Module                |
| TEC    | Thermoelectric Cooler                |
| TEG    | Thermoelectric Generator             |
| PV-TEC | Photovoltaic Thermoelectric          |
| SAURAN | South African Radiometry Network     |
| Z      | Impedance                            |
| W      | Watts                                |
| MPPT   | Maximum Power Point Tracker          |
| P & O  | Perturb and Observe                  |
| I-V    | Current-Voltage                      |
| GA     | Generic Algorithm                    |
| PWM    | Pulse Width Modulation               |
| DC     | Direct Current                       |
| GHI    | Global Horizontal Irradiance         |
| DNI    | Direct Nominal Irradiance            |
| DHI    | Diffuse Horizontal Irradiance        |
| TS     | Sampling Time                        |
| LCC    | Life Cycle Cost                      |
| SSP    | Simple Payback Period                |
| BCR    | Benefit-to-Cost-Ratio                |
| IRR    | Initial Rate of Return               |
| BEP    | Break-Even Point                     |

## ABSTRACT

Solar energy, as the most abundant renewable resource, has seen a remarkable surge in utilization, predominantly through the adoption of solar photovoltaic panels. This adoption is driven by its eco-friendly nature and minimal environmental impact. Nonetheless, akin to any imperfect system, not all incident light photons are successfully converted into usable electrical energy. Instead, some solar energy remains unconverted, dissipating as heat across the surface of photovoltaic panels. This heat dissipation adversely affects the electrical efficiency of photovoltaic panels.

Efficient cooling of the photovoltaic panel's operational surface is crucial in the quest for higher efficiency in solar photovoltaic systems. Effective cooling not only substantially improves the electrical efficiency of photovoltaic modules however further mitigates cell degradation, thus extending the lifespan of these systems.

The influence of temperature on the electrical efficiency of photovoltaic panels is particularly pronounced, when temperatures exceed 25°C. However, a gap in research has been identified in the development and application of optimizing control methods to reduce photovoltaic panel operating temperatures, without employing traditional cooling mediums.

One promising approach, involves attaching a thermoelectric cooler to the rear of the photovoltaic panel, effectively reducing surface temperatures. To evaluate the economic viability of this approach, a comparative analysis will be conducted between the conventional reference system and the photovoltaic-thermoelectric cooler hybrid system.

Therefore, in order to address the identified gap in research, a mathematical model describing the cooling process of photovoltaic modules was formulated and simulations were carried out. MATLAB was used and the optimization problem was solved, using the SCIP (Solving Constrained Integer Programs), in OPTI toolbox. The simulation outcomes, illustrate that precise control of the thermoelectric cooler has the potential to increase the electrical output power efficiency of photovoltaic modules by 9.27%, all while efficiently regulating the surface temperatures. Furthermore, the life cycle cost comparison, reveals that over the long term, the hybrid system may be more cost-effective, boasting a 10.56% cost saving over the 20-year project lifespan. A break-even point analysis indicated that the proposed system may break even in 6.5 years.

**Keywords:** Photovoltaic, thermoelectric cooler, efficiency enhancement, temperature control, mathematical modelling, MATLAB SCIP simulation, economic feasibility.

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# CHAPTER I: INTRODUCTION

## 1.1 BACKGROUND

Renewable energy sources are rapidly gaining traction in response to the globalizing world and economic expansion. As concerns around pollution and the sustainability of conventional energy sources grow, a pivotal question arises: What will emerge as a reliable energy source, once fossil fuels are exhausted?

From nature's abundant resources, solar irradiance emerges as one of the most prolific and inexhaustible forms of energy. Amid the array of methods for harnessing electrical energy from solar irradiance, photovoltaic cells (PV cells), stand as highly efficient contenders. Their practicality remains noteworthy, despite efficiency levels ranging from approximately 5% to 20% [1]. However, as temperatures escalate, a significant attenuation, in the overall efficiency of photovoltaic cells, becomes visible. This efficiency reduction transpires at a rate of 0.25% to 0.5% per degree Celsius [2], contingent upon the specific cell material employed.

This degradation in efficiency, becomes notably pronounced, when temperatures exceed 25°C under standard test conditions (STC) and an irradiance of 1000  $W/m^2$  and it can be effectively mitigated, through strategic cooling of the PV panel's surface. Employing efficient cooling mechanisms, holds the potential to substantially elevate the electrical efficiency of photovoltaic modules. While numerous cooling techniques for PV panels have been conceived and substantiated to augment total power output, many necessitate the utilization of external media (such as water or forced air) for cooling, which may prove impractical, under specific operational conditions.

Enter the Thermoelectric Cooler (TEC), a promising solution. TECs operate by exploiting the Peltier effect, generating a temperature gradient when an electrical current flows across a junction formed by dissimilar materials. This thermoelectric process facilitates the transfer of heat from one side to another resulting in one side being cooled. This unique characteristic may be harnessed to efficiently cool PV panels, without relying on external mediums. Comprising two dissimilar materials, a TEC functions through the movement of the electrical current across the junction connecting these materials [3].

This process leads to the emission, or absorption of heat, to equalize the chemical potential difference between the materials: a phenomenon known as the Peltier effect. In a circuit



composed of dissimilar semiconductor materials, such as P-type and N-type materials, an electrical voltage prompts electrons to transition from the P-type to the N-type material through a connector. This migration causes the electrons to absorb thermal energy, resulting in a cooler state (cold side). Continuing through the material matrix, the electrons flow from the N-type material to the P-type material, via another connector, releasing energy as heat to a heat sink (hot side), as they return to a lower energy state. The primary objective of this study is to create an optimized control model, with the aim of enhancing the efficiency of a hybrid PV-TEC system, by implementing TEC-based cooling.

## 1.2 PROBLEM STATEMENT

The electrical efficiency of a PV module decreases, as it operates at temperatures exceeding 25°C, with its dependency on the specific materials used in the solar cells. Any solar energy that is not converted into electricity is, instead, released as heat on the surface of the PV module. Consequently, this dissipated heat leads to an increase in the overall temperature of the PV module, causing a decline in the electrical efficiency of the PV panel.

## 1.3 OBJECTIVE OF THE STUDY

The objective of this study is to devise a control methodology that mitigates the efficiency decline in a PV module, resulting from an elevated operating temperature, achieved through the implementation of a Thermoelectric Cooler (TEC).

Specifically, this research aims to achieve the following objectives:

- Model and simulate an optimally dimensioned TEC-based control strategy, capable of maintaining the surface temperature at 25°C, accommodating the variable operational temperature range.
- Undertake an economic feasibility assessment of the proposed TEC-integrated system.

## 1.4 RESEARCH METHODOLOGY

The research methodology outlined below will be employed in this study:

- **Literature Review:** A comprehensive analysis of existing literature has been conducted, focusing on diverse techniques, utilized to counteract efficiency reduction in PV modules. Particular emphasis has been placed on the application of thermoelectric devices and their operational principles.

- **System Model Development:** The core of the research involved developing a model aimed at regulating the operation of a Thermoelectric Cooler (TEC), to curtail the temperature of the PV module, as it approaches 25°C.

The model encompasses two distinct systems:

- A standalone PV module (termed as the standard PV).
- A PV module incorporating a TEC, with its associated control circuit.

System variables of the design research modelling process are defined as following:

- State variables:  
Solar irradiation, and Ambient temperature.
  - Control variables:  
Switching status of the dc supply to the TEC.
  - Input variables:  
The mass and specific heat capacity of the PV module, the cooling capacity of the TEC, and the Heatsink's thermal resistance.
- **Simulation of the optimized operation of the PV system:** The impact of the devised control approach, employed to manage the TEC and lower the module temperature, was simulated, using actual data sets encompassing irradiation and temperature. MATLAB served as the simulation platform for these analyses.
  - **Economic analysis:** A Break-even point (BEP) will be used to determine the total cost saving over a 20-year period.

## 1.5 HYPOTHESIS

- The output power of the PV-TEC system will increase through optimal control of the PV panel's surface temperature.

## 1.6 DELIMITATIONS OF STUDY

The study will be steered with the following delimitations:

- The investigation was explicitly centred on mitigating the decline in efficiency within the PV-TEC system.

- The primary emphasis of the study was directed toward the formulation of mathematical models and subsequent simulations.

## 1.7 PUBLICATIONS DURING THE STUDY

Conferences papers:

- G. Mooko, and K. Kusakana, “Prospect of use of a thermoelectric device for PV panel cooling,” *2018 Open Innovations Conference*, pages: 1 -5

Journal papers submitted to be published:

- G. Mooko, P. Hohne, K. Kusakana, “PV energy yield maximization through optimally controlled PV panel cooling using a Thermoelectric cooling device” (in progress).

## 1.8 DISSERTATION LAYOUT

This dissertation has been structured as follows:

**Chapter I:** comprises of the research background, problem statement, and provides the objective of the study and the research methodology.

**Chapter II:** A literature review on the various cooling methodologies used for photovoltaic cooling.

**Chapter III:** Presents the planned thermoelectric cooling model and switching methodology.

**Chapter IV:** provides and discusses the simulated control method results obtained through the use of MATLAB.

**Chapter V:** presents the economic analysis of the proposed photovoltaic thermoelectric cooling control methodology.

**Chapter VI:** concludes the work of this dissertation and indicates the next level for future studies to be carried out.

## CHAPTER II: LITERATURE REVIEW

### 2.1. INTRODUCTION

This Chapter serves as an in-depth exploration of the existing literature on Photovoltaic-Thermoelectric Cooling (PV-TEC), a technology aimed at enhancing the efficiency of PV panels, by leveraging TEC for cooling purposes. There are seven Sections following the introduction in this Chapter. The operation of a photovoltaic panel and thermoelectric cooler, as well as its operation are discussed in Sections 2.2, 2.3 and 2.3.1, respectively. The hybrid PV-TEC arrangement, is discussed in Section 2.4.

The review encompasses an in-depth study of the literature comprising of the utilization of TECs, to cool PV panels. This assessment encompasses a thorough analyses of the experimental setups, control strategies and the resulting system performance, which are concisely summarized in Section 2.5. Section 2.6 further presents a comprehensive discussion, elucidating aspects derived from the literature review, offering valuable insights into the primary findings and observations. Lastly, Section 2.7 presents a concise summary, encapsulating the essential points from the review, offering a consolidated perspective on the subject matter.

#### 2.1.1 Solar photovoltaic system operation

A PV cell is fundamentally constructed, using two layers of differently doped semiconductor material, with its p-n junction exposed to light [4]. When a PV cell is visible to solar radiation, photons are absorbed by the P-N junction within the cell, leading to the creation of a potential variance across the junction. This phenomenon initiates the flow of charge carriers and the resultant photocurrent is typically represented as  $I_{PV}$ . This photocurrent is linked to a P-N junction diode, operating in parallel, to enable the conversion of solar energy into electrical power [5]. A simplified structure of a typical silicon PV cell, is depicted below.

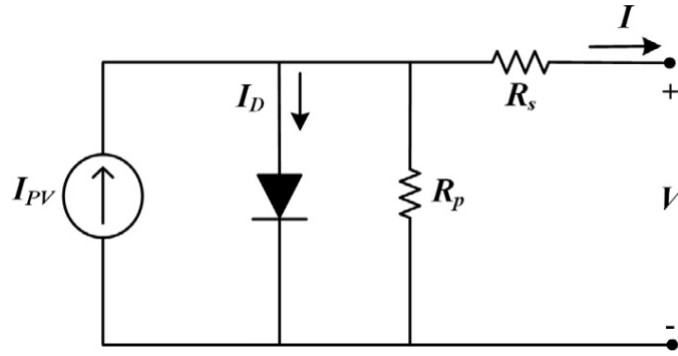


Figure 2.1: The single diode  $R_p$ -model of PV cell [6]

The sun energy that is not transformed into electricity, within a PV panel, is dissipated as heat on the panel's surface. This wasted heat contributes to a reduction in the PV panel's electrical efficiency. To mitigate this efficiency decrease, several mechanisms have been developed and validated. These mechanisms are designed to counter the adverse effects of elevated temperatures, which often exceed  $25^\circ\text{C}$ , ensuring that the PV system remains as efficient as possible, under various operating conditions [7].

Figure 2.2, illustrates the recommended operating temperature range, which spans from  $0^\circ\text{C}$  to  $75^\circ\text{C}$ . Within this range, the P-V characteristics are illustrated, demonstrating the connection between the outputs of power and voltage. It is important to note, that these characteristics are established, while maintaining constant values for solar irradiance and module temperature [8].

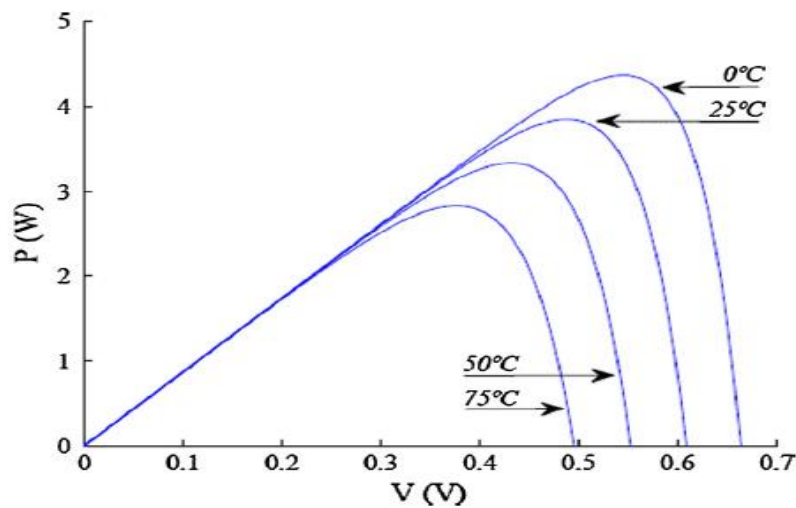


Figure 2.2: P-V characteristics as a function of the module temperature [8]

The influence of temperature on the electrical efficiency of a solar panel, may be analyzed through the utilization of the following equation [5]:

$$\eta_{PV} = \eta_{TR} [1 - \beta_R (T_c - T_R) + \gamma \log_{10} I_{PV}] \quad (2.1)$$

Where:

$\eta_{PV}$  signifies the PV module efficiency evaluated at the reference cell temperature ( $T_R$ ) of 25°C,  $\beta_R$  signifies the temperature coefficient characterizing the impact on cell efficiency, typically falling within the range of 0.004 to 0.005/°C [9],  $I_{PV}$  denotes the average hourly irradiance received by the PV module while operating at its nominal temperature (NT);  $T_c$  represents the actual temperature of the PV module and,  $\gamma$  is the radiation-intensity coefficient of cell efficiency. It's pertinent to note that, in many cases,  $\gamma$  is assumed to be negligible [5], resulting in a simplified form of the equation as follows:

$$\eta_{PV} = \eta_{TR} [1 - \beta_R (T_c - T_R)] \quad (2.2)$$

By incorporating the ambient temperature,  $T_A$ , through addition and subtraction of the respective temperature terms, we arrive at the following expression [9]:

$$\eta_{PV} = \eta_{TR} [1 - 0.9\beta \left( \frac{I_{PV}}{I_{PV,NT}} \right) (T_{C,NT} - T_{A,NT}) - \beta (T_A - T_C)] \quad (2.3)$$

Where:

$T_{C,NT}$  (commonly 45°C) and  $T_{A,NT}$  (generally 20°C) are the cell temperature and ambient temperature. When utilizing Equation (2.3), it is apparent that when  $T_{A,NT}$  increases, this results in a decrease in efficiency.

### 2.1.2 Thermoelectric module

Thermoelectric (TE) technology, represents the direct conversion of a thermal gradient between the junctions of two dissimilar materials, commonly known as a thermocouple, into electrical energy [10]. The Seebeck effect, a pivotal thermoelectric phenomenon, is depicted in Figure 2.3. In this illustration, thermocouple wires A and B, are joined at both extremities and, a voltmeter is incorporated into the circuit, establishing a connection within wire B.

This setup demonstrates the underlying principle of the Seebeck effect, where the temperature gradient  $\Delta T$  between the junctions of dissimilar materials (wires A and B), generates an electromotive force, as measured by the voltmeter, thereby, showcasing the direct conversion of thermal energy into electrical potential. The potential difference across the junctions, is proportional to the temperature difference between the hot ( $T_h$ ) and cold ( $T_c$ ) ends [10]. The thermoelectric generator (TEG) module, may directly convert heat into electricity, through the Seebeck effect [11].

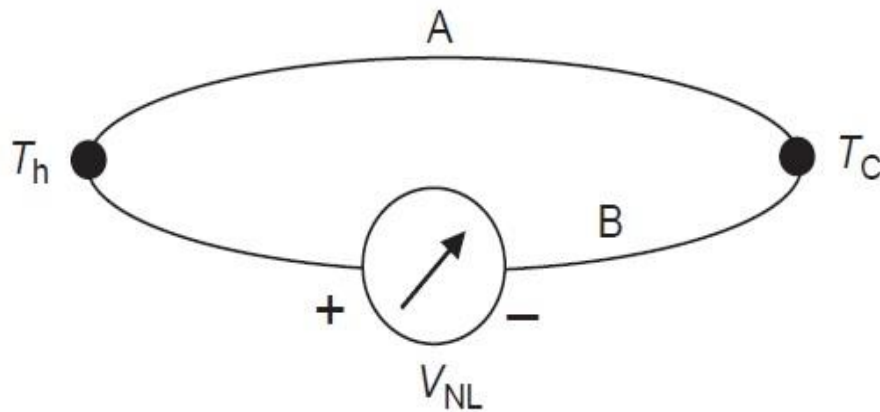


Figure 2.3: Seebeck effect across a thermocouple [10]

Conversely, a different effect known as the Peltier effect, may be created using a thermocouple, with no physical alterations to the module. The Peltier effect is a phenomenon that is created, when a voltage  $E_{in}$  is applied across the terminals T1 and T2 of a thermocouple, resulting in the creation of a temperature differential between its junctions. In this process, a hot surface, in contact with the cold junction  $Q_c$  of the thermoelectric element, experiences a cooling effect, whereas a cold surface, in contact with the hot junction  $Q_h$ , undergoes a heating effect, as illustrated in Figure 2.4 [12].

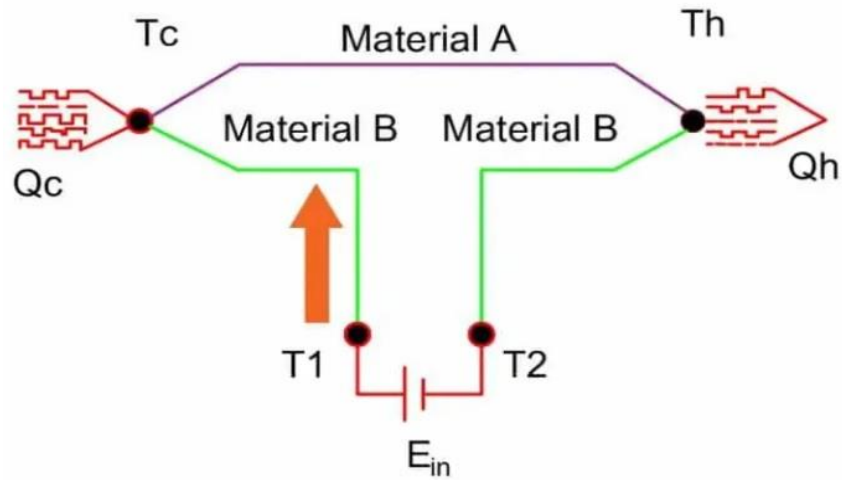


Figure 2.4: Peltier effect across a thermocouple [13]

A Thermoelectric Module (TEM), represents a solid-state energy conversion device at the heart of thermoelectric applications. Typically, this module comprises an array of  $2N$  pellets, crafted from dissimilar semiconductor materials, encompassing both p-type and n-type elements [14]. These elements collectively form  $N$  thermoelectric couples, intricately designed to operate in tandem. They are thermally connected in parallel, while electrically linked in series, as illustrated in Figure 2.5. The TEM may be used for heating, cooling and energy generation [15].

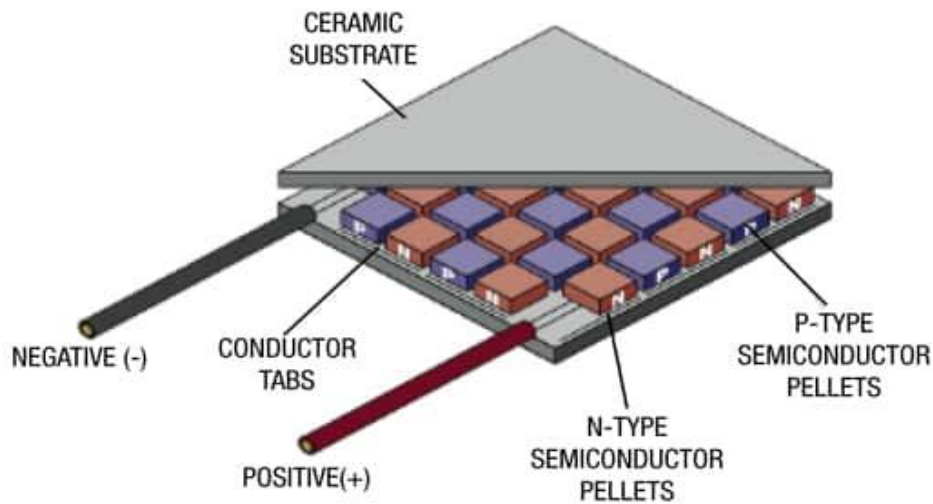


Figure 2.5: Thermoelectric module's pn-junctions and connecting wires [16]



### 2.1.3 Principles of operation

In a TEM, five primary physical processes are at play, as outlined in Reference [15][17]. One of these processes is thermal convection, often explained through the Fourier process. This phenomenon, is characterized by a physical constant denoted as  $k$ , measured in watts per meter Kelvin ( $W/m \cdot K$ ). The value of  $k$ , is a direct outcome of the thermal conductivity and geometric properties of the pellet. It quantifies the module's capacity to conduct heat, providing valuable insights into its thermal performance and efficiency.

The equation of heat transfer in a pellet is:

$$q = kA \frac{\partial T}{\partial x} \approx -k \frac{A}{L} \Delta T = -\frac{\Delta T}{2\Theta} \quad (2.4)$$

Where  $x$  represents the distance along the heat flow path;  $L/A$  is a geometry factor;  $L$  denotes the height of the pellet measured in meters;  $A$  represents the cross-sectional area of the pellet in square meters;  $T$  stands for temperature in Kelvin and,  $q$  denotes the heat in watts, the parameter  $\Theta$  (in Kelvin per watt), signifies the thermal resistance of the pair of pellets. It is mathematically expressed as follows:

$$\Theta = \frac{1}{k} \frac{L}{2A} \quad (2.5)$$

Where:

- $\Theta$  is the thermal resistance in Kelvin per watt ( $K/W$ );
- $L$  is the height of the pellet in meters ( $m$ );
- $A$  is the cross-sectional area of the pellet in square meters ( $m^2$ );
- $k$  is the thermal conductivity of the pellet material, often expressed in watts per meter Kelvin ( $W/m \cdot K$ ).

This thermal resistance  $\Theta$ , provides a measure of the resistance to heat flow through the pellet and helps in characterizing the thermal behavior of the thermoelectric module.

The total thermal resistance ( $\Theta_{\text{total}}$ ) of the  $N$ , couples in a thermoelectric module, when they are connected thermally in parallel, may be calculated as follows:

$$\Theta_m = \Theta/N \quad (2.6)$$

Where:

- $\Theta_{\text{total}}$  is the total thermal resistance of the  $N$  couples, measured in Kelvin per watt ( $K/W$ );
- $\Theta$  is the thermal resistance of an individual couple of pellets, further measured in Kelvin per watt ( $K/W$ );
- $N$  represents the number of thermoelectric couples in the module.

This equation reflects the concept that, when the thermoelectric couples are connected thermally in parallel, the overall thermal resistance decreases, as the heat may flow through multiple couples simultaneously.

Joule heating is the physical process, by which heat is generated and dissipated within resistive elements. The electrical resistance ( $R$ ) of a pair of thermoelectric pellets, is a critical factor in understanding this phenomenon. It may be defined as:

$$R = \rho \frac{2L}{A} \quad (2.7)$$

$$q_j = I^2 R_m \quad (2.8)$$

Where:

- $R$  is the electrical resistance, typically measured in ohms ( $\Omega$ );
- $\rho$  (rho) represents the resistivity of the material, measured in ohmmeters ( $\Omega \cdot m$ );
- $L$  is the length of the pellet in meters ( $m$ );
- $A$  is the cross-sectional area of the pellet in square meters ( $m^2$ );
- $q_j$  is the Joule heating of the TEM in Watts ( $W$ ).

This equation highlights the relationship between the electrical resistance of the pellets and their physical dimensions, as well as the electrical resistivity of the material from which they are constructed. Joule heating occurs due to the flow of electrical current, through a resistive material, such as the thermoelectric pellets, resulting in the generation of heat under the resistance and the square of the current passing through it ( $P = I^2 \cdot R$ ). This heat is thereafter dissipated into the surroundings.

Seebeck power generation, is a process in which the heating or cooling of the junction between two dissimilar materials, leads to the generation of an electrical potential across that junction.

$$\pi = \alpha T \quad (2.9)$$

In this context, we have  $\pi$ , known as the Peltier coefficient, representing the electrical potential measured in volts at the junction. Additionally, there is  $\alpha$ , which is the Seebeck coefficient for a specific combination of materials, expressed in volts per Kelvin. For  $N$  couples in a TEM.

$$\alpha_m = \alpha N \quad (2.10)$$

Therefore, the electromotive force (EMF) of the thermoelectric module (TEM), will be as follows:

$$U = \alpha_m (T_a - T_e) \quad (2.11)$$

The heat-absorbing junctions are referred to as the ( $a$ ) side, while the heat-emitting junctions are designated as the ( $e$ ) side of the TEM. The temperature of the heat-absorbing junction is denoted as  $T_a$  and the temperature of the heat-emitting junction is denoted as  $T_e$ , as illustrated in Figure 2.6 This arrangement and temperature difference, are fundamental to the operation of Peltier cooling, a process that utilizes the Peltier effect to achieve cooling or heating as needed.

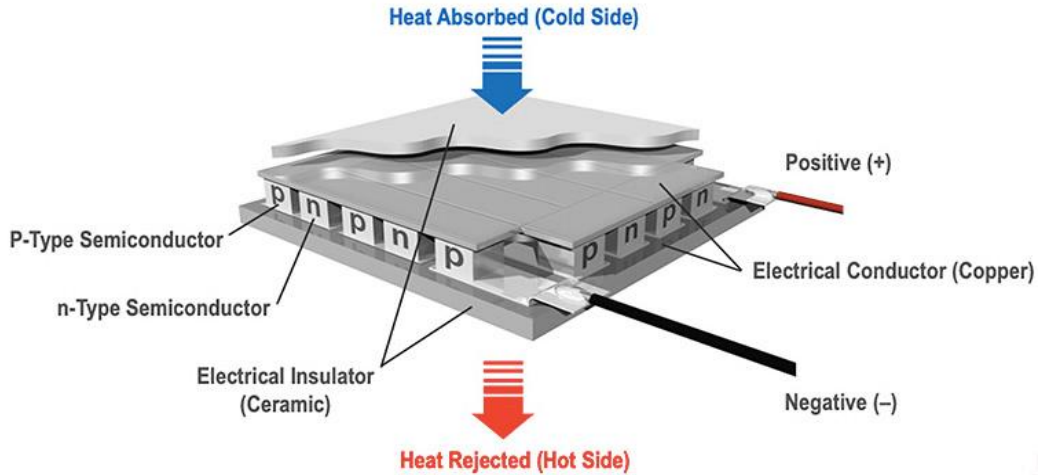


Figure 2.6: Thermocouple denoting the cold and hot side [18]

Peltier cooling/heating, refers to the phenomenon where a junction between two dissimilar materials absorbs or dissipates heat, when an electrical current flows through it. This effect enables the generation of either cooling or heating at the junction, depending on the direction of the electrical current and is a fundamental principle in thermoelectric technology. The heat  $q_{pa/pe}$  absorbed/emitted by the TEM is:

$$q_{pa/pe} = \alpha_m T_{a/e} I \quad (2.12)$$

Peltier cooling/heating, represented by  $q_{pa/pe}$ , is highly dependent on the direction of the electrical current. Consequently, in a TEM, half of the junctions that carry the current in one direction will absorb heat, while the remaining half, where the current flows in the opposite direction, will release heat. This bidirectional nature of Peltier cooling and heating, allows for the control of temperature differentials and is a fundamental aspect of thermoelectric systems.

### 2.1.4 Hybrid photovoltaic/thermoelectric (PV-TE) system

In the realm of thermoelectric devices, it is notable that a thermocouple exhibits a useful functionality, capable of serving as both a TEG and a TEC. The primary focus of this research, revolves around harnessing the TEC attributes of a thermocouple, to enhance the operational efficiency of PV panels. This arises from the inherent temperature sensitivity of PV modules, which experience a decline in efficiency beyond the critical threshold of 25°C [4,7]. Upon the application of an electrical voltage to a thermoelectric device, it transitions into the role of a

TEC, thereby producing a temperature differential across its structural profile. This transformation precipitates the heating of one side, while the opposite side undergoes a cooling process, a phenomenon known as the Peltier effect [19].

Within the specific setting of a Hybrid PV/TEC system, the TEC unit is affixed on the rear surface of the PV module, with secure adhesion by a thermal transfer compound. The cold side of the TEC interfaces directly with the PV module, whereas a heat sink, affixed using a thermal transfer compound, is mounted on the TEC's warm side. This configuration serves as a channel for the efficient dissipation of excess heat, into the surrounding ambient environment.

Crucially, the precision control of the TEC's operational parameters, plays a pivotal role in effecting the desired outcome. Through this approach, the temperature of the PV module is effectively reduced, thereby providing a clear and measurable improvement in its operational efficiency and overall performance. A typical setup is illustrated in Figure 2.7.

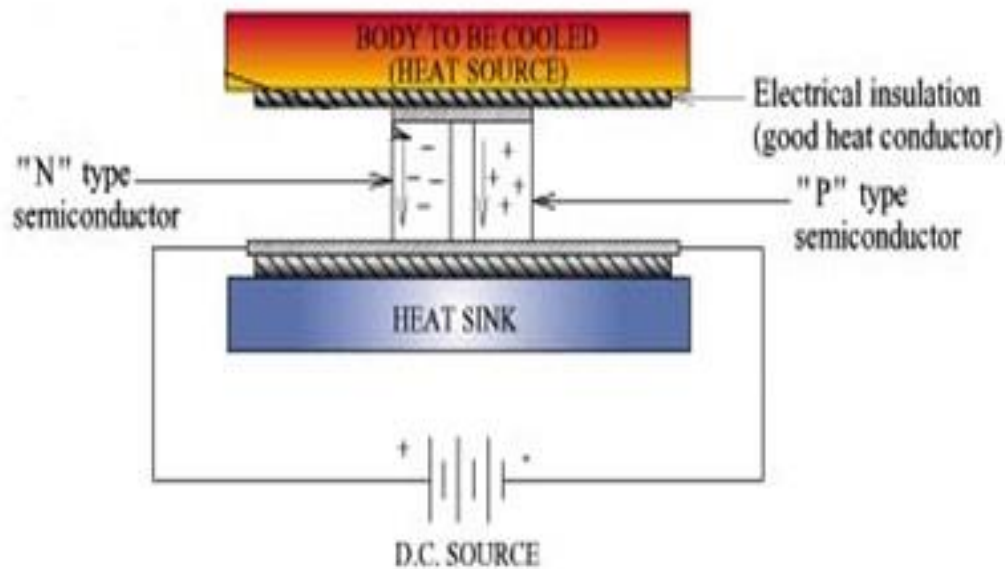


Figure 2.7: Setup of PV cooling using a TEC [20]

The PV/TE system described above comprises the following essential components:

- Thermoelectric device ("P" and "N" type semiconductor)
- Photovoltaic module (Body to be cooled)
- Thermal transfer compound (Electrical insulation)
- Heat sink
- DC source

These essential elements collaborate to facilitate the dynamic operation of the PV-TEC system, ensuring optimal thermal management and enhanced performance.

## 2.2 REVIEW OF RELEVANT LITERATURE

A multitude of researchers have undertaken efforts, aimed at elevating the efficacy of PV panels, by mitigating challenges related to the operating temperature of PV surfaces, employing TECs as a potential solution. The forthcoming literature reviews encompass some of the investigations conducted by various researchers, shedding light on their distinct methodologies and emphasizing the outcomes, assembled from their respective studies.

Kumar et al. (2015) [21], conducted a study that integrates photovoltaic, thermal and cooling functionalities, by leveraging semiconductor components to simultaneously generate electrical energy, heat and cold energy. At the core of this system, lies the integration of a TEC module, affixed to the rear surface of the solar PV module, with an aluminium heatsink, tasked with the absorption of heat from the PV panel and its transfer to a heatsink.

A model was developed and solved, by using MATLAB, to obtain temperatures and heat fluctuations through the PV-TEC system, at each given ambient temperature and Solar radiation level. The conclusion drawn, is that this approach will be effective when the TEC module possesses a high Z value and will demonstrate enhanced efficiency, under elevated solar radiation levels [22].

Within this paper, a thorough thermal model of the solar panel is simulated, using ANSYS Workbench, allowing for an in-depth analysis of the thermal characteristics of each layer within the PV panel. The research involved a comparison between simulation results and experimental measurements, revealing a consistent correlation between the two datasets. Additionally, the research paper provides data relating to the maximum electrical efficiency, panel temperatures and outlet air temperature of the PV-TEC panel.

Temperature measurements were taken at the bottom panel glass surface of the PV-TEC from 8 a.m. to 5 p.m. No control method was applied in this study and the authors concluded that automatically switching off the power input to the TEC, when the panel temperature reaches a safe level, may improve the efficiency of the system.

The obtained results are summarized as follows:

- The PV-TEC system exhibited a maximum electrical efficiency, ranging from 11.52% to 11.87%, whereas, without a TEC, it ranges from 10.18% to 11.37%.
- The temperature of the rear panel of the PV/TEC panel, was measured at approximately 33.3°C, while the maximum temperature was around 43.1°C.
- The simulated results from the geometric model in ANSYS Workbench showed a satisfactory agreement with the experimentally measured values.

Praveen et al. (2022) [23], presented a paper that extensively describes the configuration of their test rig and the mathematical equations, employed for result computations. Their experimental setup, featured two panels: one equipped with a thermo-electric cooler (referred to as the cooled panel) and the other panel remained unaltered, serving as a reference module. The test rig comprised of 4 TEC's mounted on the rear side of a PV panel, a heat sink mounted on the TEC's hot side and a cooling fan attached to the heat sink.

The key findings from their study may be summarized as follows:

- The temperature of the cooled PV panel averaged 33.37°C, whereas the reference PV panel maintained an average of 45.60°C. The implementation of the TEC, resulted in a temperature reduction, lowering the PV panel's temperature to 12.23°C.
- The measured electrical efficiency of the cooled PV panel, was 20.88%, when compared to the reference PV panel.
- The economic analysis of the cooled module, revealed a comparatively lower levelized cost of electricity (LCE), when compared to the reference module. This outcome was observed, despite the initial investment costs associated with the cooling system being higher.

Moshfegh et al. (2018) [24], conducted a study with the primary aim of optimizing the output power of photovoltaic panels, through the implementation of thermoelectric cooling. Their study focused on optimizing the PV panel's temperature, using a genetic algorithm, that does not cover the effects of wind speed, ambient temperature and fin area. A simulation of the TEC model was developed using MATLAB, to assess the effects of ambient temperature, fin area variation, radiation variation and wind speed variation.

This investigation considered a range of design and operational parameters, leading to the following key findings:



- The net power output of the PV cells gradually decreases, increasing cell temperature; and the ambient temperature plays a significant role in influencing the cell temperature. The simulations confirmed the accuracy of the model.
- The variation in the fin area affects the net output power, with the greater fin area leading to lower PV panel temperatures and improved performance.
- Wind velocity has a complex impact on the net power output, dependent on ambient temperature and incoming radiation. At low irradiation levels, wind manages to reduce PV cell efficiency, as the PV panel becomes cooler than the ambient temperature, while at high irradiation levels, wind cools the system and enhances efficiency.
- However, at significantly high wind velocities, the net power output may decrease as the thermoelectric cooler consumes power, without providing effective cooling.

Kane et al. (2017) [25], presented a paper, outlining a temperature-driven Maximum Power Point Tracking (MPPT) strategy, designed to maintain thermoelectric modules at the optimal temperature for a PV system. The enhancement in the performance of the PV panel with TEC, is demonstrated by simulated results, using MATLAB/SIMULINK, to calculate the adequate heat sinking from the PV panel. The MPPT algorithm in use, is the Perturb and Observe (P & O) for its simplicity and reasonable accuracy. The P&O-based algorithm, swings the PV panel's temperature, by controlling the current to the TEC, to pivot the temperature at the MPPT point.

The key findings of the study may be summarized as follows:

- Enhancements in the electrical efficiency of the PV module, ranging from 1% to 18%, have been documented. These improvements are notable within the solar insolation range of 0.8 to  $1kW/m^2$  and the temperature range of 25°C to 45°C, effectively compensates for the power consumption of the TEC system.
- The outcomes reveal a substantial reduction in PV panel temperatures, ranging from 6% to 26%. These reductions are achieved within the solar insolation range of 0.8 to  $1kW/m^2$  and a temperature range of 25°C to 45°C, employing the suggested temperature based MPPT controller.

Dimri et al. (2018) [26], investigated enhancing the electrical efficiency of an opaque photovoltaic module. Their approach involved integrating a TEC at the base of the module. The study encompassed the creation and validation of a thermal model, specific to this PV-TEC collector. Three PV-TEC collectors, with different packing areas, were used. One was



partially covered with TEC's, the other was fully covered with TEC's. Both did not contain an air duct, while the third one solely had an air duct. The research explored the influence of TEC module coverage, specifically comparing scenarios involving partial and full coverage. This research involved the use of 36 TEC modules, each having dimensions of  $4\text{ cm} \times 4\text{ cm}$ .

The key findings of the study may be summarized as follows:

- The fully covered TEC configuration demonstrated superior electrical efficiency, outperforming the partially covered configuration by a margin ranging from 4.46% to 6.23%.
- The enhancement in electrical efficiency of the PV panel equipped with an air duct, may be attributed to the convective airflow within the duct. This airflow efficiently mitigated the operational temperature of the PV panels, resulting in improved performance.
- This leads to thermal energy gain in the range of 15W to 37W, due to the air duct.

Amelia et al. (2017) [27], conducted a study, to assess the efficiency of TEC. The researchers established an experimental setup, consisting of three distinct configurations, alongside a reference PV panel lacking any form of cooling. The first configuration employed a TEC module, without any control mechanism. The second employed water as the cooling medium. The third combined both the TEC and water cooling. Given this research's primary focus on TEC for PV panel cooling, we will exclusively discuss the TEC setup and the results.

A 10W PV panel, with a surface area of  $105\text{mm}^2$ , was utilized in the experiment, along with eleven (11) TEC modules, each having a surface area of  $40 \times 40 \times 4.3\text{mm}^3$ . Notably, no heat sink was installed on the TEC modules. The experiment took place outdoors on a sunny day, commencing at 11:30 and concluding at 14:15.

The obtained results were compared to those of the reference PV panel, leading to the following observations:

- The reference PV panel generated 8.59 W, at a temperature of  $56.03^\circ\text{C}$ .
- The cold side maintained an average surface temperature of  $49.13^\circ\text{C}$ , resulting in an approximate  $2.2^\circ\text{C}$  temperature difference between the cold and hot sides.
- The PV panel with a TEC exhibited a power output that was 1.5% higher than that of the reference PV panel, after the cooling process.

This fact is supported by studies that states that the output power of the PV panel will be increased when its operating temperature is decreased [28].

Benghanem et al. [29], situated in Madinah, Saudi Arabia, where ambient temperatures soar to 50°C, an investigation was carried out to address the issue of PV panel overheating. Under these environmental conditions, PV panel temperatures can reach up to 83°C, posing a substantial challenge to their efficiency and lifespan. The primary focus of this study was to implement TEC modules as a cooling mechanism for PV panels. The experimental setup featured two miniature PV panels, measuring 188 x 188mm. One of these panels was equipped with a TEC module mounted on its rear surface, while the other panel remained devoid of any cooling mechanism. The TEC module was powered directly from the PV panel that it was mounted on, establishing an integrated and self-contained cooling system.

The experimentation conducted produced the following findings:

- As solar radiation increases, the PV panel powering the TEC modules, provides higher voltage to drive the TEC system. Therefore, the cold side of the TEC modules' temperature drops even more, leading to a continuous improvement in the overall efficiency of the PV panel.
- An improvement in efficiency of 0.5% per °C decrease in temperature, was realized.
- The maximum power generated was 181mW, at 940  $W/m^2$  per 25°C.

Maryani et al. (2023) [30], conducted an investigation involving three (3) monocrystalline PV panels, each with a power rating of 50W. Each of these PV panels was configured uniquely, to explore their thermal performance under varying conditions. For the cooling aspect of the study, TECs with dimensions of 40 x 40 x 3.9mm were employed.

The configurations of the PV panels were as follows:

- a) The first panel remained devoid of any TECs (no cooling applied).
- b) The second panel featured 20 TEC's connected in series and mounted on the side of the PV panel.
- c) The third panel further incorporated 20 TEC's connected in series, however, mounted on both sides and rear surfaces of the PV panel.

These panels were positioned at an elevation of approximately 12 meters above the ground and were inclined at an angle of 15°. Data collection took place over ten hours, from 07:00 to 17:00.

The outcomes of this investigation yielded the following results:

- Under the ambient conditions of 40.2°C, the performance of the PV panels (a), (b) and (c), revealed distinct voltage outputs. Specifically:
  - PV panel (a) generated a voltage of 22.7V.
  - PV panel (b) exhibited a slightly higher voltage of 22.8V.

- PV panel (c) achieved the highest voltage output among the three, registering 23V.

These findings underscore the influence of the cooling configurations on the electrical performance of the monocrystalline PV panels.

- The average power outputs of the different PV panels under consideration, were as follows:
  - PV panel (a) exhibited an average power output of 3.34W;
  - PV panel (b) displayed a higher average power output of 4.19W;
  - PV panel (c) demonstrated the highest average power output of 12.26W.
- The overall efficiency of PV panel (c) was 32.6%, when compared to PV panel (a).

Al-Otab et al. (2019) [31], conducted a study with the primary focus on experimentally assessing the cooling impact of TEC, to enhance the energy yield of various types and dimensions of PV panels. To aid in the efficient dispersion of accumulated heat, a fin fan heat sink was additionally affixed to the hot side of the TEC. Notably, two TEC's were deployed simultaneously during the experiment to explore the upper limits of achievable temperature differentials. The PV panels utilized in this investigation, encompassed a range of power outputs, spanning from 2W to 10W and were composed of various semiconductor materials, including Polycrystalline, Monocrystalline and Amorphous Silicon thin-film varieties.

Table 2.1 Specifications of the tested solar cells and modules

| Model                      | Specifications |              |                 |
|----------------------------|----------------|--------------|-----------------|
|                            | Power (W)      | $V_{oc}$ (V) | Dimensions (mm) |
| Mini Polycrystalline       | 5              | 7            | 135 x 110       |
| Solar cell Monocrystalline | 5              | 5            | 190 x 220       |
| Monocrystalline            | 5              | 20.37        | 216 x 33        |
| Amorphous Si thin film     | 5              | 22.8         | 293 x 330       |
| Polycrystalline            | 10             | 20.8         | 438 x 238       |

During the experiment, a halogen lamp served as the irradiance source for the various PV panels. Once these panels reached a juncture, where the current-voltage (I-V) curve exhibited the influence of temperature on the solar cell characteristics, the lamp was deactivated. Subsequently, the PV panels and cells were left to cool down, undergoing natural cooling, as well as assisted cooling, with the use of a TEC device. Measurements were taken at 30-second intervals, throughout this cooling process.

The findings of the experiments for the 2W solar cell are as follows:

- The TEC module was able to obtain a maximum temperature difference of 73°C at a power consumption of 88.8W.

- An increase in temperature resulted in a decrease in cell voltage. Conversely, an increase in current was observed, due to the growth in the number of carriers generated thermally in the solar component.
- With the use of a single TEC module, a power enhancement of 7.02%, was achieved.

A comparable methodology, such as that implemented on the 2W solar modules, was applied to generate heat within the 5 to 10W PV modules. These PV modules were permitted, to attain a temperature of 65°C, subsequently undergoing cooling processes, both with and without the incorporation of a TEC module. Given the larger dimensions of the PV modules, the experimentation involved the utilization of two TEC's, and the following observations are explained below:

- A 7.5°C temperature difference was realized, resulting in a power increase of 4.67% and an open-circuit voltage increase of 4.34%, as compared to the PV module without cooling.

This experiment highlights that employing a TEC was inefficient, primarily attributable to the considerable power consumption required to attain these outcomes. This suggests that this approach is economically impractical. Universally, solar cell performance improvements are more observable and efficient, in comparison to solar modules. This discrepancy arises primarily from the reduced thermal insulation properties of the encapsulation materials, used in solar cells.

Moshfegh et al. (2017) [32], conducted a study that took on a feasibility assessment, to investigate the practicality of incorporating TEC modules into photovoltaic cells. The governing equations relevant to this study are simulated using MATLAB, across varying environmental conditions, facilitating a comprehensive comparison between scenarios, involving active TEC cooling and those without it. Furthermore, the disparities in net power generation between photovoltaic cells with cooling and those without, are analyzed, particularly under conditions of high irradiation levels. The TEC is powered by the PV cells in question, to operate and increase the efficiency of the PV cells.

The study produced the following findings:

- Observations reveal that employing optimal thermoelectric cooling significantly enhances efficiency, with the cooling effect becoming more pronounced and noticeable under higher irradiation conditions.

- A 6.35% increase in PV cell output power, was attainable with the use of a TEC module at an irradiance of  $6000 \text{ (W/m}^2\text{)}$ , with the PV cells reaching a temperature of 310K ( $36^\circ\text{C}$ ).
- The maximum net output power is reached, at an irradiance of  $4100 \text{ (W/m}^2\text{)}$ , causing the PV cells to reach a temperature of 300K ( $26^\circ\text{C}$ ), with an output power increase of 3.26%.

Montayre et al. (2015) [33], proposed a PV-TE system, that alternated between energy harvesting mode and cooling mode. Data from PV systems equipped with TE attachments, operating in both generator and cooling modes, were collected and subsequently compared with a dataset obtained from PV systems, operating without TE components. The layout design of the aforesaid configuration, is seen below.

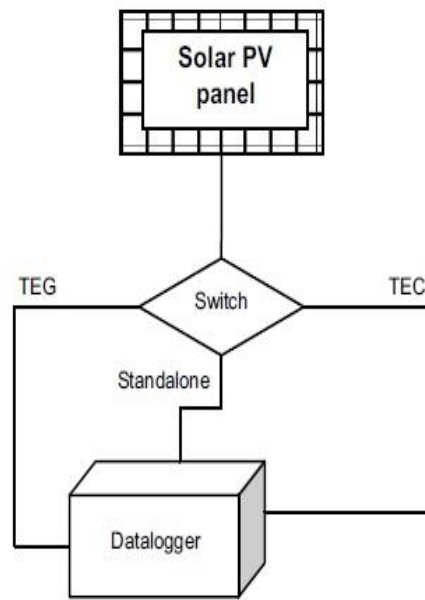


Figure 2.8: Layout design of the model of a PV-TE system [33]

The utilization of a TE module in its generator configuration represents a recognized form of passive cooling [34]. This approach involves the TE module absorbing heat from the PV modules and converting it into electrical energy. On the other hand, the TE module in its cooling mode may be perceived as a form of active cooling. In the experimental setup, the TE module TEG configured as a generator, was attached to the rear of the PV module, with the TE module TEC functioning as a cooler, affixed to the generator module. Eight (8) TEC modules, each equipped with heat sinks, were evenly distributed across the rear surface of the PV panel.

The system operated in generator mode, during specific times of the day, when it was deemed more efficient in that mode. Conversely, it switched to a cooling operation, during periods when this mode was found to be more effective. Simulations of this setup were conducted using MATLAB, indicating that a power output of 21W, may be achieved when 20 TEG modules with a 60°C temperature difference, are used. Due to the focus of this study being on the use of TEC to improve the efficiency of PV modules, only the TEC results will be listed and discussed.

The following results were realized:

- Experimental results were less by an average of 3.7%, from the simulated results when the TE was used as a cooler.
- The TE module as a TEC showed a 2% increase in PV module output power, when compared to a module without cooling during outdoor deployments.

Najafi et al. (2013) [35], proposed the use of a TEC attached to the rear of a single PV cell. The power required to run the TEC, is provided by the PV cell itself. The setup was modeled using MATLAB, to simulate and determine the temperatures with the systems, the power required to run the TEC and the surplus power generated by the cooling effect of the PV cells.

Two approaches were applied in the proposed system:

- The primary objective is to regulate the temperature of the photovoltaic cell to maintain it below a predefined threshold, adapting to varying environmental conditions, as needed.

This approach uses the TEC to protect the PV cells, by maintaining the temperature within certain limits, to keep it from degradation, due to high cell temperature.

- A genetic algorithm-based optimization method, is employed to determine the optimal value of the supplied electrical current for the thermoelectric cooling module. This optimization process, aims to identify the current level that results in the highest generated power output by the entire system.

The genetic algorithm (GA), serves as a stochastic numerical search technique in this context. A suite of MATLAB functions has been developed, to facilitate the GA optimization process. The objective function is formulated as the difference between the power savings, resulting from the temperature reduction in the PV cell and the power consumed by the TEC module. Specifically, the optimization variable under consideration, is the electrical current supplied to the TEC module ( $I_c$ ). Therefore, for a given ambient temperature and solar radiation level, the

GA is employed, to identify the optimal value of ( $I_c$ ), that maximizes the system's output power.

The findings from these results, are discussed below:

- The high temperature was kept at 340K, for different ambient temperatures at an irradiance of  $2000 \text{ W/m}^2$ , see Table 2.2 below.
- It has been demonstrated that the TEC module may serve as an effective means for regulating and controlling the temperature of PV cells. See Table 2.2 below.
- Using the GA may lead to the highest net output power, however, this approach is significantly more promising when the TEC module in use has a high Z value and will be more effective for higher solar radiation levels.

Table 2.2. Power required to maintain PV module temperature (solar irradiance:  $2000 \text{ W/m}^2$ )

| $T_{amb} (K)$ | $I_c (A)$ | $P_{TEC} (W)$ | $P_{Net} (W)$ |
|---------------|-----------|---------------|---------------|
| 300           | 0         | 0             | 2.9           |
| 301           | 0.24      | 0.0451        | 2.8838        |
| 302           | 0.25      | 0.046         | 2.8515        |
| 303           | 0.3       | 0.1229        | 2.7655        |
| 304           | 0.39      | 0.3422        | 2.5577        |
| 305           | 0.45      | 0.4853        | 2.4033        |
| 306           | 0.54      | 0.8357        | 2.0605        |
| 307           | 0.6       | 1.0439        | 1.8389        |
| 308           | 0.69      | 1.5234        | 1.363         |
| 309           | 0.8       | 2.0881        | 0.7995        |
| 310           | 0.88      | 2.7372        | 0.1492        |

$P_{Net}$  is the power generated minus the power consumed by the TEC module.

Table 2.3. Power required to maintain PV module temperature (ambient temperature: 300K)

| $G (W/m^2)$ | $I_c (A)$ | $P_{TEC} (W)$ | $P_{Net} (W)$ |
|-------------|-----------|---------------|---------------|
| 2000        | 0         | 0             | 2.97          |
| 2100        | 0.25      | 0.0324        | 3.0287        |
| 2200        | 0.45      | 0.4372        | 2.8155        |
| 2300        | 0.55      | 0.7516        | 2.64          |
| 2400        | 0.75      | 1.64          | 1.93          |
| 2500        | 0.95      | 2.86          | 0.8775        |



Algu et al. (2021) [36], conducted a pilot model, which was employed to explore the utilization of a TEC module. This investigation aimed to enhance the efficiency of PV panels, addressing two prevalent challenges: excessive heating in PV panels during the summer months and snow accumulation on PV panels, during the winter season. The TEC module was configured to function both in TEC, often known as the Peltier effect and TEG, commonly referred to as the Seebeck effect, modes.

The Peltier and Seebeck effects, which exhibit opposite behaviours, constitute the fundamental principles underlying the thermoelectric effect. Consequently, the collective phenomenon is commonly referred to as the "Peltier-Seebeck Effect" in the literature, as noted by Ahiska in 2007.

The experimental setup, consisted of several key components, including a thermoelectric module, a temperature control unit, a 12V 7Ah lead acid battery, and a modified fan-equipped PV panel. The battery, characterized as a 12V 7Ah lead acid type was charged by a 20W polycrystalline PV panel and it supplied power to the thermoelectric module.

In the modified PV panel, adjustments were made to the voltage direction to enable cooling of the panel (TEC mode), within a predefined temperature range, specifically set between 30°C and 40°C, utilizing a temperature control sensor. Additionally, a standard PV panel with identical specifications, lacking any cooling mechanism, was incorporated into the pilot setup, for comparative purposes.

Observations made from the experiment in the summer season:

- The standard PV panel's output voltage decreased by 15%, at a temperature of 56.2°C.
- The modified PV panel's output voltage decreased by 3%, at a temperature of 41.9°C, which was controlled by a TEC.

The following observations were made during the winter season:

- A direct correlation was observed between the extent of snow accumulation on the panel surface and a reduction in energy efficiency. As the snow cover increased, the efficiency declined, reaching a point of complete loss of efficiency, when the panel surface was entirely covered with snow.
- With the thermoelectric module operating a TEG, the PV panel was heated and the PV panel was completely cleaned from the snow.
- At an ambient temperature of 3°C, the PV panel was capable of reaching a maximum achievable voltage of 13.3V, as per manufacturer specifications, after 15 minutes of PV panel heating.
- The standard PV panel recorded a 15% reduction in efficiency.



The incorporation of the system, led to a 40% cost escalation for the standard photovoltaic panel and the author states, that the panel will provide more than a 50% efficiency increase every year in summer and winter, which will offset the initial costs over the lifetime of the PV panels.

Kusuma et al. (2023) [37], focused on investigating the cooling mechanism of a PV panel through the utilization of a TEC controlled by a Microcontroller. This research involved a comprehensive experimental setup, comprised of key components, including a PV panel, an Arduino Uno microcontroller, a TEC, a heat sink and a DC fan.

The TEC module was strategically positioned on the rear side of the PV panel, serving as the primary heat transfer interface. Concurrently, the heat sink was securely affixed to the TEC module, functioning as the secondary heat dissipation element. To enhance the dissipation efficiency, a DC fan was mounted onto the heat sink. Its purpose was to facilitate the dispersal of heat, that had been absorbed by the heat sink, from the TEC module.

The role of the Arduino Uno microcontroller, in this setup, was to continuously monitor the temperature at the rear surface of the PV panel. When the temperature reached a predetermined threshold of 40°C, the microcontroller activated both the TEC and the fan, through a relay mechanism. This activation was critical for initiating the cooling process to prevent the PV panel from overheating. Conversely, when the temperature dropped to 38°C, the microcontroller promptly deactivated the TEC and fan, to conserve energy and maintain optimal operating conditions.

Throughout the duration of the experiment, temperature measurements were taken at regular intervals of 30 minutes. These measurements were, thereafter, systematically compared to those obtained from a similar PV panel, that did not employ any form of active cooling. This comparative analysis, allowed for the researchers to assess the effectiveness of the TEC-based cooling system to enhance the thermal performance and efficiency of the PV panel, ultimately contributing valuable insights to the field of photovoltaic engineering and renewable energy technologies.

Findings from the setup are as follows:

- The PV panel's back temperature was reduced by an average of 14.5%, with TEC cooling.
- PV panel output power loss, was reduced by 4%.
- PV panels with a TEC, had an average power of 25.373 W, while the standard PV panel averaged 23.820 W.

Nadimuthu et al. (2022) [38], delved into an investigation of the performance characteristics of a PV panel, integrated with a TEC, using the MATLAB Simulink platform. To conduct their research, they developed a computational model, however, furthermore, established an experimental setup, to validate their findings.

The experimental model that the researchers constructed, consisted of several key components, including a 100W polycrystalline PV panel, a 60W TEC module and an essential heat dissipation component in the form of a fan. This fan was strategically attached to a heat sink, connected to the TEC, functioning as a convective forced air-cooling system. This cooling system played a pivotal role in maintaining the temperature of the PV panel, within optimal operating limits. Additionally, the setup was equipped with a Pulse Width Modulation (PWM), based charge controller and a 35Ah lead-acid battery, to manage the electrical aspects of the system, ensuring efficient energy utilization.

For the development of the computational model within MATLAB Simulink, the researchers gathered intrinsic parameters specific to the PV panel and TEC. These parameters served as the foundational data, for creating a comprehensive Solar PV-TEC system model. This model incorporated both electrical and thermal energy conversion equations, drawing upon the capabilities of MATLAB Simscape for the thermal modelling aspects. Notably, the PV panel was represented in the Simulink model, as a block, with 36 solar cells connected in series, accurately capturing the electrical behaviour of the panel.

By integrating both experimental and computational approaches, aimed to comprehensively explore the behaviour and performance of the PV-TEC system, shedding light on its potential applications and enhancing the understanding of as to how integrated systems operate.

The following observations were made during the simulation:

- The TEC's cooling capacity of 70 W at 3A, was achieved.
- The operating current and voltage of the configuration, reached 55 W.

The findings from the experimental analysis were as follows:

- A maximum cooling capacity of 58.15 W, was achieved.
- A cooling capacity of 6.94 W, was achieved concerning the cold side, reaching a temperature of 6°C.
- The maximum temperature reduction was achieved, during an input current of 4.9A.
- Forced air circulation increased heat removal, by reducing the hot side temperature by 33.41%.

Najafi et al. (2012) [39], conducted research, to ascertain temperature values across distinct system sections and calculate the essential power input for the TEC module, as well as the additional power generated by PV panels, owing to the cooling phenomenon. With a Solar Concentrating Photovoltaic (CPV) system and TEC mounted on the back side of the PV in mind, a heat transfer model using MATLAB, was developed and simulated. A fraction of the electrical output produced by the PV panel, is allocated for powering the TEC modules.

The primary objective of this study, was to maintain the PV panel temperature within the range of 355K, which aligns with the typical operating limits of most commercially available PV cells. However, in the context of CPV, at a 2X concentration level, to mitigate long-term degradation and sustain optimal efficiency, the temperature threshold, was set at 330K. This allowed for the determination of the minimum required electrical current supply to the TEC module, ensuring adequate cooling for the PV system.

Below, the table presented provides insights into the solar irradiation levels required to power the selected TEC module and quantifies the surplus power generation achieved after powering the TEC, using the PV panel. The ensuing results are derived from the simulation and are presented in tabular form, for clarity.

The following measurements were taken on an hourly basis:

- $T_{amb}$  - Ambient temperature (K)
- $G$  - Solar radiation (W)
- $T_{cell}$  - Cell temperature (K)
- $I_c$  - Electrical current (TEC) (A)
- $P_{TEC}$  - Power consumption (TEC) (W)
- $P_{PV}$  - Power of the PV cell at original temperature (W)
- $P_{PV,330K}$  - Power of the PV cell at reduced temperature (W)

Table 2.4: Simulation results with respect to time throughout the day

| Time  | $T_{amb}$ | $G$    | $T_{cell}$ | $I_c$ | $P_{TEC}$ | $P_{PV}$ | $P_{PV,330K}$ |
|-------|-----------|--------|------------|-------|-----------|----------|---------------|
| 8 AM  | 298       | 1125.1 | 328.9      | 0     | 0         | 1.678    | -             |
| 9 AM  | 300       | 1286.2 | 333.4      | 0.26  | 0.1116    | 1.862    | 1.934         |
| 10 AM | 302       | 1257.7 | 333.7      | 0.28  | 0.134     | 1.808    | 1.885         |
| 11 AM | 302       | 1318.6 | 335        | 0.39  | 0.3107    | 1.881    | 1.99          |

|       |     |        |       |      |        |       |       |
|-------|-----|--------|-------|------|--------|-------|-------|
| 12 AM | 304 | 1296.9 | 335.4 | 0.43 | 0.3899 | 1.837 | 1.952 |
| 1 PM  | 304 | 1228.9 | 333.9 | 0.3  | 0.1592 | 1.75  | 1.835 |
| 2 PM  | 305 | 1232.9 | 334.5 | 0.35 | 0.2355 | 1.751 | 1.842 |
| 3 PM  | 305 | 1255.7 | 335   | 0.4  | 0.3276 | 1.778 | 1.88  |
| 4 PM  | 301 | 1114.2 | 330   | 0    | 0      | 1.64  | -     |

The measurements demonstrate that the incorporation of a TEC into a PV panel system, yield marked enhancements in PV panel efficiency, albeit under conditions, where temperatures surpass the 300K threshold. It is noteworthy that this efficiency is most pronounced when the system is subjected to elevated levels of solar irradiance. These results underscore the pivotal role of TEC technology in optimizing PV panel performance, particularly in environments characterized by high solar energy input. The TEC's ability to mitigate temperature-related losses emphasizes its effectiveness in ensuring maximum energy conversion, even in challenging thermal conditions, thus promoting the overall efficiency and sustainability of PV systems.

Teffah et al. (2017) [40], proposed a model that integrates a Multi-Junction Solar Cell (MJSC), with a Thermoelectric Cooler-Thermoelectric Generator (TEC-TEG) module, within a roof-mounted solar energy system. This module incorporates a TEC positioned on the rear side of the PV panel, to cool the solar cells through the Peltier effect. Simultaneously, a TEG is mounted on the hot side of the TEC, serving as both a heat sink for the TEC and a mechanism to harness waste heat via the Seebeck effect, thereby generating additional electrical power. This approach enhances the overall efficiency of the entire system, by maximizing energy utilization.

To assess the system's performance under varying high sun concentration factors, MATLAB/Simulink was employed for modelling and simulation. Additionally, this study involved experimental validation, to quantify the cooling effect and the electrical contribution of the TEC-TEG, module to the overall system efficiency.

The core photovoltaic component employed in this setup, is the Triple Junction Solar Cell (TJSC), a specialized cell comprised of three distinct layers, with varying band-gap energies. The electrical circuit is configured in such a way that these three sub-cells are connected in series, with each sub-cell adhering to the conventional circuit design of a single solar cell. This

system design holds significant promise for advancing the efficiency and performance of solar energy harvesting, especially in regions characterized by high sun concentration.

The design and configuration of the PV-TEC-TEG hybrid system, in COMSOL MULTIPHYSICS software, are depicted in Figure 2.8. In this comprehensive model, the incident of solar energy is substantially concentrated, targeting the TJSC-PV at a high level of intensity. To facilitate efficient heat transfer, the cold side of the TEC is firmly affixed to the lower surface of the TJSC, with a copper block sandwiched in between, to enhance thermal conductivity.

Concurrently, the hot side of the TEC and the TEG, are thermally interconnected in series, ensuring a seamless flow of heat. On the other hand, the cold side of the TEG is securely attached to a copper heat sink, designed to effectively dissipate heat. This thermal and electrical arrangement is designed to optimize energy conversion and heat management within the PV-TEC-TEG hybrid setup.

The study yielded several key findings:

- Both simulation and experimental results, indicated that the sun concentration ratio has a notable effect on the open-circuit voltage of the photovoltaic panel, both before and after the cooling process.
- Under a solar irradiance level of  $300 \text{ W/m}^2$ , the TEC effectively lowered the PV panel's temperature from an initial  $368.2\text{K}$ , to a reduced temperature of  $322.6\text{K}$ . This cooling resulted in a discernible power increase of  $1 \text{ W}$ , showcasing the TEC's capacity to enhance performance, under these conditions.
- At a higher solar irradiance of  $1000 \text{ W/m}^2$ , the TEC exhibited further substantial cooling capabilities. The PV panel's temperature, which initially stood at  $529\text{K}$ , was reduced to  $403\text{K}$ , with the TEC activated. This enhanced cooling translated into a significant power gain of  $3 \text{ W}$ , further illustrating the TEC's effectiveness, in optimizing PV panel performance, when subjected to higher solar energy levels.

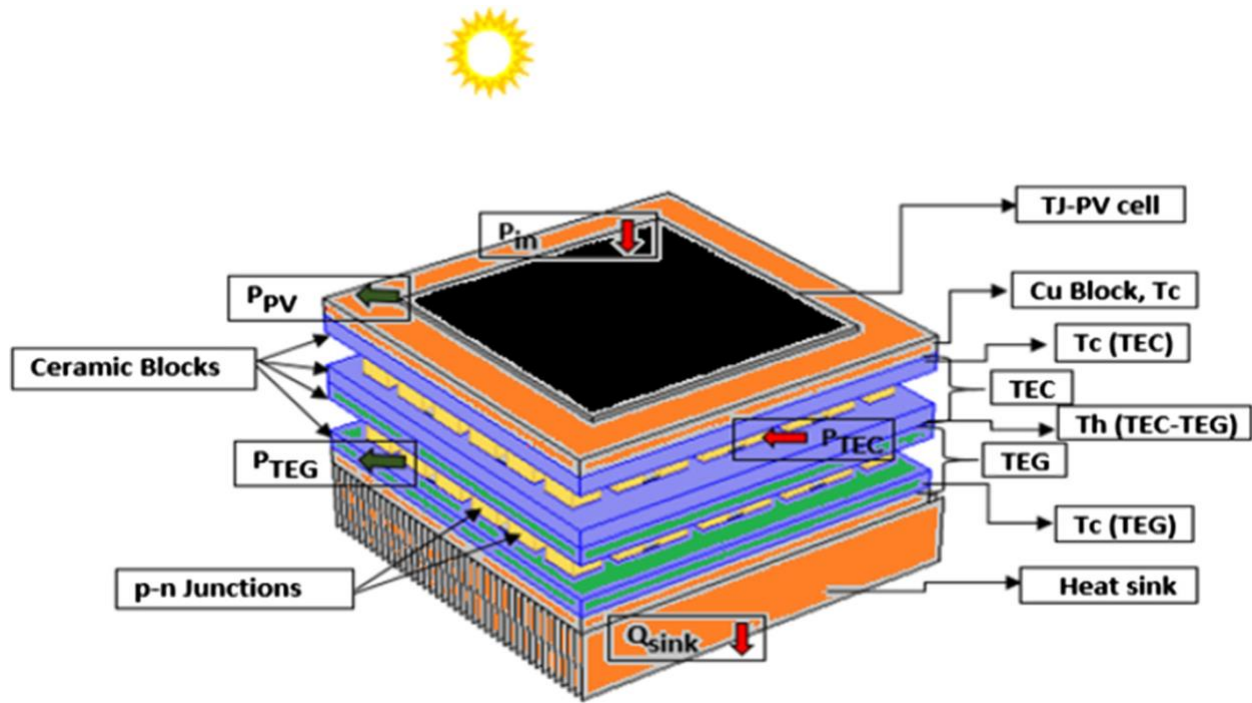


Figure 2.9: COMSOL MULTIPHYSICS' PV-TE hybrid system model [40]

## 2.3 DISCUSSION

Upon conducting a comprehensive review of research studies, related to hybrid photovoltaic/thermoelectric cooling technology, it becomes evident that these investigations have yielded favourable outcomes and promising results. All studies, which may be simulations and experimentally demonstrate success in the different methodologies, applied under various conditions. Additionally, it is noteworthy that renewable energy systems operate exceptionally well in unique environmental conditions, with high radiance, leading to their highest overall performance, in this region.

The following topics have been previously addressed in this research, with relevance to the ongoing study:

- The hybrid PV-TEC system may be deployed anywhere, without a need for any cooling medium.
- Photovoltaic module efficiency is achieved, even at a minimum scale such as a single PV cell.
- The life cycle of the photovoltaic panels is extended, due to the low operating temperature.



- The initial cost of investment is offset in the long run by the cost savings, due to improved photovoltaic module efficiency.
- A medium to large-scale PV module/panel may power the TEC, without the use of an external power source, such as a battery.

## 2.4 SUMMARY

In the context of hybrid PV-TEC systems, it is notable that their cooling mechanism relies on the utilization of ambient air as the heat exchange medium, thus avoiding the requirement of any additional coolant or thermal fluid. However, it is imperative to underscore that, the operation of such systems, is contingent upon the provision of an electrical voltage. This electrical input, while essential for the systems' function, introduces a degree of energy consumption into the equation. Consequently, this characteristic renders them somewhat less optimal for deployment in smaller-scale PV systems, where the surplus energy generated by the efficiency gains might not offset the energy consumption associated with the electrical voltage requirement.

Furthermore, to further enhance the efficiency of the PV panel, the incorporation of a DC fan becomes a mandatory measure. This auxiliary component plays a crucial role in augmenting the convective heat transfer within the system, thereby improving the cooling effect on the PV module. However, it is imperative to acknowledge that the inclusion of a DC fan, entails an increment in the power consumption drawn from the PV panel itself. This dichotomy underscores the importance of system design and energy balance considerations, when implementing hybrid PV-TEC systems, particularly in the context of smaller-scale PV installations.

This Chapter undertakes a comprehensive literature review, analyzing research activities globally, concerning hybrid PV-TEC systems, particularly in regions characterized by abundant solar irradiance. The collective body of literature surveyed consistently, demonstrates an enhancement in PV efficiency, as a direct consequence of the cooling effect, imparted by the TEC technology. This improved efficiency, in turn, extends the operational lifespan of the PV cells, highlighting the sustainability and durability advantages of such systems.

It is important to highlight that, the magnitude of this efficiency gain, is fundamentally tied to several key factors. The type and size of the photovoltaic panel under consideration, plays a pivotal role, with larger panels often exhibiting further pronounced benefits. Additionally, ambient temperature conditions exert a substantial influence, as higher temperatures typically

yield more substantial efficiency improvements, through effective cooling and higher power consumption by the thermoelectric module. Additionally, the number of thermoelectric modules incorporated into the system, is a critical determinant of its overall performance. TEC modules possess noticeable features of being lightweight, absence of moving mechanical parts, compactness, noiseless in operation, transferability, highly reliable, long working life and less maintenance requirements.

However, a notable gap in the existing literature pertains to the detailed evaluation of control techniques applied to the TEC. While it is evident that the TEC's performance directly impacts photovoltaic efficiency, a comprehensive analysis of the control strategies and their resultant effects on PV efficiency, remains relatively unexplored. This area represents a promising avenue for further research, offering the potential for refined system optimization and enhanced photovoltaic efficiency, in hybrid PV-TEC systems.



# CHAPTER III: MATHEMATICAL MODEL DEVELOPMENT AND OPTIMIZATION ALGORITHM FORMULATION

## 3.1 INTRODUCTION

In this Chapter, the mathematical modelling of the PV-TEC system is discussed. This hybrid configuration entails a PV panel integrated with a thermoelectric device, affixed to its reverse side, a heatsink interconnected with the opposing face of the thermoelectric device and a switching mechanism. The TEC is powered by the PV panel, that it is intended to cool.

The model's creation, is detailed and presented with the overarching aim of enhancing the efficiency of the PV panel. This objective is achieved, by maintaining the panel's surface temperature around 25°C. Section 3.2, delves into an in-depth examination of the pertinent components. The development of the optimal efficiency management model, including its related constraints, is examined in Section 3.3. The concluding portion, Section 3.4, delivers a concise overview of the content, covered in this Chapter.

## 3.2 MATHEMATICAL MODEL FORMULATION

The suggested hybrid scheme comprises a PV panel and a thermoelectric device, as depicted in Figure 3.1. The thermoelectric device, denoted as TEC, is accompanied by a heatsink, attached to the hot side. This configuration facilitates the efficient dissipation of heat absorbed by the TEC, from the PV panel. The arrangement's visual representation, is provided in Fig. 3.1.

Furthermore, comprehensive mathematical models are developed, to delineate the distinct components, within the system. These models are formulated, with both heat and electrical energy considerations.

### 3.2.1 Dynamic model of the PV-TEC system

It is essential, in the process of developing a mathematical model, to account for all factors associated with the operation of the proposed system. This holistic approach, ensures the model's accuracy and relevance. The resultant model may subsequently serve as a valuable tool for simulation during experimental investigations. The dynamic model of the PV/TEC system, encompasses multiple variables. It encompasses the dynamic variation of the PV

panel's temperature, influenced by solar irradiance and the integration of a TEC device. This model provides insights into the intricate interactions, shaping the performance of the system under changing conditions.

In Figure 3.1, as a reference, the process is as follows: incoming solar irradiance prompts photons to impact the PV panel, thereby generating a voltage output. Given the solar photon abundance, any surplus photons are converted into heat, upon the PV panel's surface. This conversion culminates in the reduction of the PV panel's efficiency. A TEC is positioned on the PV panel's rear side, to counteract this effect. It harnesses some of the PV panel's power, with the cold side affixed to the PV panel. The TEC's counterpart parallel to the cold side is instrumental in dissipating the accumulated heat from the PV panel. This heat dispersion is facilitated, using a dedicated heatsink. Ensuring controlled operation, a switch in series with the PV, governs the power supply to the TEC.

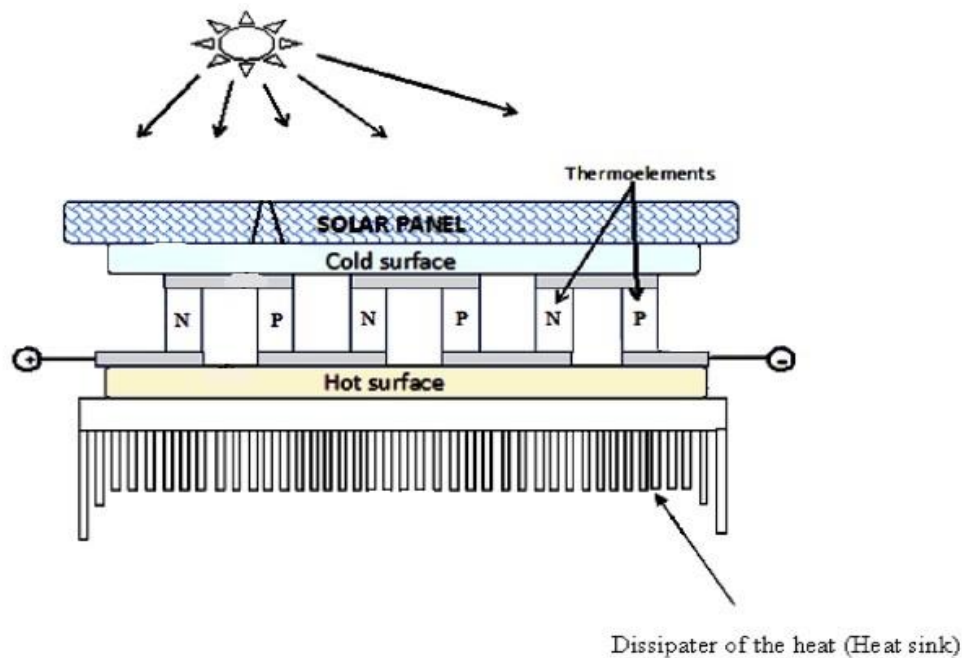


Figure 3.1: Setup of PV-TEC system layout [2]

The configuration encompasses a PV panel, integrated with the cold side of a thermoelectric device on its backside. On the flip side of this thermoelectric device, lies the hot side, conjoined with a heatsink. The thermoelectric device's operation is regulated by a switch, connecting it to a photovoltaic module.

### 3.2.2 Energy balance equation

It is assumed that the influence of temperature on thermoelectric properties, the impact of ceramic plates and electrical contact resistances are insignificant within the thermal equilibrium equation. The energy equilibrium equation, regarding the cold side of a single TEC, yields the cooling capacity, denoted as  $q_c$  (rate of heat absorbed), at the cold junction:

$$q_c = \alpha_m \cdot T_c \cdot I - \Theta_m \cdot \Delta T - 0.5 \cdot R_m \cdot I^2 \quad (3.1)$$

Where:

$q_c$  is the amount of heat dissipated by thermal load = amount of heat pumped out by the TEC (W);

$I$  is the electrical current across the TEC (A);

$\alpha_m$  is the energy conversion coefficient of the TEC ( $V \cdot K^{-1}$ );

$T_c$  is the temperature of the cold surface = temperature of the cold side of the TEC (K);

$\Theta_m$  is the thermal resistance of the TEC (K/W);

$R_m$  is the electrical resistance of the TEC ( $\Omega$ );

$$\Delta T = T_h - T_c \text{ (K)}. \quad (3.2)$$

$T_h$  is the temperature of the hot side of the TEC (K), equal to the temperature of the hot side of the TEC (K). Substituting  $T_h - T_c$  with  $\Delta T$  into Equation. (3.1) and producing the TEC temperature on the cold side. The subject of the formula from the equation yields:

$$q_c = \alpha_m \cdot T_c \cdot I - \Theta_m \cdot (T_h - T_c) - 0.5 \cdot R_m \cdot I^2 \quad (3.3)$$

$$q_c = \alpha_m \cdot T_c \cdot I - \Theta_m \cdot T_h + \Theta_m \cdot T_c - 0.5 \cdot R_m \cdot I^2 \quad (3.4)$$

$$q_c + \Theta_m \cdot T_h + 0.5 \cdot R_m \cdot I^2 = \alpha_m \cdot T_c \cdot I + \Theta_m \cdot T_c \quad (3.5)$$

$$q_c + \Theta_m \cdot T_h + 0.5 \cdot R_m \cdot I^2 = T_c (\alpha_m \cdot I + \Theta_m) \quad (3.6)$$

$$T_{c(t)} = \frac{q_c + \theta_m \cdot T_h + 0.5 \cdot R_m \cdot I}{\alpha_m \cdot I + \theta_m} \quad (3.7)$$

Within each sampling interval, the disparity between the supplied and consumed energies should equate to the energy generated by the PV panel at its maximum power point, when operating under temperatures both below and at 25°C.

The subsequent equation outlines the energy equilibrium relationship:

$$Q_{pv(t)} = Q_{SOLAR(t)} - Q_{TEC(t)} - Q_{Heatsink(t)} \quad (3.8)$$

Where:

$Q_{pv(t)}$  is the total output power generated by a PV panel at time  $t$ ;

$Q_{SOLAR(t)}$  is the energy generated by a PV panel at time  $t$ ;

$Q_{TEC(t)}$  is the energy consumed by the TEC to cool down a PV panel at time  $t$ ;

$Q_{heatsink(t)}$  is the heat dissipated by the heatsink at time  $t$ .

and:

$$Q_{pv(t)} = M_{pv} \cdot C_{pv} \cdot T_{pv} \quad (3.9)$$

$$Q_{SOLAR(t)} = M_{pv} \cdot C_{pv} \cdot T_{cell} \quad (3.10)$$

Where:

$C_{pv}$  is the global specific heat capacity of the materials that make up a PV panel;

$T_{cell}$  is the PV cell temperature;

$T_{pv}$  is the PV panel temperature;

$M_{pv}$  is the mass of the PV panel.

$C_{pv}$  may be determined using the geometry of the system, that contains the following parts:

Solids (domains and shells) [42]:

- Aluminium frame of the PV panel.

- The glass of the cover. Thickness: 3mm
- The Silicon Cells. Thickness: 0.4mm
- The EVA (Ethylene-Vinyl-Acetate) film. Thickness: 0.8mm
- The Tedlar back film. Thickness: 0.05mm. White reflective colour.

Solid subdomains: Solely heat conduction, where the heat generation  $Q$  is zero for the Tedlar, glass and EVA parts, as well as has a non-zero value in the silicon cells, which corresponds to an incident irradiation of  $1000 \text{ W/m}^2$ , homogeneously distributed, minus a 15% efficiency of electrical conversion [46].

The thermal conductivities of the glass, EVA, silicon and Tedlar are  $1.7 \text{ W/(m} \cdot \text{K)}$ ,  $0.2349 \text{ W/(m} \cdot \text{K)}$ ,  $148 \text{ W/(m} \cdot \text{K)}$  and  $0.1583 \text{ W/(m} \cdot \text{K)}$ , respectively. The specific heat capacity at constant pressure of the glass, EVA, silicon and Tedlar is  $780.33 \text{ J/(kg} \cdot \text{K)}$ ,  $3135 \text{ J/(kg} \cdot \text{K)}$ ,  $710.08 \text{ J/(kg} \cdot \text{K)}$  and  $1090 \text{ J/(kg} \cdot \text{K)}$ , respectively [42].

Table 3.1: Specific heat capacity of a typical PV panel's materials

| Material      | Description                                                 | Value  |
|---------------|-------------------------------------------------------------|--------|
| $C_{glass}$   | Heat capacity of glass ( $\text{J/(kg} \cdot \text{K)}$ )   | 550.13 |
| $C_{silicon}$ | Heat capacity of silicon ( $\text{J/(kg} \cdot \text{K)}$ ) | 66.74  |
| $C_{EVA}$     | Heat capacity of EVA ( $\text{J/(kg} \cdot \text{K)}$ )     | 589.38 |
| $C_{Tedlar}$  | Heat capacity of Tedlar ( $\text{J/(kg} \cdot \text{K)}$ )  | 12.82  |

From Table 3.1, using the solid subdomains, the global heat capacity  $C_{pv}$  of a PV panel was calculated to  $1219.07 \text{ J/(kg} \cdot \text{K)}$ .

The most common manner in determining the cell temperature  $T_{cell}$  consists of using the Normal Operating Cell Temperature  $T_{NOC}$  [43]. The value of this parameter, is given by the PV module manufacturer.  $T_{cell}$  is, thereafter dependent on the ambient temperature  $T_{amb}$  and on the solar irradiance,  $I_{total}$  according to equation (3.11)

The cell temperature [44], may further be calculated as:

$$T_{cell} = T_{amb} + \frac{I_{total}}{800} (T_{NOC} - 20) \quad (3.11)$$

Where:

$T_{amb}$  is the ambient air temperature;

$T_{NOC}$  is the nominal operating cell temperature in °C;

$I_{total}$  is the total solar irradiance on a tilted surface ( $Wh$ ).

$T_{NOC}$  is calculated for a wind speed at a PV module height of  $v = 1ms^{-1}$ , an ambient temperature of  $T_{amb} = 20^{\circ}C$  and a hemispherical irradiance of  $800Wm^2$ .  $T_{NOC}$  depends strongly on the type of encapsulation of the PV module [46].

The total irradiance  $I_{total}$ , received by the PV cell, may be calculated concerning the three components of irradiance. These components are Direct Nominal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI) and Global Horizontal Irradiance (GHI), noted as  $I_{DNI}$ ,  $I_{DHI}$  and  $I_{GHI}$ , respectively. Eq. (3.12), denotes as to how these components of solar irradiance may be incorporated, to determine the total irradiance on a tilted surface [45].

$$I_{DNI} \cos \theta_{\beta} + I_{DHI} \left( \frac{1 - \cos \beta}{2} \right) + \rho I_{GHI} \left( \frac{1 - \cos \beta}{2} \right) \quad (3.12)$$

Where:

$\theta_{\beta}$  is the angle of incidence of the solar irradiance on a tilted surface in degrees (°);

$\beta$  is the tilted angle in degrees (°);

$\rho$  is the reflectance factor of the surrounding area.

Substituting Eqs. (3.9) and (3.10) into Eq. (3.8) yields:

$$M_{pv} \cdot C_{pv} \cdot T_{pv} = M_{pv} \cdot C_{pv} \cdot T_{cell} - Q_{TEC(t)} - Q_{Heatsink(t)} \quad (3.13)$$

$$M_{pv} \cdot C_{pv} \cdot T_{pv} = M_{pv} \cdot C_{pv} \cdot \left( T_{amb(t)} + \frac{I_{total}}{800} (T_{NOC} - 20) \right) - Q_{TEC(t)} - Q_{Heatsink(t)} \quad (3.14)$$

Making the PV temperature the subject of the formulae:

$$T_{pv} = \frac{M_{pv} \cdot C_{pv} \left( T_{amb(t)} + \frac{I_{total}}{800} (T_{NOC} - 20) \right) - Q_{TEC(t)} - Q_{Heatsink(t)}}{M_{pv} \cdot C_{pv}} \quad (3.15)$$

$$T_{pv} = T_{amb(t)} + \frac{I_{total}}{800} (T_{NOC} - 20) - \frac{Q_{TEC(t)} - Q_{Heatsink(t)}}{M_{pv} \cdot C_{pv}} \quad (3.16)$$

Eq. (3.16) may be expressed in a state-space form as:

$$\dot{T}_c(t) = A(t) \cdot T(t) + B \cdot S_w(t) \quad (3.17)$$

Where:

$\dot{T}_c(t)$  is the temperature derivatives;

$$A = T_{amb(t)} + \frac{I_{total}}{800} (T_{NOC} - 20);$$

$$B = \frac{Q_{TEC(t)} - Q_{Heatsink(t)}}{M_{pv} \cdot C_{pv}}$$

In Eq. (3.17), A(t) represents the state matrix, B(t) corresponds the input matrix, Ts(t) denotes the state variable (vector) and Sw(t) signifies the control (input) variable, specifically denoting the switch status of the dc supply.

### 3.2.3 Discretized thermoelectric cooler model

As numerical methods are generally more straightforward, compared to analytical techniques, Eq. (3.17) is discretized at every  $k^{th}$  sampling interval, with a sampling period denoted as  $t_s$ . The overall discrete representation of Eq. (3.17), concerning the  $k^{th}$  cooling thermoelectric cooler, is expressed in the following equation:

$$T_{cell}(k+1) = (1 + t_s \cdot A(k)) \cdot T(k) + t_s B(k) \cdot S_w(k) \quad (3.18)$$

As the state variable,  $T_{k+1}$ , should be represented in relation to its initial value,  $T_0$  and the control variable,  $S_w(k)$ , of the initial value of  $T_{k+1}$ , at each interval, is initially determined as follows:

When substituting  $k = 0$ , then  $T_1$  in Eq. (3.18) becomes Eq. (3.19):

$$T_1 = (1 + t_s \cdot A_0) \cdot T_0 + t_s \cdot B_0 \cdot S_{w0} \quad (3.19)$$

Similarly, when  $k = 1$ , then  $T_2$  is given in Eq. (3.20)

$$T_2 = (1 + t_s \cdot A_1) \cdot T_1 + t_s \cdot B_1 \cdot S_{w1} \quad (3.20)$$

Substitute  $T_1$  in Eq. (3.19) into Eq. (3.20) so that Eq. (3.21):

$$T_2 = (1 + t_s \cdot A_1)[(1 + t_s \cdot A_0) \cdot T_0 + t_s \cdot B_0 \cdot S_{w0}] + t_s \cdot B_1 \cdot S_{w1} \quad (3.21)$$

After expansion and factorization,  $T_2$  will become Eq. (3.22):

$$T_2 = T_0[(1 + t_s \cdot A_1)(1 + t_s \cdot A_0)] + t_s[(1 + t_s \cdot A_1) \cdot B_0 \cdot S_{w0} + B_1 \cdot S_{w1}] \quad (3.22)$$

Applying the same procedure as those used for Eq. (3.19), through (3.22), starting from  $k = 0$ ,  $T_3$  may be expressed, as shown in Eq. (3.23):

$$T_3 = T_0[(1 + t_s \cdot A_2)(1 + t_s \cdot A_1)(1 + t_s \cdot A_0)] + t_s[(1 + t_s \cdot A_2) \cdot B_0 \cdot S_{w0} + (1 + t_s \cdot A_2) \cdot B_1 \cdot S_{w1} + B_2 \cdot S_{w2}] \quad (3.23)$$

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$$T_{cell_{k+1}} = T_0 \cdot \prod_{j=0}^k (1 + t_s \cdot A_j) + \sum_{j=0}^k B_j \cdot S_{wj} \cdot \prod_{i=j+1}^k (1 + t_s \cdot A_i) \quad (3.24)$$

Where:

$T_0$  is the initial PV panel temperature;

$T_k$  is the  $k$ th PV panel temperature;

$t_s$  represents the sampling time and;

$S_{wj}$  denotes the  $j$ th switching status, which may take on values between 1 or 0.



### 3.3 CONTROL OPTIMIZATION PROBLEM

#### 3.3.1 Algorithm formulation

##### 3.3.1.1 Objective function

The primary goal is to maximize the power output from the PV-TEC system. Essentially, the control algorithm should identify the optimal switching configuration, that leads to an optimized efficiency enhancement in the hybrid PV-TEC system. The aim is to maximize the power produced by the PV module with respect to the power consumed by the TEC and the heatsink combination. As a result, the central objective function, is defined by Eq. (3.25):

$$J_p = -t_s \left( \sum_{k=1}^N (P_{PV} - P_{TEC} S_{TEC} - P_{HEATSINK}) \right) \quad (3.25)$$

Where:

$t_s$  is the sampling time (hours);

$P_{PV}$  is the rated power of the PV panel ( $W$ );

$P_{TEC}$  is the rated power of the TEC module ( $W$ );

$S_{TEC}$  is the switching status function for the associated TEC;

$P_{HEATSINK}$  is the rated power dissipated by the Heatsink ( $W$ ).

##### 3.3.1.2 Constraints on the state of the PV panel temperature

When the cell temperature exceeds  $25^{\circ}\text{C}$ , the targeted temperature range for the PV panel, lies between  $23^{\circ}\text{C}$  and  $27^{\circ}\text{C}$ . When the cell temperature remains above  $25^{\circ}\text{C}$ , the panel's temperature may fluctuate throughout the day, without any restrictions. The objective function, is subjected to the following constraints:

$$T_{cell(min)} \leq T_0 \cdot \prod_{j=0}^k (1 + t_s \cdot A_1) + \sum_{j=0}^k B_j \cdot S_{w_j} \cdot \prod_{i=j+1}^k (1 + t_s \cdot A_i) \quad (3.26)$$

$$T_{cell(max)} \geq T_0 \cdot \prod_{j=0}^k (1 + t_s \cdot A_1) + \sum_{j=0}^k B_j \cdot S_{w_j} \cdot \prod_{i=j+1}^k (1 + t_s \cdot A_i) \quad (3.27)$$

The constraints noted in Eq. (3.26) – (3.27), are required to maintain the desired temperature levels. The  $T_{cell(min)}$ , denotes the minimum permissible temperature of the PV panel. Conversely,  $T_{cell(max)}$  is the maximum threshold that the temperature may not exceed, for any given interval [47].

$$S_{TEC} \in \{0,1\} \quad (3.28)$$

$$T_{cell(min)} \leq \Delta T \leq T_{cell(max)} \quad (3.29)$$

The switching function, denoted as  $S_{TEC}$ , defines the logic governing the activation and deactivation of the TEC. This means the switching status will be variable from any value above 0 and not above 1, as illustrated in Eq. (3.28).

### 3.3.2 Proposed optimization solver and algorithm

The objective function, as defined in Eq (3.25), takes the form of a linear function that incorporates an integer control variable. This function should be solved, to ascertain the optimal operating temperature for the PV panel. This specific type of problem is amenable to resolution through the versatile SCIP (Solving Constraint Integer Programs) solver, within the MATLAB optimization toolbox. SCIP is well-known for its high-speed computational capabilities, positioning it as one of the fastest solvers available, within the MATLAB interface OPTI-Toolbox. [48].

For appropriate operation, it is essential to adhere to the MINLP (Mixed-Integer Nonlinear Programming) formulation. This MINLP structure is clarified in Equation (3.30), where the default aim, is to minimize the objective function, while complying with the outlined

constraints. To meet SCIP's specific requirements, it is necessary to reorganize the mathematical model, aligning it with SCIP's constraints. This adjustment enables the efficient resolution of the optimization problem. The outcome manifests as an optimal switching status function, constrained to assume a variable value.

$$\begin{aligned}
 & \text{Min}_x f(x) \\
 & \text{Subject to:} \\
 & \quad Ax \leq b \\
 & \quad A_{eq}x = b_{eq} \\
 & \quad lb \leq x \leq ub \\
 & \quad c(x) \leq d \\
 & \quad c_{eq}(x) = d_{eq} \\
 & \quad x_i \in Z \\
 & \quad x_j \in \{0,1\}
 \end{aligned} \tag{3.30}$$

Where:

$f(x)$  is the objective function;

$Ax \leq b$  is the linear inequality constraint;

$A_{eq}x = b_{eq}$  is the linear equality constraint;

$lb \leq x \leq ub$  is the decision variable bounds;

$c(x) \leq d$  is the nonlinear inequality constraint;

$c_{eq}(x) = d_{eq}$  are the nonlinear equality constraints;

$x_i$  is an integer number decision variable;

$x_j$  is a variable number decision variable.

The objective function in Eq. (3.25) is subsequently substituted with  $f(x)$ , devoid of linear inequality or equality constraints. The decision variable, indicated in Eq (3.30), assumes a continuous value, implying that any value ranging from 0 to 1, may serve as the switching

status. This continuous nature is reflected in the lower and upper boundaries, delineated in Eq (3.31) and Equation (3.32), respectively:

$$lb^T = [0 \dots 0_N] \quad (3.31)$$

$$ub^T = [1 \dots 1_N] \quad (3.32)$$

The control variable that requires optimization, is subject to constraints, as illustrated in Equation (3.33).

$$lb \leq x \leq ub \quad (3.33)$$

### 3.4 SUMMARY

In this Chapter, the mathematical definitions, have been methodically identified and provided for the objective function, control variables, state variables and disturbances within the formulated model. For hybrid systems featuring distinct design parameters and operational circumstances, encompassing factors, as solar irradiation and ambient temperature, the decision variables of the developed model may be optimized through the application of sophisticated algorithms, fitted for addressing such complexities. To address this optimization challenge, we have chosen the SCIP solver, which is accessible through the MATLAB OPTI-Toolbox, as the preferred solution.

The constraints governing system operation, have been defined, aligning with the pursuit of the optimum operational temperature for the PV panel while, simultaneously, maximizing its efficiency. This dual objective is realized, by maintaining the PV panel's temperature at approximately 25°C, thereby augmenting the panel's operational lifespan.

# CHAPTER IV: SIMULATION RESULTS AND DISCUSSION

## 4.1 INTRODUCTION

In this Chapter, the simulation of the optimal operational control model for the hybrid PV-TEC system is conducted, utilizing the SCIP solver, within the MATLAB OPTI Toolbox. The central purpose of the simulation efforts is to showcase the efficacy of the deployed optimal control strategy, within the hybrid arrangement.

Furthermore, this Chapter outlines the advancements achieved in the efficiency of the PV panel, accompanied by a comparative analysis against a baseline scenario. Detailed information regarding environmental conditions during both the summer and winter seasons, is further provided and illustrated.

## 4.2 DATA DESCRIPTION

This segment investigates a scenario that provides an exposition of the environmental data and system components. This dataset serves as the input for the optimization tactic developed for the suggested hybrid system.

In Section 4.2.1, the data is graphically displayed with 1-minute averaging intervals, for visual representation. By employing a 15-minute sampling interval, the subsequent total sampling period and control horizon, along with pertinent parameters, are thoroughly scrutinized in Section 4.2.2.

### 4.2.1 Case study

The scenario under consideration, involves using meteorological data obtained from Bloemfontein, Free State, South Africa, depicted in Fig. 4.1. The principal objective is to optimize the energy output of the PV module, by effectively reducing its surface temperature through the control of a thermoelectric cooler. The sampling time, denoted as  $t_s$ , has been set to 15 minutes for implementation, to ensure a balance between computational time and simulation results resolution.

## 4.2.2 Data acquisition

The specific dataset encompasses diffuse horizontal, diffuse normal and global horizontal irradiance, along with ambient temperature values, delineating a typical winter day on 17 July 2021 and a summer day on 17 January 2021 as depicted in Table 4.1. These datasets are visualized in Fig. 4.2 and 4.3, for the summer and winter seasons, respectively. The chosen dates were the best representation of typical summer and winter days in the region. These figures highlight the data's origin, derived from a weather station stationed at the Central University of Technology (CUT) (latitude: -29.121337, longitude: 26.215909, elevation: 1397m), in Bloemfontein [49].



Figure 4.1: Irradiance, temperature and wind sensors located at CUT [49]

The dataset was sourced from the original Excel spreadsheet and the extraction process was executed by utilizing state-of-the-art SAURAN devices [50]. The numerical data about the summer and winter seasons has been compiled and presented in Appendices A1 and A2, respectively.

The Table 4.1 below, lists the parameter, unit of measurement and the type of instruments used for the required data.

Table 4.1: Radiometry, meteorological and metadata as well as its respective instruments.

| Acronym               | Parameter                     | Unit        | Instrument                                    |
|-----------------------|-------------------------------|-------------|-----------------------------------------------|
| <b>Radiometry</b>     |                               |             |                                               |
| GHI                   | Global horizontal irradiance  | $W/m^2$     | Kipp & Zonen CMP11 pyranometer                |
| DNI                   | Direct normal irradiance      | $W/m^2$     | Kipp & Zonen CHP1 pyrheliometer               |
| DHI                   | Diffuse horizontal irradiance | $W/m^2$     | Kipp & Zonen CMP11 pyranometer                |
| <b>Meteorological</b> |                               |             |                                               |
| Air_Temp              | Air temperature               | $^{\circ}C$ | Campbell Scientific CS215                     |
| <b>Metadata</b>       |                               |             |                                               |
| TS                    | Time Stamp                    | hh:mm:ss    | All times are South African Standard (GMT +2) |

### Solar irradiance: Summer

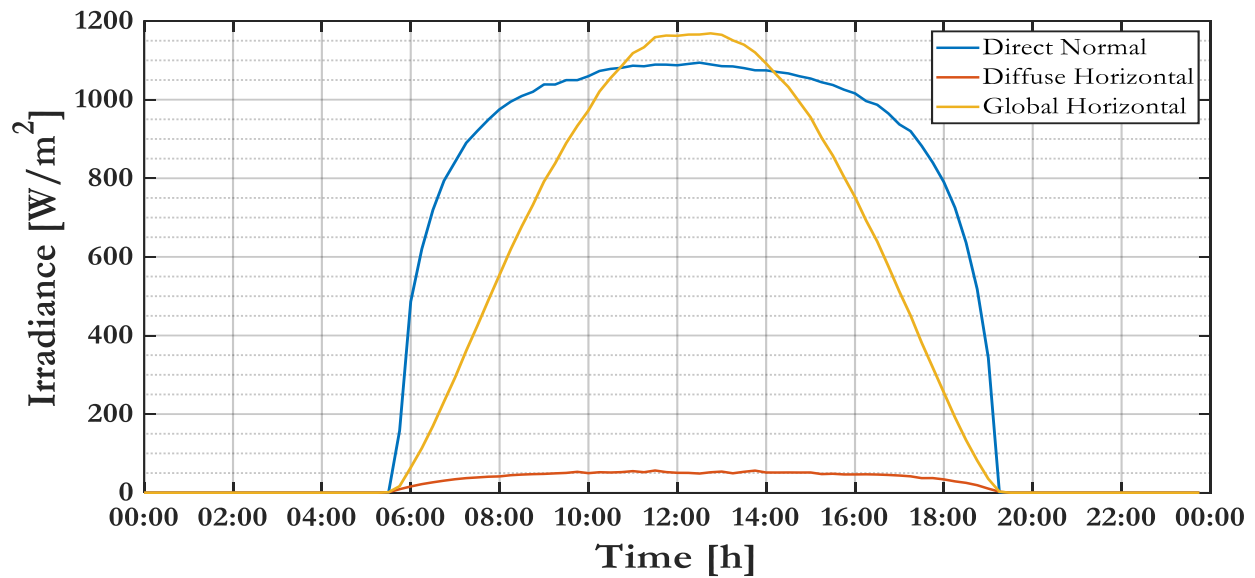


Figure 4.2: Solar radiation during a typical summer day

## Solar irradiance: Winter

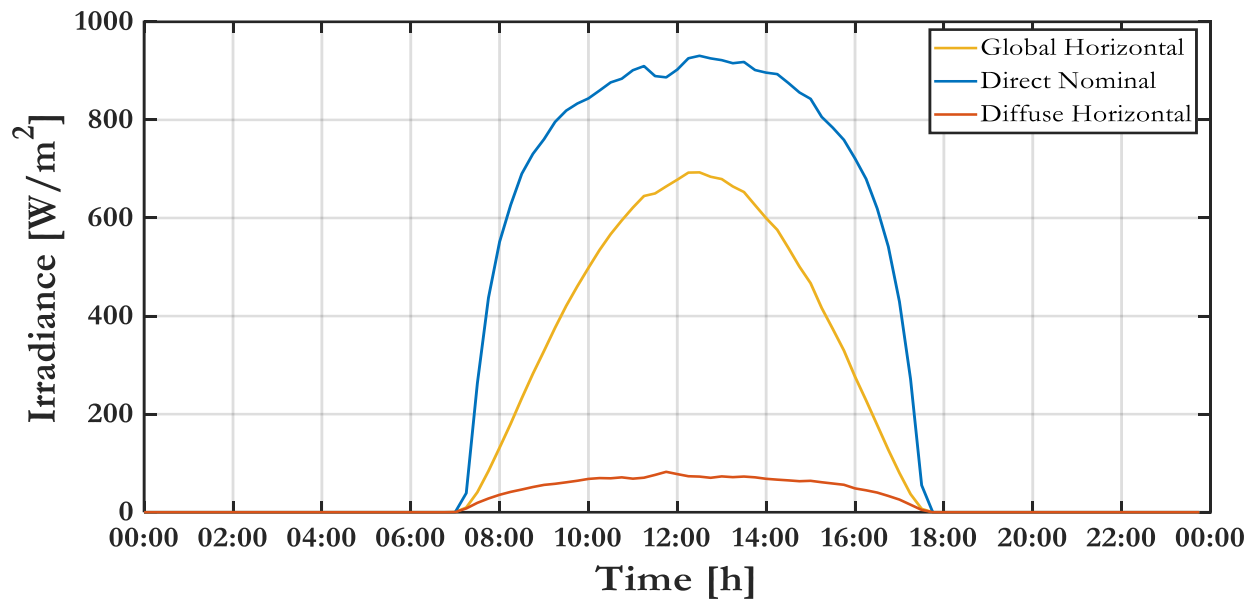


Figure 4.3: Solar radiation during a typical winter day

Upon referencing Figures 4.2 and 4.3, a visible difference in the magnitude of solar irradiance between the two seasons, are evident, with summer exhibiting greater irradiance levels, compared to winter.

Figures 4.4 and 4.5, visually represent the ambient and PV module's temperatures data collected, on corresponding summer and winter days, concurrent with the measurements acquired for diffuse horizontal irradiance, diffuse normal irradiance and global horizontal irradiance. Notably, these graphical representations highlight a visible rise in ambient and PV module's temperatures during the summer season, when compared to the winter season.

Figure 4.4, illustrates the temperature differential between the PV module's and the surrounding ambient temperature. It is important to highlight that the PV module's temperature exhibits a peak difference of approximately 7°C, compared to the ambient temperature of 29.3°C. This variance may be attributed to the waste energy that is transformed into heat on the surface of the PV modules. Specifically, the PV module's surface temperature reaches its highest point, reaching 36.1°C, occurring just after 15:30, on this specific summer day.



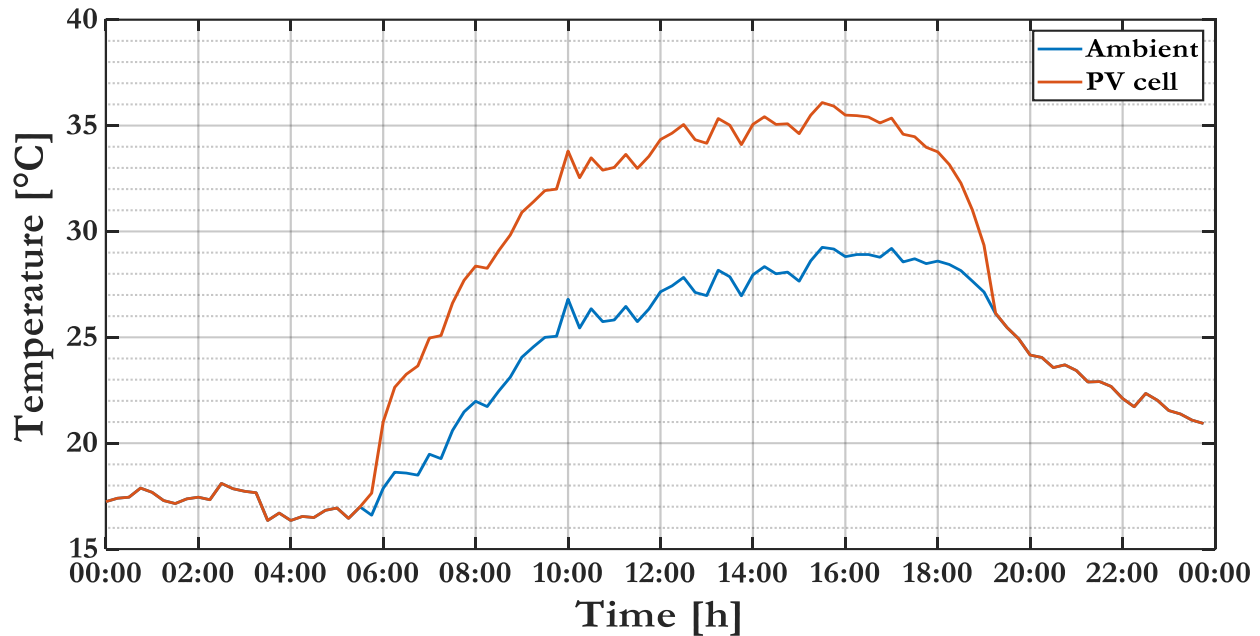


Figure 4.4: Ambient and PV module temperature in summer

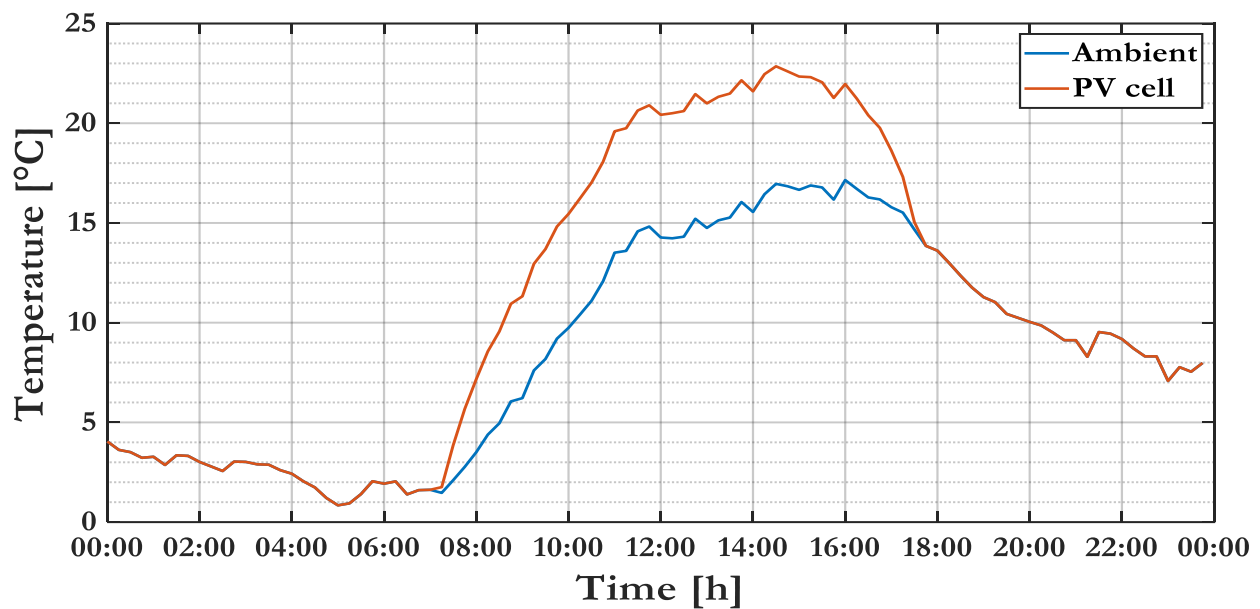


Figure 4.5: Ambient and PV module temperature in winter

Figure 4.5 illustrates the temperature gap between the PV cell and the ambient temperature, with a differential of approximately 6°C between the two. The highest recorded temperature of 23°C, is observed shortly after 14:30 during the winter period, while the ambient temperature remains at 17°C.

The PV module's surface temperature undergoes substantial fluctuations, in line with the ambient temperature at a higher degree. It is noteworthy that, during the summer, the ambient temperature surges to around 13°C above the winter levels. In both seasons, the temperature peaks occur between 14:00 and 16:00, while the lowest points are reached between 04:00 and 05:30 local time.

### 4.2.3 Component size and simulation model parameters

As delineated in the study's objective (Chapter 1, section 1.5), the central focus of this research revolves around achieving optimal control in a hybrid system, that combines PV, TEC and a Heatsink. Tables 4.2, 4.3 and 4.4, provide a comprehensive overview of the module dimensions and parameters, for both the baseline and hybrid configurations. For the PV panel, its dimensions are 995 x 680 x 30mm, with a rated capacity of 100W.

Table 4.2: Component size and parameters of the PV panel.

| Parameter | Description                         | Value        |
|-----------|-------------------------------------|--------------|
| $P_{max}$ | Maximum power at STC ( $W$ )        | 100          |
| $V_{mp}$  | Optimum operating Voltage ( $V$ )   | 18.0         |
| $I_{mp}$  | Optimum operating Current ( $A$ )   | 5.56         |
| $V_{oc}$  | Open-Circuit Voltage ( $V$ )        | 22.30        |
| $I_{sc}$  | Short-Circuit Current ( $A$ )       | 5.59         |
| $\eta$    | Solar module efficiency (%)         | 17.80        |
| $M_{pv}$  | Weight of the solar module ( $kg$ ) | 7            |
| Size      | Dimensions                          | 995x680x30mm |

The choice of the TEC was made with consideration of both its cooling capacity and cost-effectiveness. This decision aimed to achieve a balance between the TEC's ability, to efficiently manage temperature and its affordability, ensuring an optimal solution, while maintaining cost efficiency.

Table 4.3: Component size and parameters of the TEC

| Parameter        | Description                            | Value       |
|------------------|----------------------------------------|-------------|
| $I_{max}$        | Maximum current ( $A$ )                | 6.1         |
| $V_{max}$        | Maximum Voltage ( $V_{dc}$ )           | 17.2        |
| $P_{C_{max}}$    | Cooling Power ( $W$ )                  | 66.7        |
| $\Delta T_{max}$ | Temperature difference ( $^{\circ}C$ ) | 79          |
| Size             | Dimensions                             | 40x40x3.8mm |

The selection of the heatsink was primarily influenced by its low thermal resistance, which was a crucial factor in optimizing the performance of the TEC. Additionally, the chosen heatsink size was considered, to ensure an ideal thermal management solution for the TEC, as it is mounted on the hot side of the TEC, to ensure heat dispersion, thereby enhancing overall system efficiency.

Table 4.4: Component size and parameters of the Heatsink

| Parameter | Description                          | Value        |
|-----------|--------------------------------------|--------------|
| $R_{th}$  | Thermal resistance ( $^{\circ}C/W$ ) | 2.6          |
| Size      | Dimensions                           | 40x40x24.5mm |

The simulation parameters are elaborated upon in Table 4.5. To augment the accuracy of the results, a sampling interval of 15 minutes was selected, covering a control horizon spanning 24 hours. As a result, the control horizon encompasses a total of 96 data points.

Table 4.5: Simulation constraints

| Parameter | Description                                    | Value |
|-----------|------------------------------------------------|-------|
| $t_s$     | Sampling time ( <i>minutes</i> )               | 15    |
| N         | Number of samples over the control horizon (—) | 96    |
| Hours     | Hours in control horizon ( <i>hours</i> )      | 24    |

## 4.2.4 Baseline

To ascertain the effectiveness of the PV-TEC switching model in optimizing the operational efficiency of the PV module, it is imperative to establish a baseline for comparative analysis. This baseline condition represents the functionality of a PV module without a TEC. Under this baseline scenario, the surface temperature of the PV module remains uncontrolled and unimpeded, and its thermal behaviour is compared with the current ambient temperature conditions. Consequently, in this unregulated baseline condition, the PV module's temperature exhibits natural fluctuations, varying in response to fluctuations in ambient temperature.

### 4.2.4.1 Baseline: Summer case

Figure 4.6 depicts the cell temperature profile of the PV module. At first, the PV module's temperature commences at 17°C and remains within a 2°C range of this starting point, until 05:45. Subsequently, the temperature begins to rise, primarily driven by the incident solar radiation. Between 05:45 and 15:30, the PV module's temperature continues to climb, ultimately reaching its peak at 36.1°C. After 15:30, there is a notable decline in the PV module's temperature, attributed to the gradual reduction in solar radiation, eventually stabilizing at 21°C by 00:00.

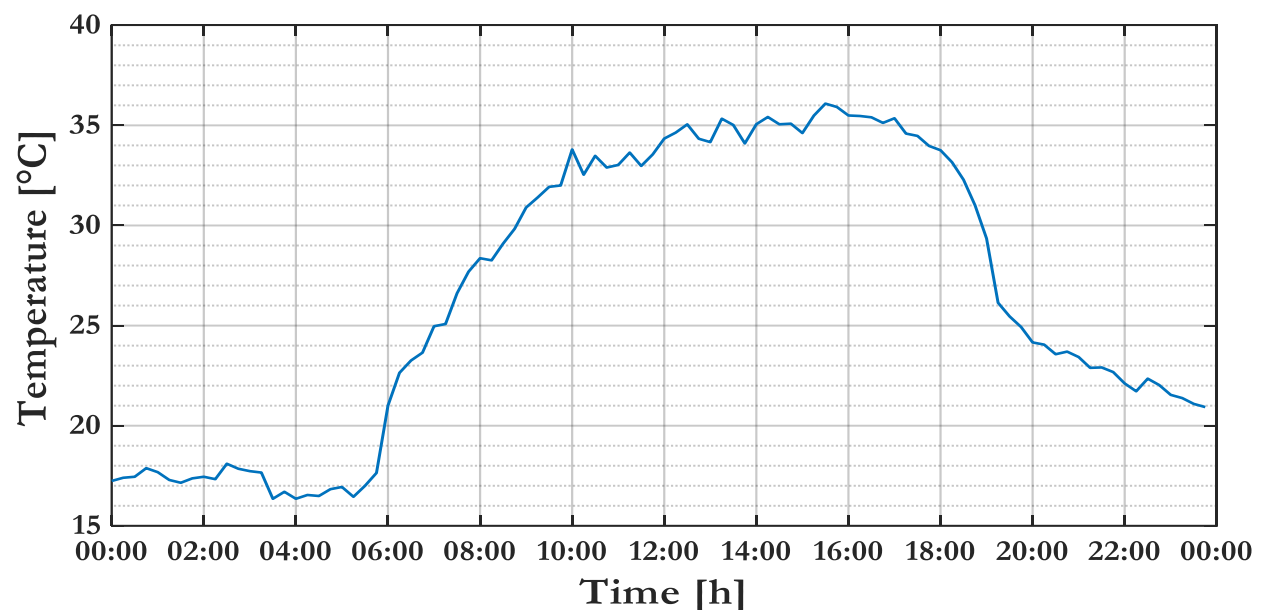


Figure 4.6: PV module temperature without cooling in summer

Figure 4.7, illustrates the power output characteristics of the PV module. It is worth emphasizing that, under the solar radiation and ambient air temperature conditions specified in Section 4.2.2, the PV module's energy output is significantly influenced by the heat generated on its surface. At the outset, the output power remains at zero, indicative of the

absence of solar radiation. Subsequently, starting at 05:45, the PV module commences energy production, with output increasing until 11:00. During the time frame from 11:00 to 11:45, the output power attains its peak value of 94.4W, primarily attributed to the exceptionally high solar radiation levels. After 11:45, the output power steadily decreases, reaching its lowest point by 19:15, coinciding with the absence of solar radiation. Typically, at STC conditions, the PV power output should be at 100W. However, the solar irradiance in the region during summer generally exceeds STC by a factor of approximately 1.2. This means that in an ideal setting where the STC temperature is 25°C the output power could reach 120W for this particular PV module, which indicates the importance of reducing the PV panel temperature.

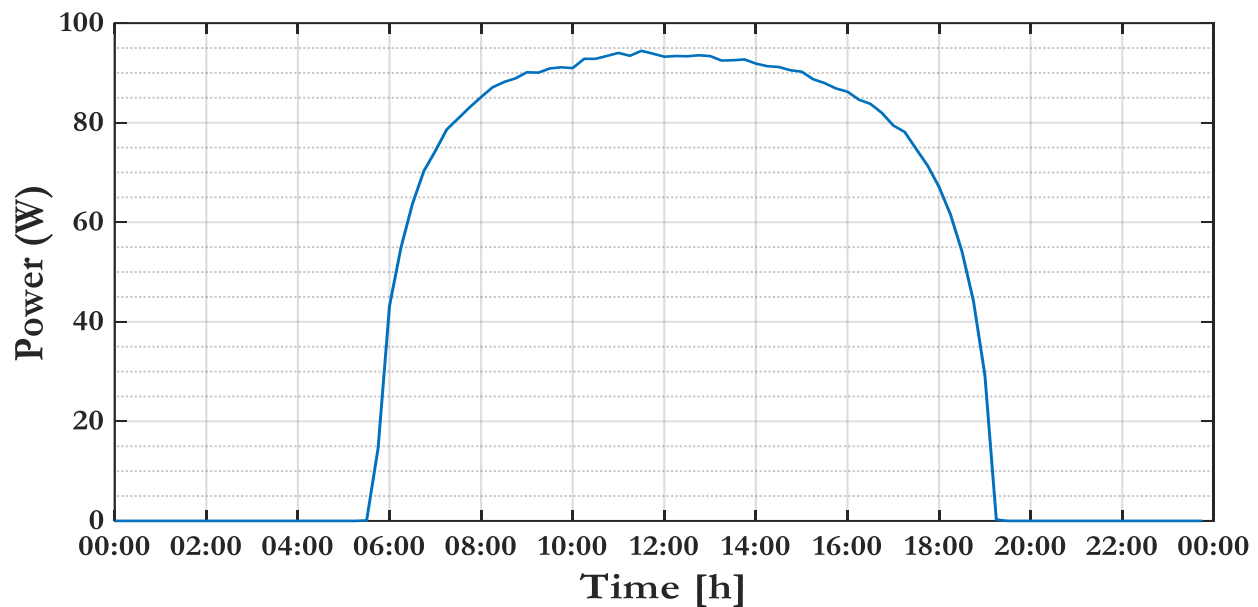


Figure 4.7: PV module power output without cooling in summer

Figure 4.8, presents the cumulative energy generation from the PV module. At the start, the cumulative energy remains at zero until 05:45, primarily as solar radiation is absent during this period, making energy production impossible. Subsequently, the module initiates energy production, steadily accumulating it throughout the day, until 00:00, ultimately reaching a total of 547.65Wh in energy generated. This would be much higher if the STC temperature of 25°C or below would have been maintained throughout the day.

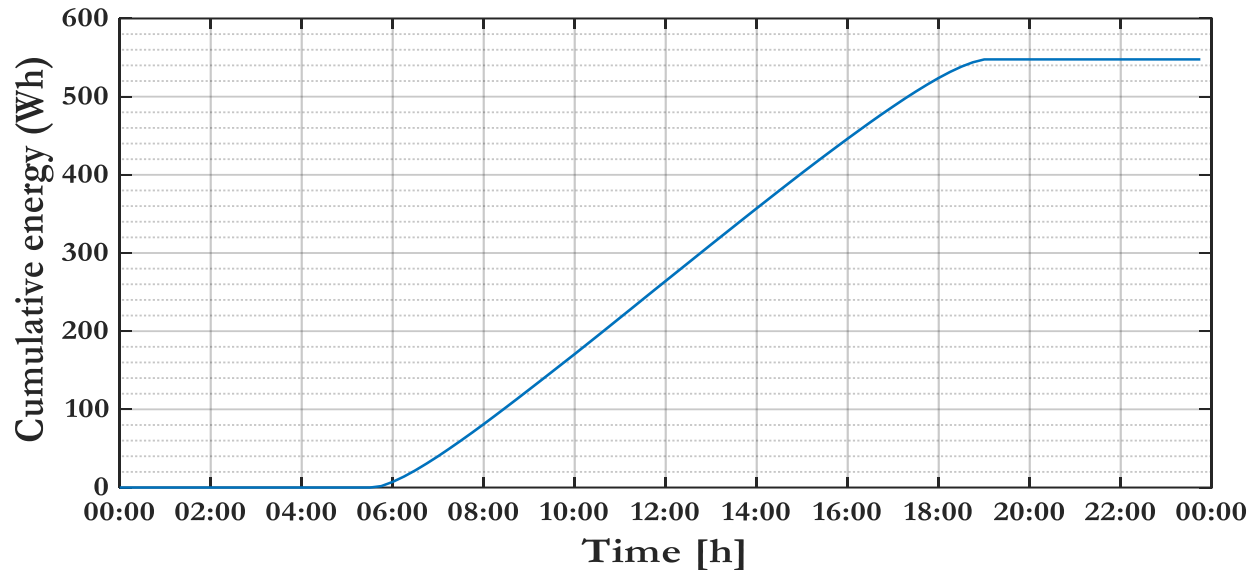


Figure 4.8: Cumulative energy in summer without cooling

#### 4.2.4.2 Baseline: Winter case

Figure 4.9, provides the cell temperature profile of the PV module. Initially, the PV module's temperature starts at 4°C and progressively decreases, until it reaches 1°C, by 05:00. Subsequently, between 05:00 and 07:15, the temperature undergoes minor fluctuations, oscillating between 1°C and 2°C. Thereafter, driven primarily by incident solar radiation, the temperature begins to rise. Between 07:15 and 14:30, the PV module's temperature steadily climbs, culminating at its peak of 22.9°C. Following 14:30, there is a noticeable decline in the PV module's temperature, attributed to the gradual reduction in solar radiation. This decline continues, until the temperature stabilizes at 8°C by 00:00. Additionally, it has to be noted that during winter months in the region, the solar irradiance is approximately 80% of STC conditions which also attributes to the lower cell temperature.

In Figure 4.10, we illustrate the output power characteristics of the PV module. Initially, the power output remains at zero, indicative of the absence of solar radiation. Subsequently, commencing at 07:00, the PV module initiates energy production, and the output power begins to rise, reaching its peak at 12:30. During the period from 12:15 to 12:30, the power output achieves its peak value of 86.9W, primarily driven by solar radiation levels. After 12:30, there is a gradual decline in the output power, reaching its minimum by 17:45, coinciding with the absence of solar radiation.

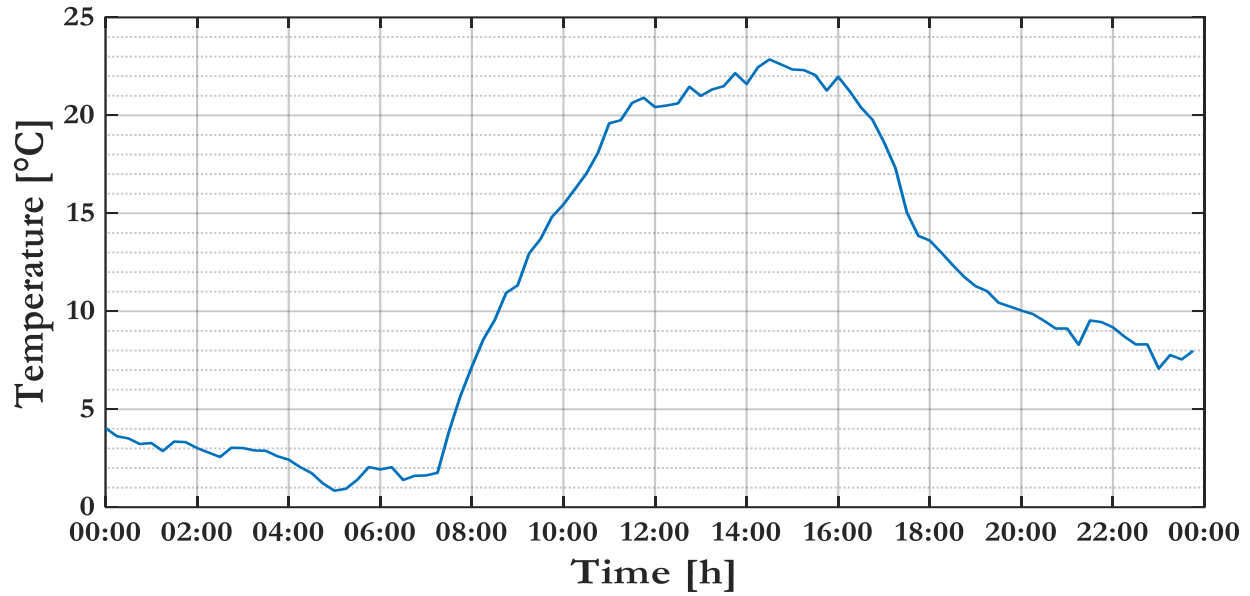


Figure 4.9: PV module temperature without cooling in winter

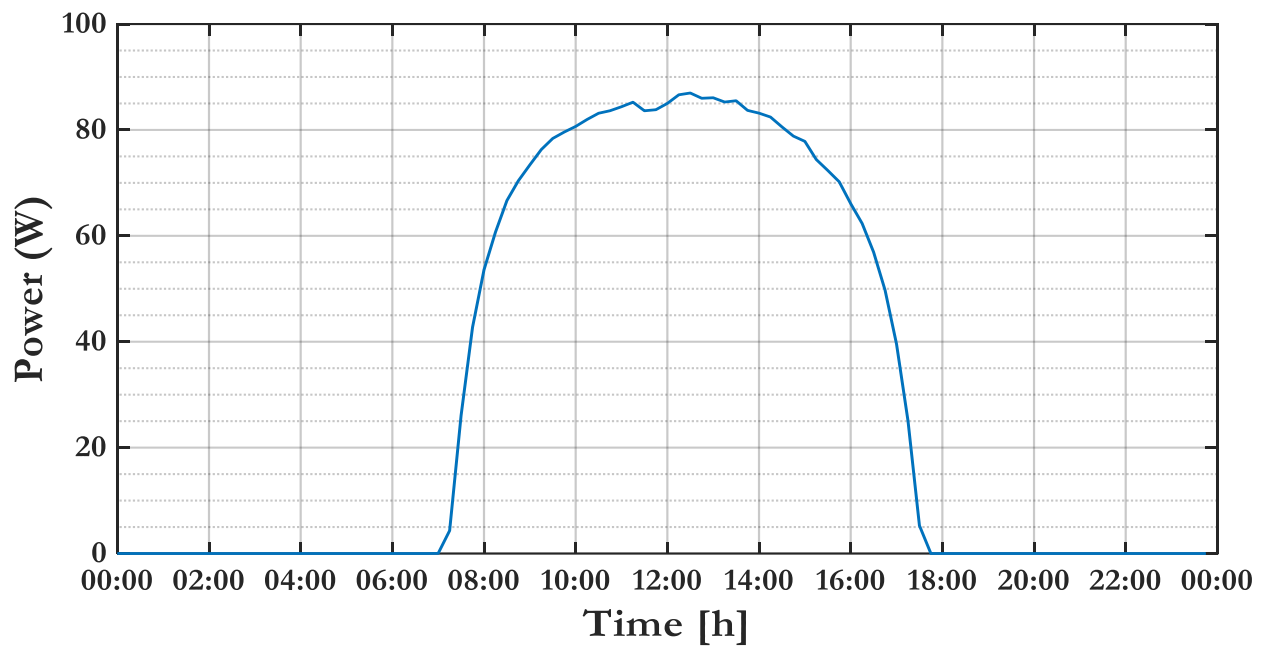


Figure 4.10: PV module power output without cooling in winter

Figure 4.11, displays the accumulation of energy produced by the PV module. Initially, the cumulative energy level stays at zero until 07:15, largely due to the absence of solar radiation during this time, rendering energy production unfeasible. Following this period, the module commences its energy generation, consistently building upon it throughout the day, until midnight, ultimately achieving a cumulative energy output of 363.47Wh.

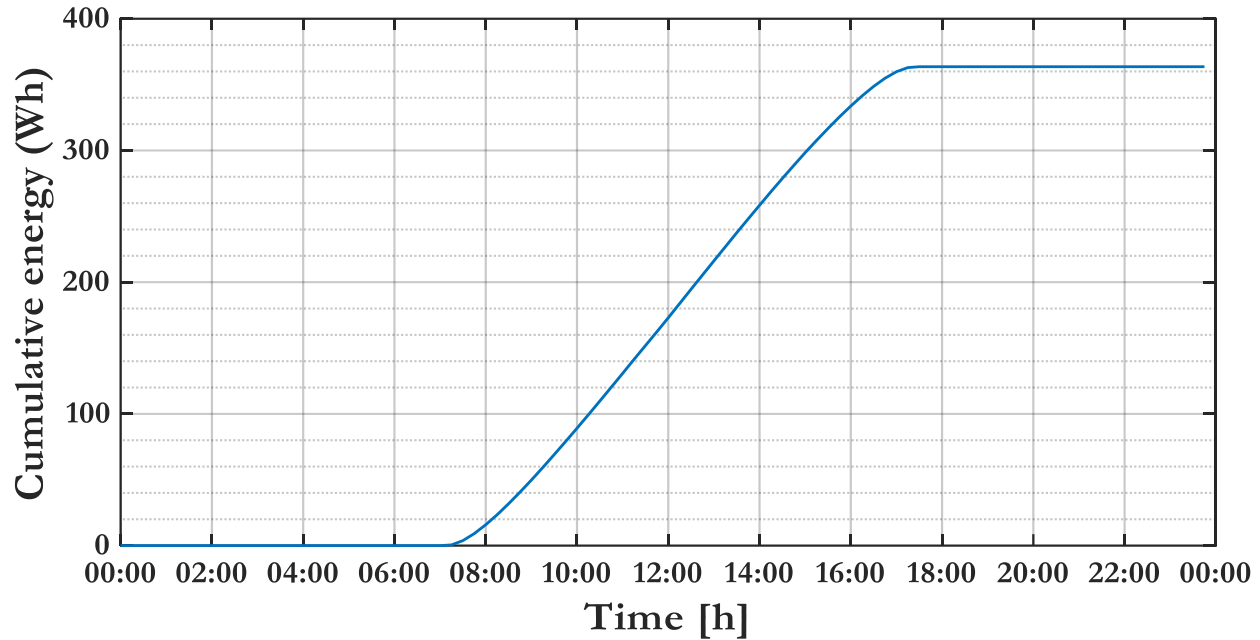


Figure 4.11: Cumulative energy in winter without cooling

### 4.3 OPTIMAL SWITCHING CONTROL MODEL

This Section outlines the functioning of the proposed hybrid system, equipped with the optimal TEC configuration. Employing the identical PV panel, utilized in the baseline model, the PV panel was coupled with a TEC, to constitute the proposed hybrid system. Comprehensive details, regarding the dimensions and parameters of the TEC, are presented in Table 4.3. The hybrid PV-TEC system incorporates a switching control strategy, which leverages TEC technology to lower the surface operating temperature of the PV panel. This temperature regulation is achieved through the implementation of an optimized switching control model, designed to maintain the desired cold temperature level. This control model is simulated, using the SCIP solver, an optimization tool within the MATLAB environment.

#### 4.3.1 Optimal switching control model: Summer case

In Figure 4.12, the cell temperature profile of the PV module, that is outfitted with a TEC system, is depicted. At the beginning, the PV module's temperature is initiated at 24.4°C. Subsequently, it undergoes fluctuations within a range of 24.3°C to 25°C, until 02:30, after which it stabilizes at 25°C from 02:30 to 03:15. From there, it gradually decreases, reaching a minimum of 23.4°C at 03:30. The temperature continues to oscillate between 23.4°C and



24.1°C, from 03:30 until 05:15. Starting at 05:15, the PV module's temperature steadily rises, reaching 25°C at 06:00. This consistent temperature is maintained until 00:00

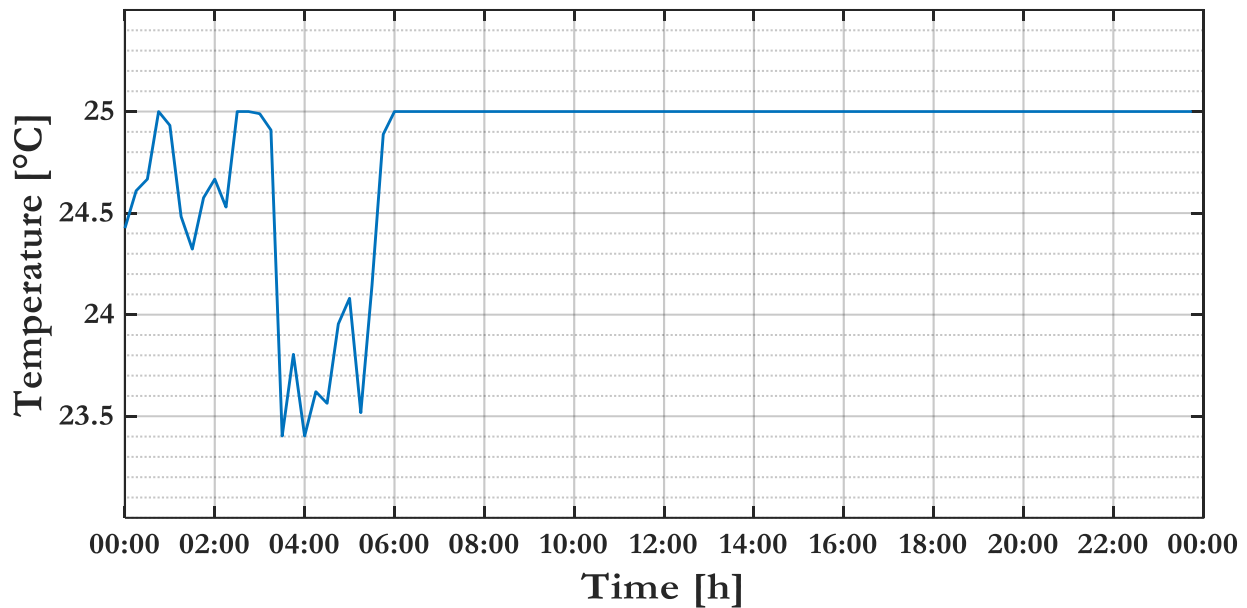


Figure 4.12: PV module temperature with cooling in summer

In Figure 4.13, a detailed representation of how the TEC functions, concerning the PV module's temperature, is provided. Initially, the TEC is in an inactive state, with some minor fluctuations noted at 00:45 and 02:30. These fluctuations are triggered when the PV module temperatures reaches approximately 25.3°C. Subsequently, from 02:30 to 05:50, the TEC remains off, as the PV module's temperature remains below the specified threshold of 25°C. Beginning at 05:50 and extending until 15:30, the TEC is gradually engaged, in response to the increasing temperature of the PV module. By 15:30, it reaches its maximum activation state, effectively cooling the PV module. However, as the PV module's temperature steadily decreases thereafter, the TEC is gradually deactivated, until it reaches its off state again at 00:00. This controlled switching of the TEC is orchestrated, to optimize the PV module's performance and maintain its temperature within the desired range.

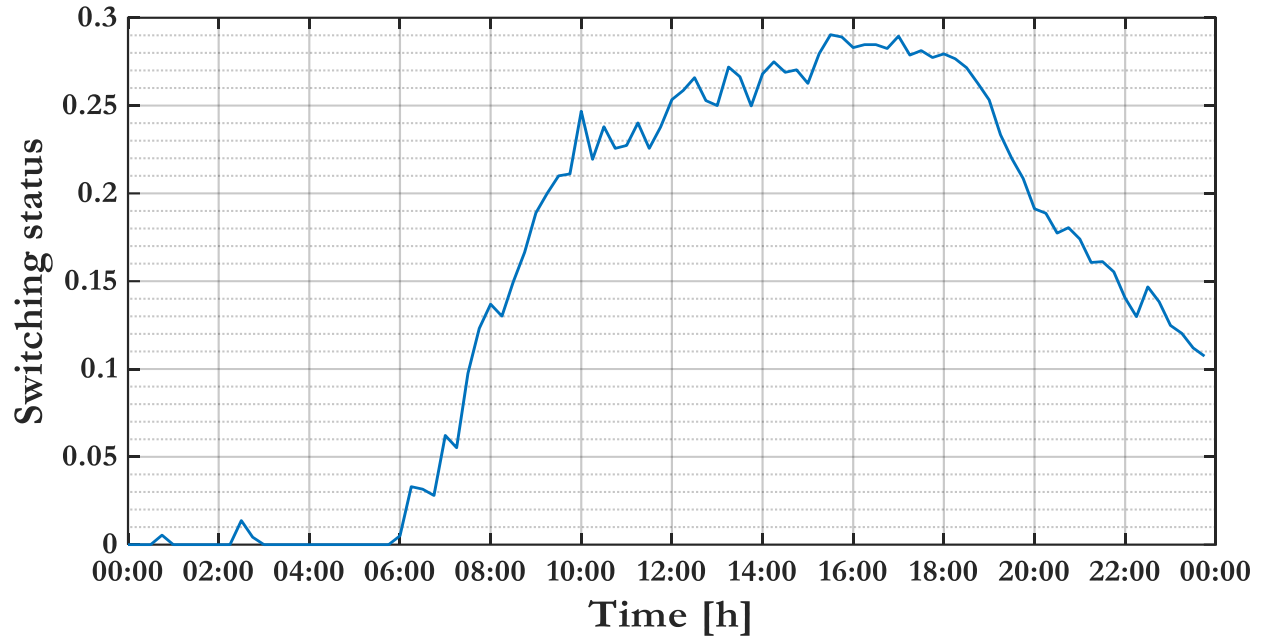


Figure 4.13: Optimal switching function of a TEC during summer

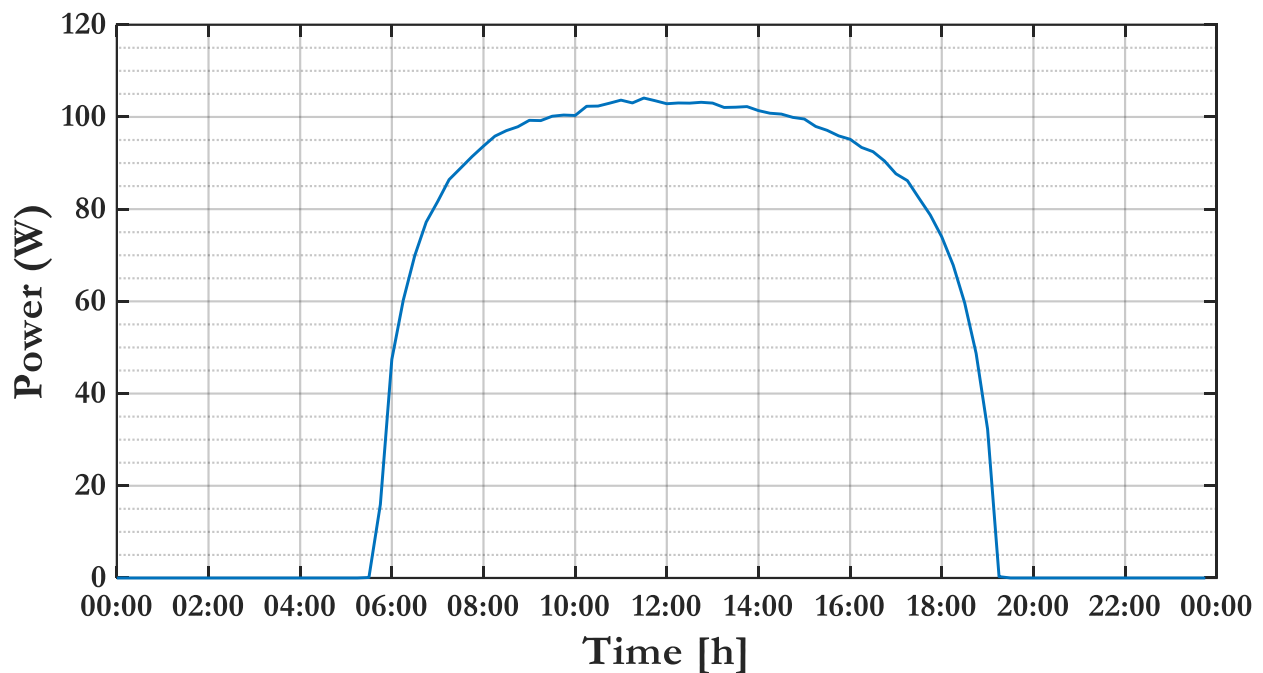


Figure 4.14: PV module power output with cooling during summer

In Figure 4.14, we present the power output characteristics of the PV module. Initially, the output power remains at zero, indicating the absence of solar radiation. Subsequently, starting at 05:45, the PV module begins generating energy and the output power progressively increases, until 11:00. Between 11:00 and 11:50, the power output reaches its peak value of 104.1W, at approximately 11:30, primarily owing to the exceptionally elevated solar radiation

levels, during that period. After 11:50, there is a gradual decline in the output power, reaching its lowest point by 19:15, which aligns with the absence of solar radiation.

Figure 4.15, displays the accumulation of energy produced by the PV module. Initially, the cumulative energy level stays at zero until 05:45, largely due to the absence of solar radiation during this time, rendering energy production unfeasible. Following this period, the module commences its energy generation, consistently building upon it throughout the day, until midnight, ultimately achieving a cumulative energy output of 603.60Wh.

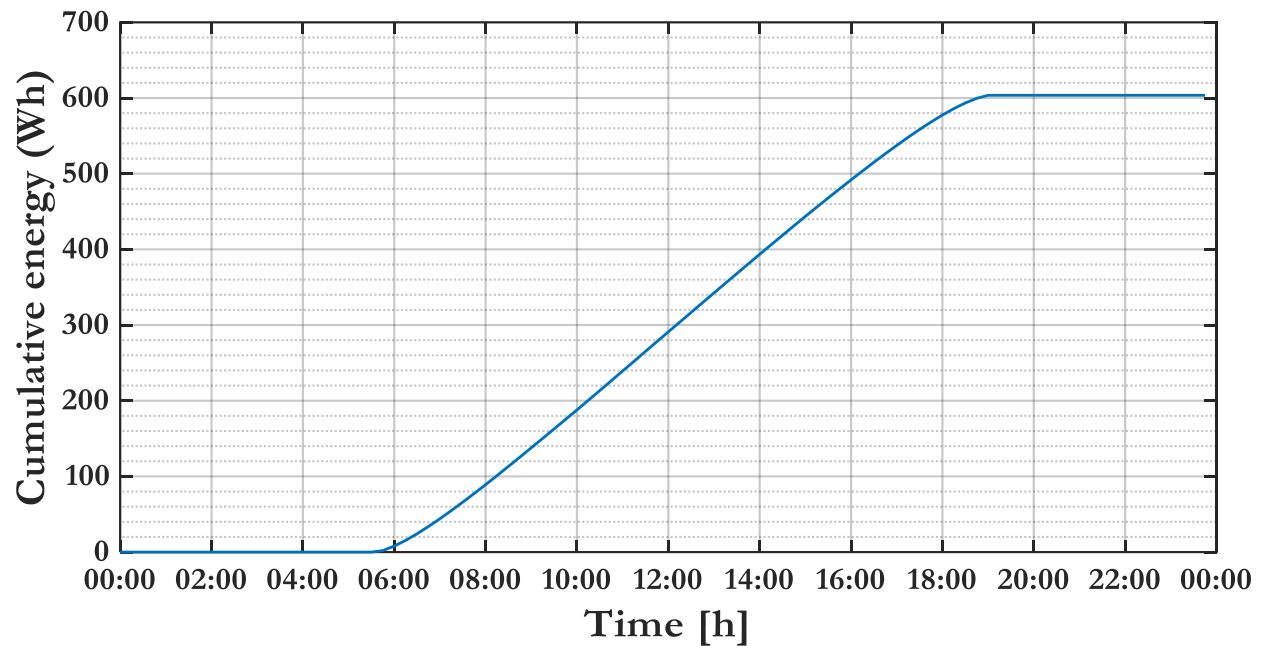


Figure 4.15: Cumulative energy in summer with cooling

### 4.3.2 Optimal switching control model: Winter case

Figure 4.16, illustrates the thermal performance of the PV module, offering a detailed insight into its temperature profile. Notably, this profile demonstrates a stable thermal behaviour, as no significant temperature fluctuation is observed the minimum threshold. This may be attributed to the inactivity of the TEC. The absence of TEC activation is primarily a result of the PV module's peak temperature, which is registered at 22.9°C. It is noteworthy that, this temperature remains below the threshold of 25°C, which serves as the critical point for TEC activation, aimed at enhancing the efficiency of the PV module.

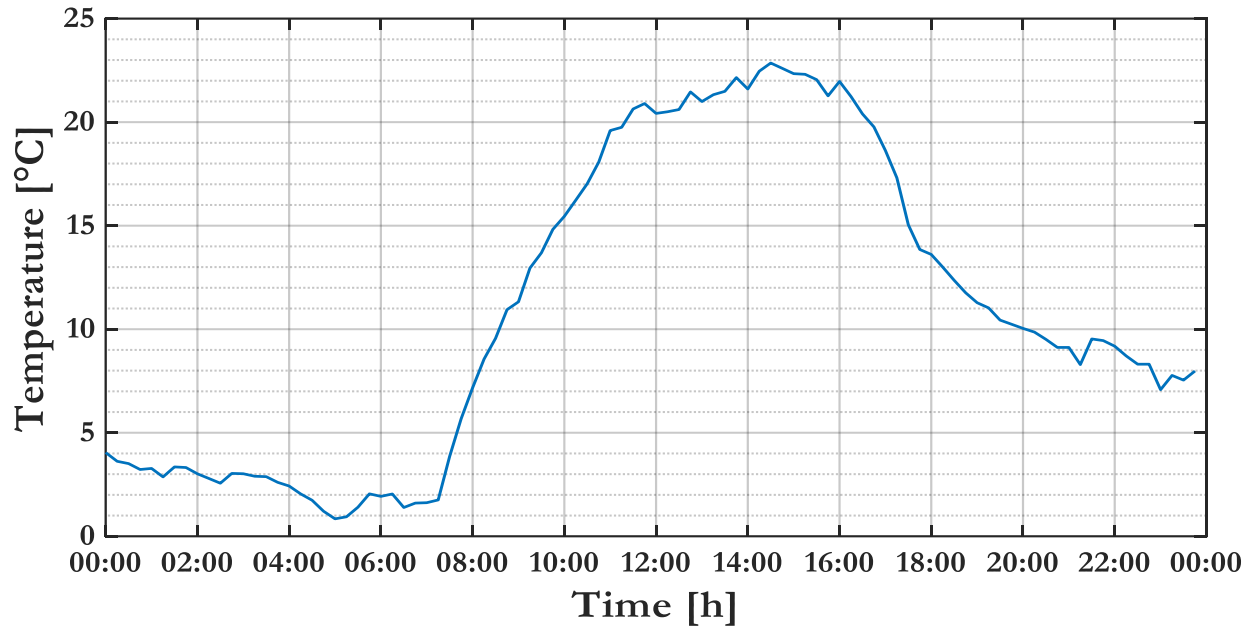


Figure 4.16: PV module temperature with cooling in winter

In Figure 4.17, we depict the control function of the TEC employed to regulate the temperature of the PV module. The TEC's operation is influenced by the PV module's temperature dynamics. Specifically, when the PV module experiences a momentary peak temperature of  $22.9^{\circ}\text{C}$ , the optimization system perceives it as impractical to activate the TEC.

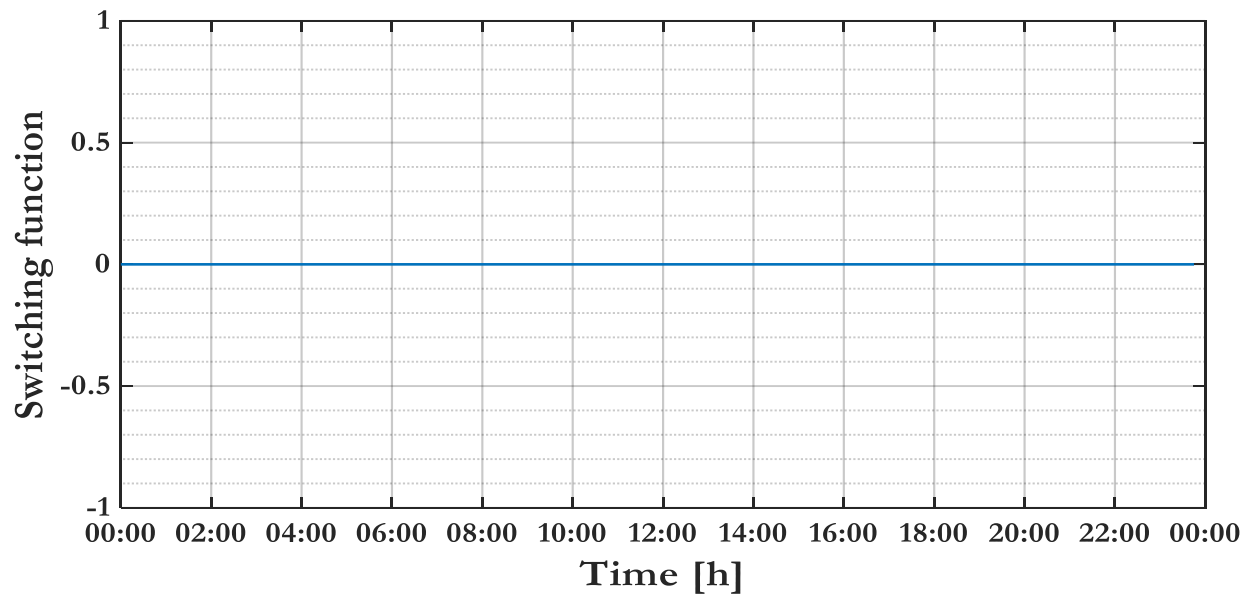


Figure 4.17: Optimal switching function of a TEC during winter

Consequently, during this period, the TEC remains off to enhance the PV module's power output. This strategic decision aligns with optimizing the PV module's performance, under the provided conditions.

In Figure 4.18, a graphical depiction of the PV module's power output characteristics is presented. Given the PV module's operating temperature of  $22.9^{\circ}\text{C}$ , which falls below the threshold PV module temperature for the TEC activation at  $25^{\circ}\text{C}$ , the TEC does not engage, due to the impracticality of doing so. Consequently, the power output of the PV module remains consistent, with an unassisted cooling scenario, yielding a constant power output of  $86.9\text{W}$ .

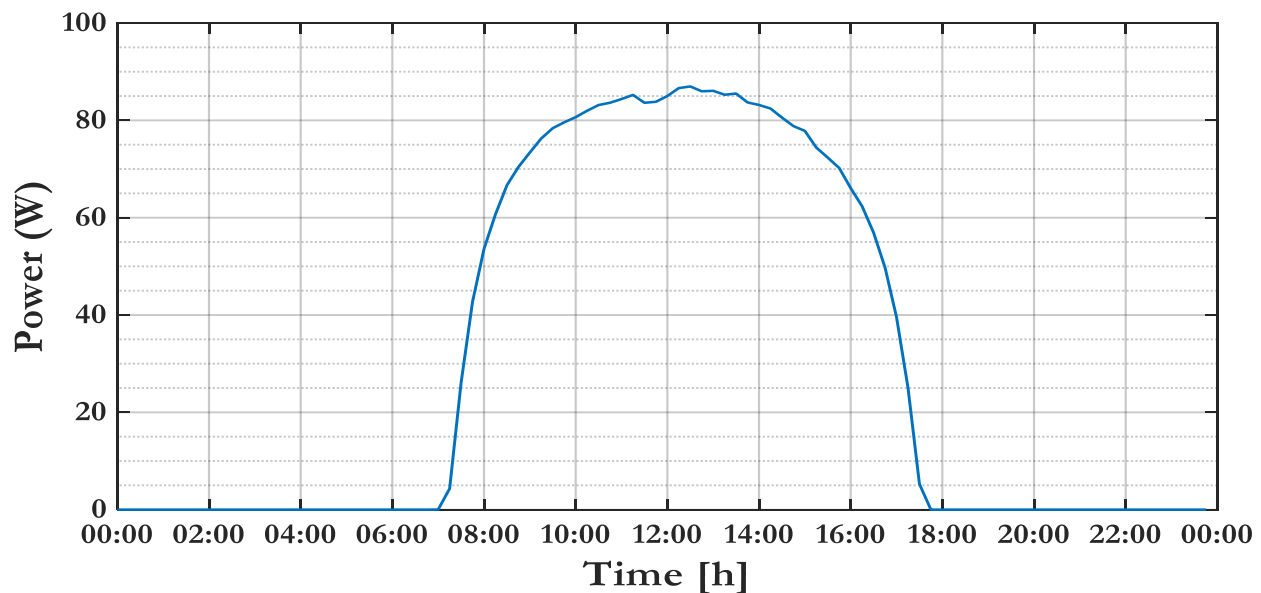


Figure 4.18: PV module power output with cooling in winter

Figure 4.19, illustrates the accumulation of energy produced by the PV module. Initially, the cumulative energy level remains at zero until 07:15, primarily due to the absence of solar radiation during this period, making energy production impossible. It is important to note that this cumulative energy value is the same as when there is a lack of cooling, resulting from the TEC not switching on. Subsequently, the energy production output is  $363.47\text{Wh}$ .

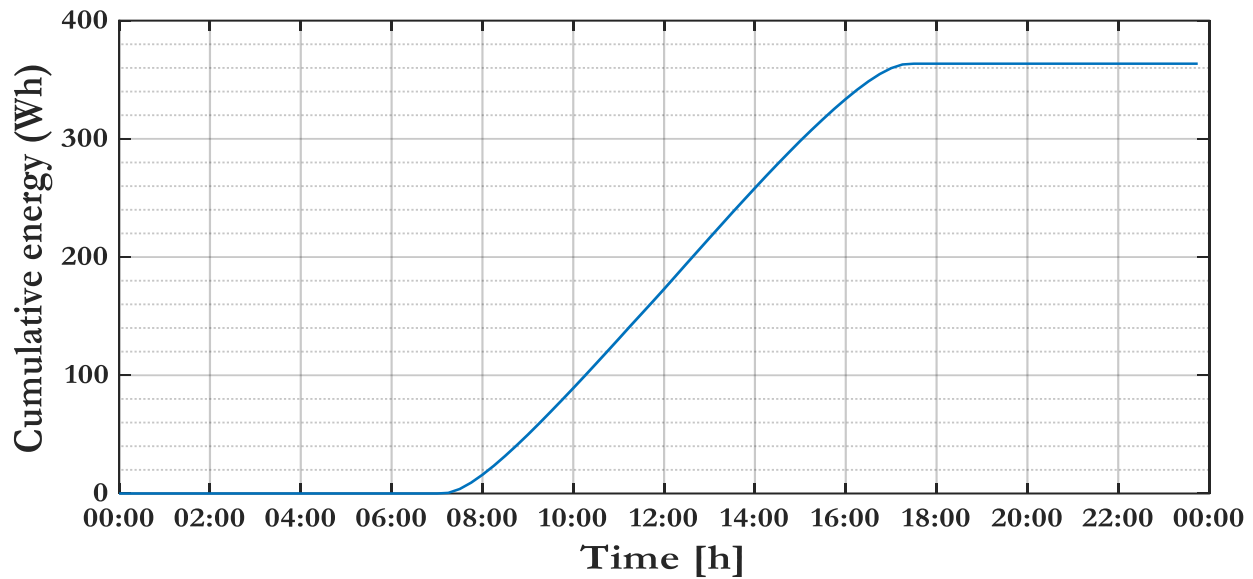


Figure 4.19: Cumulative energy in winter with cooling

### 4.3.3 Comparison between the baseline and optimal control of a PV-TEC

The developed model for both the baseline and the optimized flow switching, utilizes real historical data for summer and winter conditions. This data is crucial for achieving an accurate and effective simulation of their operational behaviour.

#### 4.3.3.1 Summer case

In Figure 4.20, a significant contrast in the temperature performance of the PV module, is observed. Without any cooling mechanisms in place, the PV module's temperature soared to a peak of 36.1°C. However, when the optimal switching control model was applied, the temperature was managed and maintained at a maximum of 25°C. This control strategy is visibly depicted in Figure 4.20, showcasing the effectiveness of the optimizer in keeping the PV module within a desired temperature range.

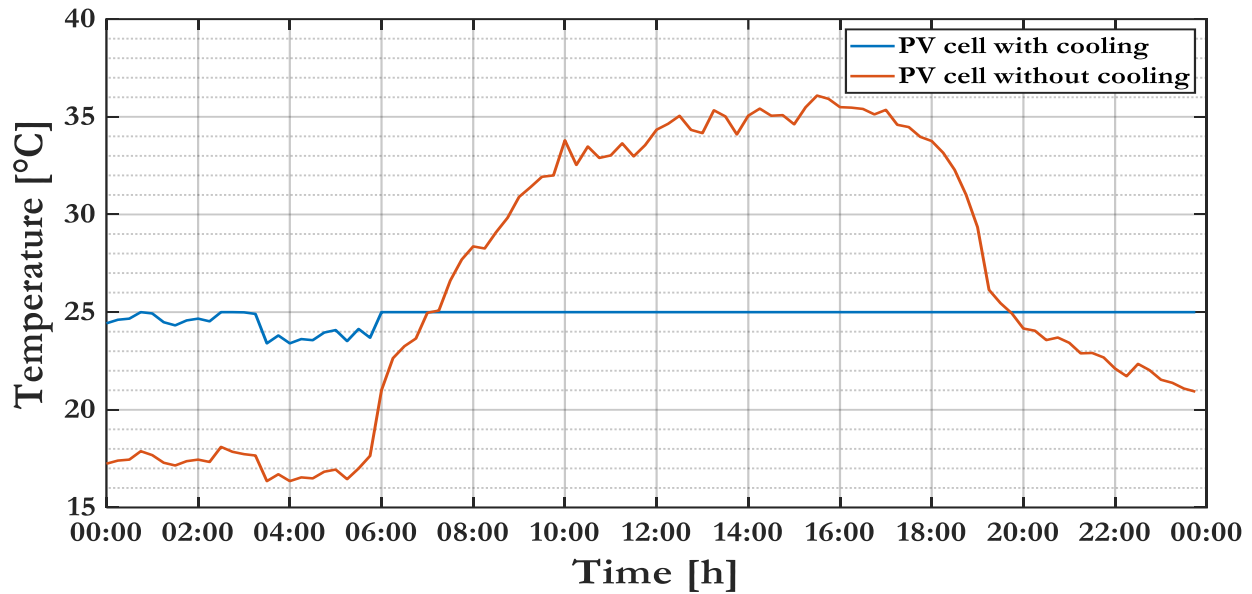


Figure 4.20: PV module temperature comparison in summer

Moving on to power output, Figure 4.21 demonstrates another notable difference. The standard PV module reached a peak power output of 94.4W, whereas the optimal switching control model achieved a higher peak power output of 104.1W. Importantly, it's crucial to recognize that the power output of the optimal switching control model, considers the energy consumed by the TEC. This is a noteworthy aspect, as it showcases the practical integration of PV and TEC technologies, to maximize energy production, while effectively managing temperature.

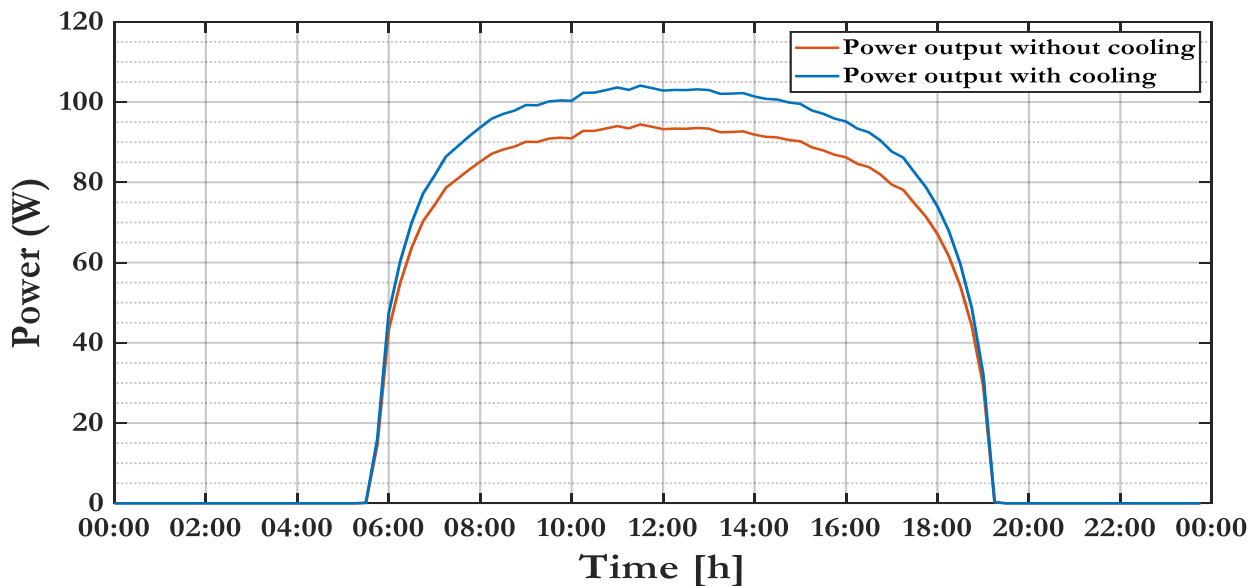


Figure 4.21: PV module power output comparison during summer

Furthermore, beyond the immediate benefits of enhanced power output and temperature control, this model holds promise for extending the lifespan of the PV module. By optimizing its operating conditions, the model offers the potential to reduce stress on the PV module components, ultimately contributing to a longer and more sustainable operational life.

#### 4.3.3.2 Winter case

The temperature of the PV module, in the absence of any cooling mechanism, reached a peak of 22.9°C. Nevertheless, the optimal switching control model remained inactive, as the PV module's temperature stayed within the predefined operational boundaries for optimizing the output power, as shown graphically in Figure 4.22.

In terms of power output, the standard PV module achieved a maximum power output of 86.9W, while the optimal switching control model's power output was the same, due to the inactive state of the optimal switching control model, as illustrated in Figure 4.23.

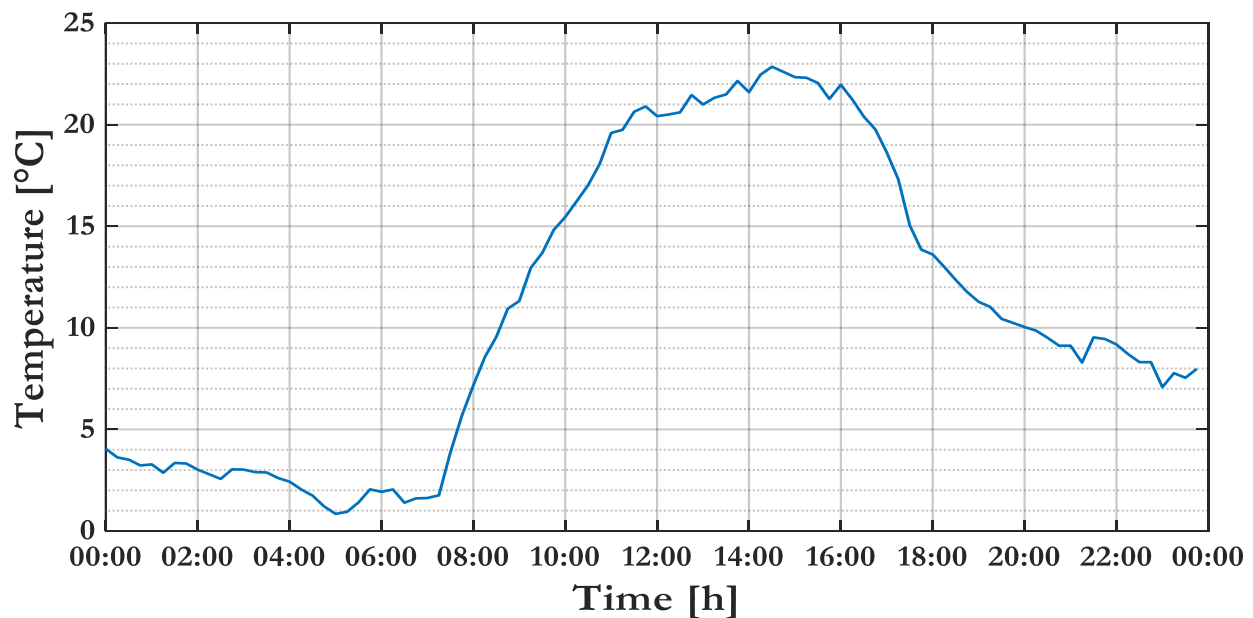


Figure 4.22: PV module temperature comparison in winter



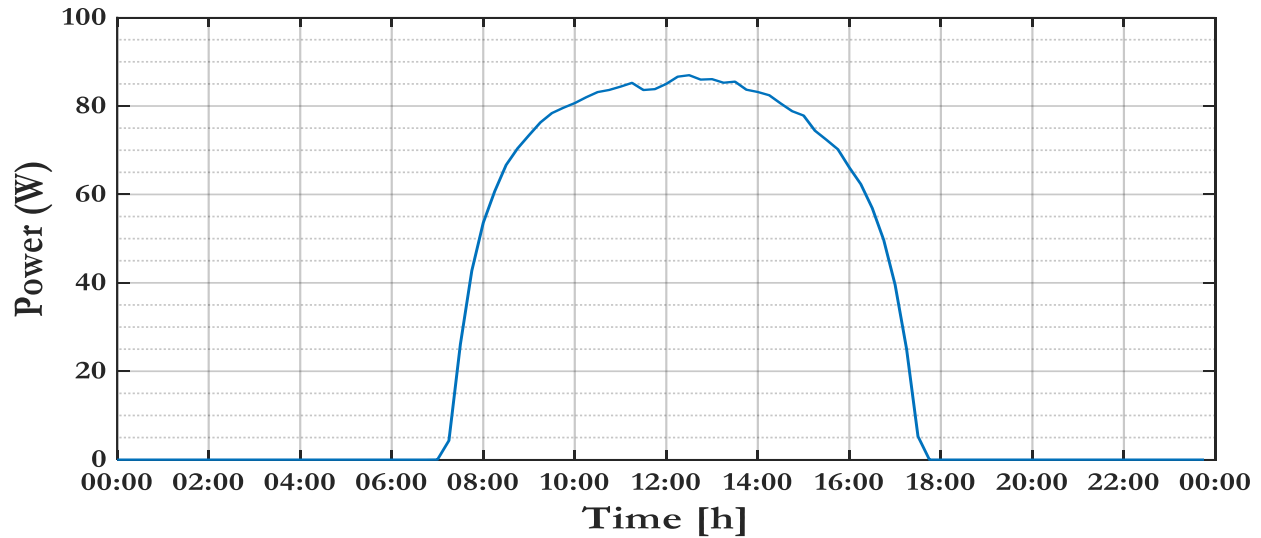


Figure 4.23: PV module power output comparison in winter

## 4.4 SUMMARY

In this Chapter, simulations of both a standard PV module (referred to as the baseline) and an optimal switching control system, incorporating a TEC, were conducted. These simulations were performed using MATLAB and the SCIP solver, within the MATLAB Optimization Toolbox. To ensure the accuracy of our simulations, we relied on historical data, to effectively replicate real-world operating conditions.

Our focus was on optimizing the output power of the PV module, particularly during the summer season. The results from our proposed model, demonstrated a substantial improvement in output power, specifically by 9.27% during the summer and no enhancement in output power was observed during the winter season, due to the inactive optimal switching control model caused by the low PV module temperature.

In addition to power output optimization, further investigation was conducted on the temperature behaviour of the PV cell, both with and without the cooling system. These temperature profiles were analyzed, for both summer and winter scenarios, allowing for a clear comparison of the PV module's performance, under these different conditions. Notably, it was observed that the heat generated on the PV module's surface is substantially higher through the summer months, compared to winter. Consequently, the TEC system is more actively engaged during summer, to manage these elevated temperatures effectively. This intervention, which combines PV and TEC technologies, presents a practical and efficient integration approach.

## CHAPTER V: ECONOMIC ANALYSIS

### 5.1 INTRODUCTION

The continual validation of cost-effectiveness in engineering projects, necessitates a consistent comparison of the proposed model against a standard PV system, referred to as the baseline. Various economic performance metrics, including the simple payback period (SPP), internal rate of return (IRR), benefits-to-cost ratio (BCR) and life-cycle cost (LCC) [51], serve as critical benchmarks. The SPP method stands out for its simplicity in both comprehension and computation. Nevertheless, it fails to incorporate the effects of depreciation over time, influenced by factors such as inflation. Additionally, this method overlooks the project's entire lifespan, leaving investors in the dark, regarding the project's long-term profitability. Therefore, the break-even point (BEP) analysis will be applied, in terms of the baseline and proposed hybrid system. This analysis will then be compared, to calculate the savings over the project lifetime for 20 years, as chosen for this study.

### 5.2 INITIAL COST OF THE PROPOSED HYBRID SYSTEM

Within this Section, a detailed breakdown of the initial investment costs for both the standard PV system and the optimal switching control model at the component level is presented. Table 5.1 below, displays the component prices utilized in the analysis of the standard PV system [53]. Notably, the solar panel stands out as the largest contributor to the initial investment in the standard PV system.

Table 5.1: Bill of materials of the standard PV system

| Component description         | Quantity | Net price (ZAR) |
|-------------------------------|----------|-----------------|
| 100W Solar panel              | 1        | 1235.00         |
| Total initial investment cost | 1        | 1235.00         |

Table 5.2 provides a breakdown of component prices for the optimal switching control model. The thermoelectric module [54], a heatsink [55], apart from the solar module, which is the same as the Standard PV used as a baseline. Additionally, it is worth observing that the optimal switching control model consists of more components, in comparison to the standard PV system, resulting in an initial investment that is higher than that of the standard PV system.

Table 5.2: Bill of materials of the proposed system with optimal switching control

| Component description         | Quantity | Net price (ZAR) |
|-------------------------------|----------|-----------------|
| 100W Solar panel              | 1        | 1235.00         |
| Peltier cooler module         | 1        | 129.95          |
| Heatsink                      | 1        | 197.82          |
| Total initial investment cost | 1        | 1562.77         |

### 5.3 CUMULATIVE COST COMPARISON

In the process of computing the cumulative saving accrued throughout the specified project's duration, notably a 20-year span, it is imperative to account for certain variables. As clarified in Section 5.2, it is imperative to differentiate the initial implementation cost from cumulative savings, as the former represents a singular expenditure incurred solely at the project's inception. Consequently, it is essential to equate the annual savings and operation & maintenance (O&M) costs from each year, after the project's commencement, to the initial implementation cost. This summation yields the comprehensive aggregate cost saving of the lifetime of the project [56].

#### 5.3.1 Cumulative energy saving

To compute the daily cumulative energy savings, we may adapt the primary objective function as previously discussed in Chapter III. This adaptation permits us to employ Equation (3.25) for the specific purpose at hand:

$$Energy\ cost\ savings = t_s \cdot Cost_{Elec} \sum_{k=1}^N (P_{PV} - P_{TEC} S_{TEC}) \quad (5.1)$$

Where:

$t_s$  is the sampling time (hours);

$P_{PV}$  is the rated power of the PV panel (W);

$P_{TEC}$  is the rated power of the TEC module (W);

$S_{TEC}$  is the switching status function for the associated TEC;

$Cost_{Elec}$  is the cost of electricity (ZAR/Wh).

### 5.3.1.1 Summer cumulative energy saving comparison

The cumulative saving associated with the summer period, as depicted in Figure 5.1, is linked to the switching function detailed in Section 4.3.1. This relationship is evident through an examination of the TEC system's switching behaviour, during surface temperature fluctuations. Notably, specific surface temperature threshold triggers discrete transitions, culminating in heightened overall cost savings. Upon the culmination of a 24-hour cycle, a comprehensive overview of total savings becomes apparent.

In Figure 5.1, the cumulative curve, clarifies a direct correlation between the baseline and optimal control strategies. The optimally controlled system strategically activates when solar irradiance is available, its intensity increasing when the surface temperature surpasses the 25°C threshold. A careful analysis reveals that the cumulative saving of the baseline system, closely approximates that of the optimally controlled system. The PV module with cooling using a TEC generates 55.95Wh more energy compared to the PV module without cooling.

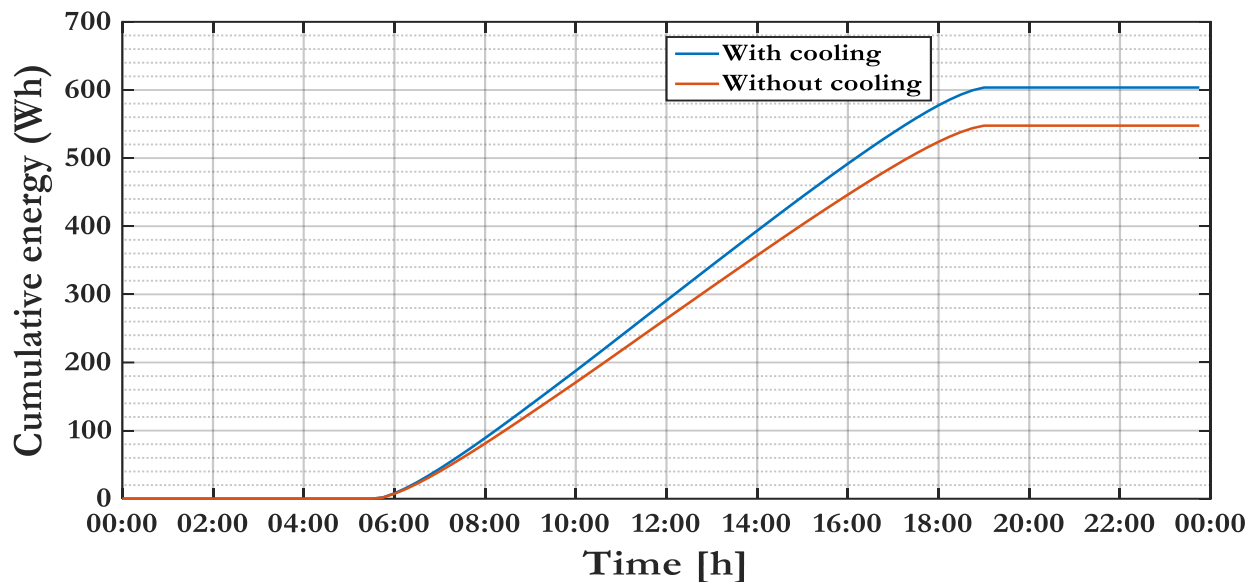


Figure 5.1: Summer cumulative energy saving

### 5.3.1.2 Winter cumulative energy saving comparison

The accumulation of savings during the winter season, illustrated in Figure 5.2, mirrors the pattern observed in summer, as demonstrated in Figure 5.1. In both cases, the baseline and optimal switching curves coincide, primarily as activating the TEC system becomes impractical, when the surface temperature falls below the prescribed threshold, for the switching mechanism. Consequently, the cumulative energy savings remain consistent,

whether the optimal switching strategy is implemented or not. The prevalence of low solar irradiance during the winter, primarily attributed to diminished savings, in comparison to the summer period, despite the equal 24-hour duration.

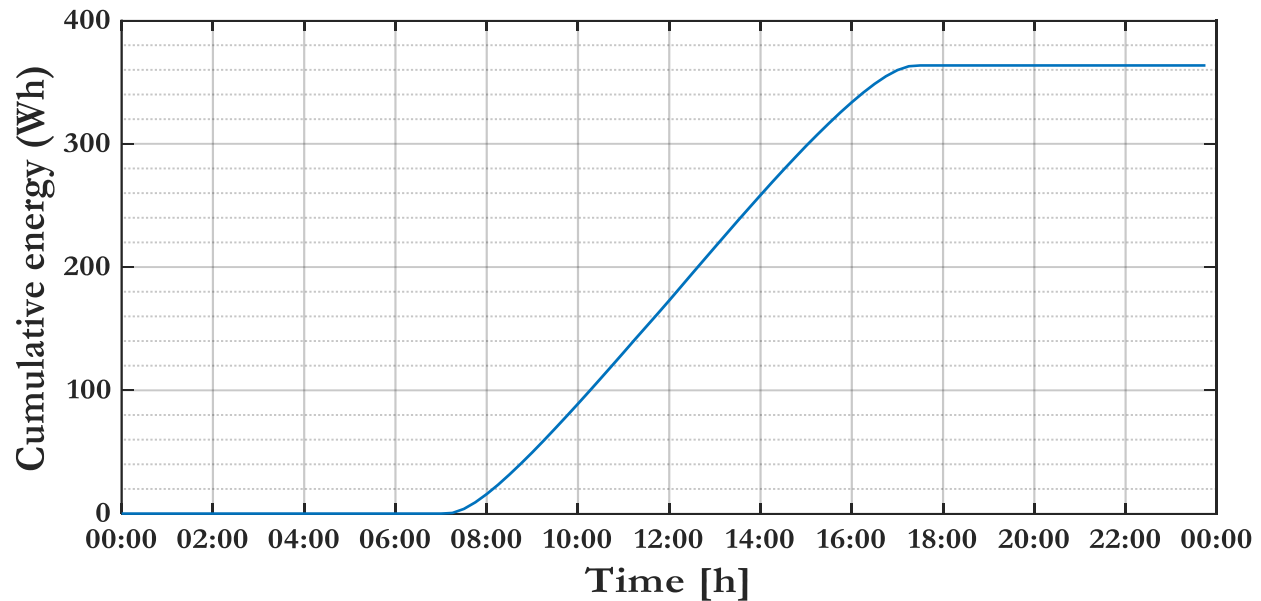


Figure 5.2: Winter cumulative energy saving

### 5.3.1.3 Daily energy savings

The progressive energy saving, achieved in successive iterations of both the baseline and optimal control strategies, is presented in Table 5.3. Specifically, during the summer season, a notable 9.27% enhancement in energy production, is observed. Whereas, in contrast, no discernible disparity in power production is observed, during the winter months. This comparative analysis underscores the critical significance of employing optimal switching control techniques for TEC, to maintain the PV temperature above the 25°C threshold.

Table 5.3 Daily energy savings

| Strategy | Baseline (PV) |                      | Optimal control (PV-TEC) |                      | Daily savings (ZAR) | Daily savings (%) |
|----------|---------------|----------------------|--------------------------|----------------------|---------------------|-------------------|
|          | Energy (Wh)   | Cost (ZAR) @3.42/kWh | Energy (Wh)              | Cost (ZAR) @3.42/kWh | Cost                | Energy            |
| Summer   | 547.65        | 1.87                 | 603.60                   | 2.06                 | 0.19                | 9.27              |
| Winter   | 363.74        | 1.24                 | 363.74                   | 1.24                 | 0.0                 | 0.0               |

#### 5.3.1.4 Annual energy savings

The yearly energy cost savings, encompass the cumulative electrical energy produced by both the PV module within the conventional PV system and the PV module, within the optimal switching control model. Additionally, we account for the power gain achieved through cooling in the optimal switching control mode and this is determined using the subsequent equation.

The cumulative energy saving, as shown in Table 5.4, is contingent upon South African Weather Service parameters. This outlines a summer season of 226 days and a winter season spanning 139 days. By multiplying the duration of each season by the corresponding cost savings, the comprehensive seasonal economizations, are derived. The summation of these seasonal savings facilitates the estimation of the approximate annual reduction in electricity expenses. Employing this methodology, the cost-saving figures for the year 2021, were determined and are presented in detail, in Table 5.4. The results underline a significant 9.27% enhancement in annual savings attributable to the implementation of the PV-TEC module, thereby illustrating its efficacy in optimizing energy utilization and cost efficiency.

Table 5.4 Annual energy savings

| Strategy<br>Season | Baseline<br>(PV) |                            | Optimal control<br>(PV-TEC) |                            | Annual<br>savings<br>(ZAR) | Annual<br>savings<br>(%) |
|--------------------|------------------|----------------------------|-----------------------------|----------------------------|----------------------------|--------------------------|
|                    | Energy<br>(kWh)  | Cost<br>(ZAR)<br>@3.42/kWh | Energy<br>(kWh)             | Cost<br>(ZAR)<br>@3.42/kWh | Cost                       | Energy                   |
| <b>Summer</b>      | 123.77           | 423.29                     | 136.41                      | 466.52                     | 43.23                      | 9.27                     |
| <b>Winter</b>      | 50.56            | 172.92                     | 50.55                       | 172.92                     | 0.0                        | 0.0                      |

#### 5.4 BREAK-EVEN POINT (BEP)

The break-even point is ascertained when the aggregated expenses, associated with implementing and operating the two systems, cease to equate. Specifically, this scenario involves a comparative analysis between the standard PV system (referred to as the baseline) and the proposed optimal control system, taking into consideration the cumulative annual energy savings over a project lifespan of 20 years [57].

To illustrate this point, cumulative cost curves are charted, encompassing the initial investment costs and the accrued total annual cost savings over the 20-year duration for both the baseline

and optimal control systems [58]. The intersection points of these two curves, represent the precise juncture in time (in years), at which the two systems attain financial equilibrium or break even.

Referring to Table 5.2, the initial total cost for implementing the optimized control system, stands at R1562.77, while the standard system registers R1235.00. These values serve as the baseline starting points for the cost curves, presented in Figure 5.3. Subsequently, after the first year of operation, the total annual energy saving is incorporated into the initial investment cost, culminating in the total present saving of energy, as depicted in Table 5.3. This aggregate saving represents the total cumulative expenditure for the initial year, following system implementation.

For each subsequent year, up to the tenth year, the calculations follow a consistent approach. An annual 10% increase in electricity prices, is considered, contributing to the computation of annual energy savings. The resulting figure is, thereafter, added to the accumulated savings from the preceding year. This methodology ensures that the cumulative saving curves in Figure 5.3, reflect the evolving financial landscape, over two decades.

In this graphical representation, we have not factored in the replacement costs and operational lifetimes of individual components. Examining Figure 5.3, a striking observation emerges: the break-even point manifests relatively early within the project's operational lifespan. To be precise, it transpires at the 6.5-year mark, at which the juncture of both systems reach an expenditure parity of R 3615.00. This means that after 6.5 years, the TEC would be less expensive to operate than the system without the TEC.

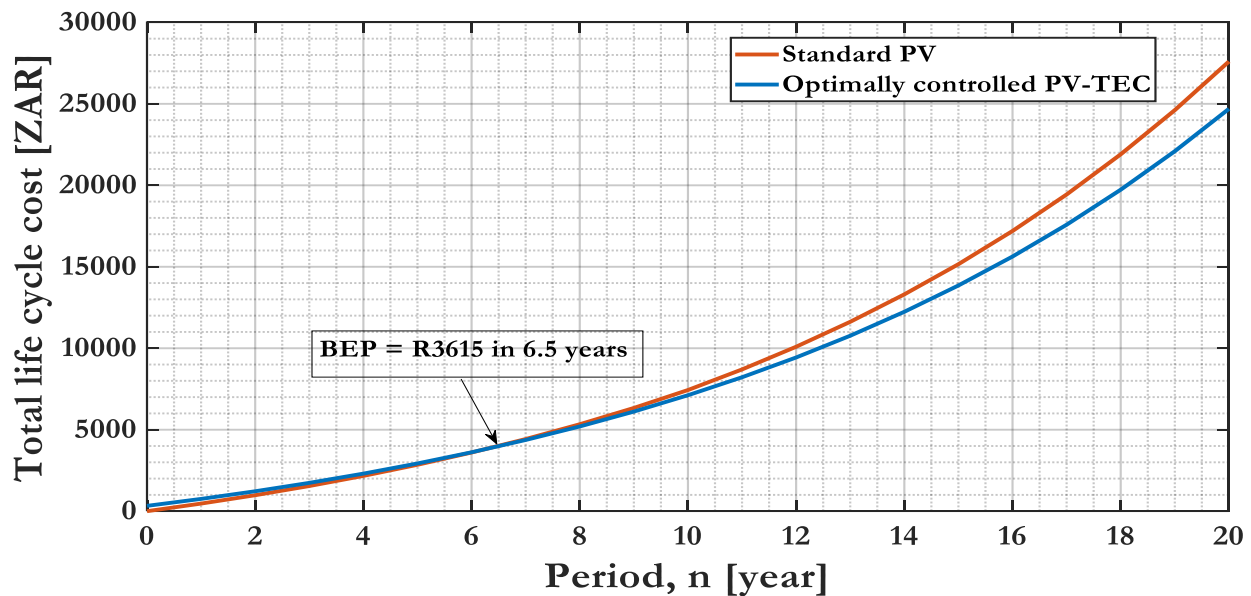


Figure 5.3: Break even point

Additionally, the disparity in total expenditures, at the culmination of the project's lifetime, stands as a pivotal indicator of its economic performance.

## 5.5 SUMMARY

In this Chapter, a cost-effectiveness assessment of the optimized PV-TEC system was conducted. The disparity in cumulative energy savings and associated costs was analyzed, enabling to perform annual comparisons of energy savings and expenses. Subsequently, a break-even point analysis was conducted to determine when the proposed system would reach an equivalent cumulative cost, in comparison to the baseline system. The results of this analysis indicated that, it took 6.5 years for the cumulative savings of the proposed system, to fall below that of the baseline.

Notably, it was observed that, beyond the break-even point, the difference in cumulative costs exhibited a significant increase and the baseline system costs, followed an exponential growth trend. Following the break-even point analysis, a life cycle cost evaluation was conducted, to compute the savings over the 20-year project duration.

The LCC comparison between the proposed system and the baseline, revealed a substantial cost savings of R2905.61, over the project's entire lifespan. These LCC calculations, were based on a relatively modest 6% interest rate and the conservative assumption of a 10% increase in electricity costs, despite historical data showing much steeper increments.

It is important to note that the proposed system, at this scale, guarantees a minimum cost saving of 10.56%.



## CHAPTER VI: CONCLUSION

### 6.1 FINAL CONCLUSIONS

This Chapter functions as the culmination of our investigation into simulating the optimal operational control of a hybrid cooling system, featuring both a solar module and a thermoelectric module. The primary focus of this study, centred on scrutinizing the impact of temperature fluctuations on the photovoltaic (PV) module, which results in a corresponding decline in its efficiency. This research endeavours were primarily centred on crafting an optimal control model, to maximize the energy yield of the PV module through the utilization of a Thermoelectric Cooler (TEC). The conclusion of this endeavour involves the formulation of an optimal control strategy model, which was subsequently employed to simulate the system operation, incorporating exogenous variables that emulate typical winter and summer conditions, in Bloemfontein.

In Chapter III, the operational framework of the hybrid PV-TEC system, was provided, subsequently presenting a mathematical model, defining the optimal control strategy for this hybrid system. The primary and foremost objective function herein, is the maximization of energy output harnessed from the PV module; a task achieved through the manipulation of the TEC switching status. The control variable is continuous, assuming values between 1 and 0, corresponding to the upper and lower bound constraints, respectively, governing the control switch.

The goal-orientated function and accompanying constraints were deduced and formulated, with the SCIP (Solving Constrained Integer Programs) solver, an integral component of OPTI-toolbox used in conjunction with MATLAB, serving as the tool of choice for the solution of these mathematical optimizations.

In Chapter IV, the solar radiation and ambient temperature data were leveraged, obtained at 15-minute intervals, as input parameters for balanced simulation requirements. A baseline scenario was established, which featured a 100W PV module operating, without any cooling in both summer and winter in Bloemfontein, Free State.

To evaluate the efficacy of the proposed optimized switching control strategy, simulations were performed, and the outcomes compared against the baseline scenario, as explained within this Chapter. The simulation outcomes indicate that, the proposed model delivers a substantial

improvement in power output, with enhancements of 9.27%, observed during summer and no enhancement was experienced in winter.

An economic analysis was further conducted and resulted in a cost saving of R2905.61, which is a 10.56% project lifetime saving over 20 years.

This research leads to several key conclusions:

- The introduced optimized switching control model for a hybrid PV-TEC system, incorporating TEC-based cooling, holds the potential for significant improvements in increasing the power output of the PV module.
- By implementing the proposed control strategy, it is possible to improve the PV module's efficiency and, consequently, its overall performance at an elevated level, ensuring sustainable and efficient energy generation, over an extended period.
- This research underscores the significance of thermal management strategies, such as TEC-based cooling, in optimizing the long-term performance and durability of PV modules, which is particularly relevant for regions with varying environmental conditions.

In summary, the findings of this study underscore the promising potential of the proposed optimal control model for enhancing PV module performance through an effective cooling mechanism and making the system cheaper in the long run.

## 6.2 SUGGESTIONS FOR FURTHER RESEARCH

This research is centred exclusively on optimizing the TEC, to facilitate the cooling of PV panels to improve their operational efficiency. In forthcoming investigations, a proportional control strategy, predicated on regulating the PV panel temperature, will be explored. This control scheme will activate the TEC, under the specific cooling demand of the PV panel, thereby ensuring precise temperature management.

Furthermore, the research will delve into the critical task of determining the optimal switching point, for diverting power from the PV panel, to supply the TEC, while further considering the energy generative abilities of the TEC. This approach not only maximizes energy utilization efficiency, however, further, minimizes the impact on the overall PV system performance.

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# APPENDIXES

## APPENDIX A: EXOGENOUS DATA (15-MINUTE AVERAGE)

### Appendix A1: Summer data

| Time | Global<br>Horizontal<br>Irradiance<br>[ $W/m^2$ ] | Direct<br>Normal<br>Irradiance<br>[ $W/m^2$ ] | Diffuse<br>Horizontal<br>Irradiance<br>[ $W/m^2$ ] | Ambient air<br>Temperature<br>[°C] |
|------|---------------------------------------------------|-----------------------------------------------|----------------------------------------------------|------------------------------------|
| 0:00 | 0                                                 | 0                                             | 0                                                  | 17.24                              |
| 0:15 | 0                                                 | 0                                             | 0                                                  | 17.4                               |
| 0:30 | 0                                                 | 0                                             | 0                                                  | 17.45                              |
| 0:45 | 0                                                 | 0                                             | 0                                                  | 17.88                              |
| 1:00 | 0                                                 | 0                                             | 0                                                  | 17.68                              |
| 1:15 | 0                                                 | 0                                             | 0                                                  | 17.29                              |
| 1:30 | 0                                                 | 0                                             | 0                                                  | 17.15                              |
| 1:45 | 0                                                 | 0                                             | 0                                                  | 17.37                              |
| 2:00 | 0                                                 | 0                                             | 0                                                  | 17.45                              |
| 2:15 | 0                                                 | 0                                             | 0                                                  | 17.33                              |
| 2:30 | 0                                                 | 0                                             | 0                                                  | 18.1                               |
| 2:45 | 0                                                 | 0                                             | 0                                                  | 17.85                              |
| 3:00 | 0                                                 | 0                                             | 0                                                  | 17.73                              |
| 3:15 | 0                                                 | 0                                             | 0                                                  | 17.66                              |
| 3:30 | 0                                                 | 0                                             | 0                                                  | 16.35                              |
| 3:45 | 0                                                 | 0                                             | 0                                                  | 16.7                               |
| 4:00 | 0                                                 | 0                                             | 0                                                  | 16.35                              |
| 4:15 | 0                                                 | 0                                             | 0                                                  | 16.54                              |
| 4:30 | 0                                                 | 0                                             | 0                                                  | 16.49                              |
| 4:45 | 0                                                 | 0                                             | 0                                                  | 16.83                              |
| 5:00 | 0                                                 | 0                                             | 0                                                  | 16.94                              |

|       |          |          |          |       |
|-------|----------|----------|----------|-------|
| 5:15  | 0        | 0        | 0        | 16.45 |
| 5:30  | 1.254274 | 1.131475 | 0        | 16.99 |
| 5:45  | 16.73888 | 8.978107 | 158.0906 | 16.6  |
| 6:00  | 63.95855 | 15.86501 | 485.9647 | 17.87 |
| 6:15  | 113.2975 | 21.83977 | 620.0624 | 18.63 |
| 6:30  | 169.7882 | 26.5001  | 719.5225 | 18.59 |
| 6:45  | 232.0494 | 30.64522 | 793.9393 | 18.49 |
| 7:00  | 293.5201 | 34.32518 | 842.057  | 19.48 |
| 7:15  | 361.3971 | 37.11646 | 890.1549 | 19.27 |
| 7:30  | 424.7253 | 38.86428 | 920.4387 | 20.6  |
| 7:45  | 490.4843 | 40.69599 | 949.3754 | 21.48 |
| 8:00  | 554.6106 | 41.4842  | 975.4568 | 21.98 |
| 8:15  | 619.1312 | 44.53522 | 994.8564 | 21.73 |
| 8:30  | 677.8233 | 46.11266 | 1009.286 | 22.46 |
| 8:45  | 732.2982 | 47.21957 | 1020.033 | 23.12 |
| 9:00  | 791.9069 | 47.86628 | 1038.765 | 24.06 |
| 9:15  | 837.9063 | 49.22398 | 1038.536 | 24.55 |
| 9:30  | 889.5566 | 50.38174 | 1049.749 | 25    |
| 9:45  | 933.4139 | 53.1707  | 1049.706 | 25.05 |
| 10:00 | 972.5704 | 49.77082 | 1059.763 | 26.8  |
| 10:15 | 1021.061 | 52.14712 | 1073.075 | 25.44 |
| 10:30 | 1055.347 | 51.4415  | 1078.353 | 26.35 |
| 10:45 | 1085.847 | 52.42292 | 1081.116 | 25.74 |
| 11:00 | 1118.334 | 54.90907 | 1086.394 | 25.82 |
| 11:15 | 1133.241 | 52.16051 | 1084.976 | 26.46 |
| 11:30 | 1159.015 | 56.50218 | 1089.203 | 25.74 |
| 11:45 | 1163.108 | 52.47465 | 1089.082 | 26.34 |
| 12:00 | 1162.442 | 50.62933 | 1087.504 | 27.15 |
| 12:15 | 1165.61  | 50.45338 | 1090.961 | 27.43 |

|       |          |          |          |       |
|-------|----------|----------|----------|-------|
| 12:30 | 1165.768 | 48.77906 | 1094.142 | 27.83 |
| 12:45 | 1168.731 | 52.00727 | 1089.602 | 27.12 |
| 13:00 | 1164.987 | 53.78705 | 1085.214 | 26.97 |
| 13:15 | 1150.885 | 49.41489 | 1084.621 | 28.17 |
| 13:30 | 1139.829 | 53.22226 | 1080.285 | 27.86 |
| 13:45 | 1120.226 | 56.24271 | 1074.743 | 26.96 |
| 14:00 | 1091.923 | 51.4114  | 1074.538 | 27.95 |
| 14:15 | 1061.073 | 51.32303 | 1070.435 | 28.34 |
| 14:30 | 1032.339 | 51.4953  | 1066.781 | 28    |
| 14:45 | 993.743  | 51.33759 | 1059.569 | 28.08 |
| 15:00 | 955.2177 | 51.45894 | 1053.805 | 27.65 |
| 15:15 | 902.7244 | 47.35105 | 1044.287 | 28.61 |
| 15:30 | 857.8724 | 48.21563 | 1037.397 | 29.25 |
| 15:45 | 803.806  | 46.49167 | 1025.49  | 29.17 |
| 16:00 | 752.2208 | 46.48195 | 1015.961 | 28.81 |
| 16:15 | 692.5352 | 46.78729 | 996.4196 | 28.91 |
| 16:30 | 639.2257 | 46.23237 | 987.017  | 28.91 |
| 16:45 | 576.295  | 45.17244 | 965.0402 | 28.78 |
| 17:00 | 511.2139 | 43.71323 | 937.0026 | 29.2  |
| 17:15 | 451.0203 | 41.6882  | 919.9286 | 28.56 |
| 17:30 | 381.7828 | 37.10257 | 882.4785 | 28.71 |
| 17:45 | 318.4495 | 37.23352 | 839.9432 | 28.48 |
| 18:00 | 254.8013 | 33.90688 | 790.2912 | 28.6  |
| 18:15 | 191.7234 | 28.85292 | 725.3438 | 28.44 |
| 18:30 | 133.7353 | 25.08132 | 636.1595 | 28.15 |
| 18:45 | 81.89775 | 19.12454 | 518.0715 | 27.65 |
| 19:00 | 35.203   | 10.41066 | 343.2429 | 27.14 |
| 19:15 | 2.652741 | 2.558122 | 0.796424 | 26.12 |
| 19:30 | 0        | 0        | 0        | 25.46 |

|       |   |   |   |       |
|-------|---|---|---|-------|
| 19:45 | 0 | 0 | 0 | 24.93 |
| 20:00 | 0 | 0 | 0 | 24.16 |
| 20:15 | 0 | 0 | 0 | 24.05 |
| 20:30 | 0 | 0 | 0 | 23.57 |
| 20:45 | 0 | 0 | 0 | 23.7  |
| 21:00 | 0 | 0 | 0 | 23.43 |
| 21:15 | 0 | 0 | 0 | 22.89 |
| 21:30 | 0 | 0 | 0 | 22.91 |
| 21:45 | 0 | 0 | 0 | 22.68 |
| 22:00 | 0 | 0 | 0 | 22.11 |
| 22:15 | 0 | 0 | 0 | 21.72 |
| 22:30 | 0 | 0 | 0 | 22.35 |
| 22:45 | 0 | 0 | 0 | 22.03 |
| 23:00 | 0 | 0 | 0 | 21.54 |
| 23:15 | 0 | 0 | 0 | 21.38 |
| 23:30 | 0 | 0 | 0 | 21.09 |
| 23:45 | 0 | 0 | 0 | 20.93 |
| 0:00  | 0 | 0 | 0 | 20.82 |

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## Appendix A2: Winter data

| Time | Global<br>Horizontal<br>Irradiance<br>[ $W/m^2$ ] | Direct<br>Normal<br>Irradiance<br>[ $W/m^2$ ] | Diffuse<br>Horizontal<br>Irradiance<br>[ $W/m^2$ ] | Ambient air<br>Temperature<br>[°C] |
|------|---------------------------------------------------|-----------------------------------------------|----------------------------------------------------|------------------------------------|
| 0:00 | 0                                                 | 0                                             | 0                                                  | 4.043                              |
| 0:15 | 0                                                 | 0                                             | 0                                                  | 3.621                              |
| 0:30 | 0                                                 | 0                                             | 0                                                  | 3.51                               |
| 0:45 | 0                                                 | 0                                             | 0                                                  | 3.225                              |
| 1:00 | 0                                                 | 0                                             | 0                                                  | 3.277                              |
| 1:15 | 0                                                 | 0                                             | 0                                                  | 2.867                              |
| 1:30 | 0                                                 | 0                                             | 0                                                  | 3.35                               |
| 1:45 | 0                                                 | 0                                             | 0                                                  | 3.321                              |
| 2:00 | 0                                                 | 0                                             | 0                                                  | 3.017                              |
| 2:15 | 0                                                 | 0                                             | 0                                                  | 2.791                              |
| 2:30 | 0                                                 | 0                                             | 0                                                  | 2.562                              |
| 2:45 | 0                                                 | 0                                             | 0                                                  | 3.036                              |
| 3:00 | 0                                                 | 0                                             | 0                                                  | 3.02                               |
| 3:15 | 0                                                 | 0                                             | 0                                                  | 2.899                              |
| 3:30 | 0                                                 | 0                                             | 0                                                  | 2.879                              |
| 3:45 | 0                                                 | 0                                             | 0                                                  | 2.605                              |
| 4:00 | 0                                                 | 0                                             | 0                                                  | 2.427                              |
| 4:15 | 0                                                 | 0                                             | 0                                                  | 2.048                              |
| 4:30 | 0                                                 | 0                                             | 0                                                  | 1.74                               |
| 4:45 | 0                                                 | 0                                             | 0                                                  | 1.21                               |
| 5:00 | 0                                                 | 0                                             | 0                                                  | 0.842                              |
| 5:15 | 0                                                 | 0                                             | 0                                                  | 0.941                              |
| 5:30 | 0                                                 | 0                                             | 0                                                  | 1.405                              |
| 5:45 | 0                                                 | 0                                             | 0                                                  | 2.05                               |

|       |          |          |          |       |
|-------|----------|----------|----------|-------|
| 6:00  | 0        | 0        | 0        | 1.927 |
| 6:15  | 0        | 0        | 0        | 2.043 |
| 6:30  | 0        | 0        | 0        | 1.39  |
| 6:45  | 0        | 0        | 0        | 1.603 |
| 7:00  | 0.321806 | 0.268932 | 0        | 1.62  |
| 7:15  | 9.594713 | 7.695428 | 38.94719 | 1.466 |
| 7:30  | 40.84966 | 19.1428  | 262.9617 | 2.104 |
| 7:45  | 84.05111 | 28.01751 | 437.361  | 2.771 |
| 8:00  | 131.6426 | 35.55624 | 551.237  | 3.508 |
| 8:15  | 180.5952 | 41.51337 | 626.6325 | 4.385 |
| 8:30  | 232.4301 | 46.3294  | 690.2367 | 4.955 |
| 8:45  | 282.3649 | 51.42259 | 730.7188 | 6.052 |
| 9:00  | 328.8493 | 55.74575 | 760.5971 | 6.217 |
| 9:15  | 376.317  | 58.00951 | 796.0008 | 7.606 |
| 9:30  | 420.8205 | 61.01582 | 818.9377 | 8.18  |
| 9:45  | 460.7096 | 64.18522 | 833.3344 | 9.2   |
| 10:00 | 498.2949 | 67.94158 | 843.8124 | 9.74  |
| 10:15 | 534.6638 | 69.64397 | 859.8494 | 10.41 |
| 10:30 | 567.0292 | 69.17764 | 876.4158 | 11.1  |
| 10:45 | 595.0137 | 71.1285  | 883.9784 | 12.08 |
| 11:00 | 621.1406 | 68.44679 | 901.2759 | 13.51 |
| 11:15 | 644.8201 | 70.41277 | 909.6738 | 13.6  |
| 11:30 | 650.0456 | 76.1208  | 889.3221 | 14.58 |
| 11:45 | 664.3621 | 82.39352 | 886.7568 | 14.82 |
| 12:00 | 678.0517 | 77.7673  | 902.6005 | 14.27 |
| 12:15 | 692.5403 | 73.43087 | 925.6341 | 14.23 |
| 12:30 | 692.9974 | 72.68312 | 930.7256 | 14.31 |
| 12:45 | 684.0642 | 70.22441 | 925.3939 | 15.21 |
| 13:00 | 679.3546 | 73.08632 | 921.8295 | 14.75 |

|       |          |          |          |       |
|-------|----------|----------|----------|-------|
| 13:15 | 664.2872 | 71.52977 | 915.5738 | 15.13 |
| 13:30 | 652.9426 | 72.75764 | 918.1337 | 15.27 |
| 13:45 | 626.1277 | 71.17872 | 901.6395 | 16.05 |
| 14:00 | 599.5709 | 68.16869 | 896.3517 | 15.55 |
| 14:15 | 575.8541 | 66.44746 | 893.3594 | 16.44 |
| 14:30 | 538.9394 | 64.95922 | 875.2158 | 16.96 |
| 14:45 | 500.6721 | 63.25608 | 855.8604 | 16.84 |
| 15:00 | 467.0454 | 64.07089 | 842.9153 | 16.66 |
| 15:15 | 416.5166 | 61.14732 | 806.0966 | 16.88 |
| 15:30 | 373.6784 | 58.56888 | 784.0546 | 16.78 |
| 15:45 | 329.831  | 55.99584 | 759.1918 | 16.17 |
| 16:00 | 276.4629 | 48.61285 | 721.3049 | 17.15 |
| 16:15 | 227.975  | 44.71922 | 679.5413 | 16.71 |
| 16:30 | 177.6893 | 40.07641 | 619.168  | 16.28 |
| 16:45 | 127.2945 | 33.23028 | 541.5024 | 16.18 |
| 17:00 | 80.05402 | 25.7999  | 429.357  | 15.79 |
| 17:15 | 36.95516 | 15.32493 | 271.606  | 15.52 |
| 17:30 | 6.929597 | 4.820571 | 55.06713 | 14.67 |
| 17:45 | 0        | 0        | 0        | 13.85 |
| 18:00 | 0        | 0        | 0        | 13.61 |
| 18:15 | 0        | 0        | 0        | 13    |
| 18:30 | 0        | 0        | 0        | 12.36 |
| 18:45 | 0        | 0        | 0        | 11.76 |
| 19:00 | 0        | 0        | 0        | 11.28 |
| 19:15 | 0        | 0        | 0        | 11.03 |
| 19:30 | 0        | 0        | 0        | 10.44 |
| 19:45 | 0        | 0        | 0        | 10.24 |
| 20:00 | 0        | 0        | 0        | 10.04 |
| 20:15 | 0        | 0        | 0        | 9.86  |

|       |   |   |   |       |
|-------|---|---|---|-------|
| 20:30 | 0 | 0 | 0 | 9.51  |
| 20:45 | 0 | 0 | 0 | 9.12  |
| 21:00 | 0 | 0 | 0 | 9.12  |
| 21:15 | 0 | 0 | 0 | 8.29  |
| 21:30 | 0 | 0 | 0 | 9.53  |
| 21:45 | 0 | 0 | 0 | 9.45  |
| 22:00 | 0 | 0 | 0 | 9.18  |
| 22:15 | 0 | 0 | 0 | 8.71  |
| 22:30 | 0 | 0 | 0 | 8.31  |
| 22:45 | 0 | 0 | 0 | 8.31  |
| 23:00 | 0 | 0 | 0 | 7.079 |
| 23:15 | 0 | 0 | 0 | 7.769 |
| 23:30 | 0 | 0 | 0 | 7.541 |
| 23:45 | 0 | 0 | 0 | 7.981 |
| 0:00  | 0 | 0 | 0 | 6.611 |

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## APPENDIX B: ANNUAL ENERGY SAVING AND CUMULATIVE COSTS (LCC)

| Year | Energy saving<br>Baseline<br>PV<br>(ZAR) | Energy saving<br>PV-<br>TEC<br>(ZAR) | Energy cost<br>Baseline<br>PV<br>(ZAR) | Energy cost PV-<br>TEC<br>(ZAR) | Life cycle<br>costs<br>Baseline<br>(ZAR) | Life cycle<br>costs<br>PV-TEC<br>(ZAR) |
|------|------------------------------------------|--------------------------------------|----------------------------------------|---------------------------------|------------------------------------------|----------------------------------------|
| 0    | -                                        | -                                    | 0                                      | 0                               | -                                        | 326.77                                 |
| 1    | 423.29                                   | 466.52                               | 423.29                                 | 466.520                         | 466.52                                   | 753.33                                 |
| 2    | 465.62                                   | 513.17                               | 888.91                                 | 979.692                         | 979.69                                   | 1,222.41                               |
| 3    | 512.18                                   | 564.49                               | 1,401.09                               | 1544.181                        | 1,544.18                                 | 1,738.26                               |
| 4    | 563.40                                   | 620.94                               | 1,964.49                               | 2165.119                        | 2,165.12                                 | 2,305.55                               |
| 5    | 619.74                                   | 683.03                               | 2,584.23                               | 2848.151                        | 2,848.15                                 | 2,929.42                               |
| 6    | 681.71                                   | 751.34                               | 3,265.94                               | 3599.486                        | 3,599.49                                 | 3,615.50                               |
| 7    | 749.88                                   | 826.47                               | 4,015.82                               | 4425.955                        | 4,425.96                                 | 4,370.02                               |
| 8    | 824.87                                   | 909.12                               | 4,840.70                               | 5335.071                        | 5,335.07                                 | 5,199.81                               |
| 9    | 907.36                                   | 1,000.03                             | 5,748.06                               | 6335.098                        | 6,335.10                                 | 6,112.38                               |
| 10   | 998.10                                   | 1,100.03                             | 6,746.15                               | 7435.127                        | 7,435.13                                 | 7,115.99                               |
| 11   | 1,097.91                                 | 1,265.03                             | 7,844.06                               | 8700.162                        | 8,700.16                                 | 8,219.75                               |
| 12   | 1,207.70                                 | 1,391.54                             | 9,051.75                               | 10091.699                       | 10,091.70                                | 9,433.65                               |
| 13   | 1,328.47                                 | 1,530.69                             | 10,380.22                              | 11622.391                       | 11,622.39                                | 10,768.69                              |
| 14   | 1,461.31                                 | 1,683.76                             | 11,841.53                              | 13306.151                       | 13,306.15                                | 12,236.97                              |
| 15   | 1,607.44                                 | 1,852.14                             | 13,448.97                              | 15158.288                       | 15,158.29                                | 13,851.80                              |
| 16   | 1,768.19                                 | 2,037.35                             | 15,217.16                              | 17195.638                       | 17,195.64                                | 15,627.82                              |

|     |          |          |           |           |           |           |
|-----|----------|----------|-----------|-----------|-----------|-----------|
| 17  | 1,945.01 | 2,241.09 | 17,162.17 | 19436.723 | 19,436.72 | 17,581.13 |
| 18  | 2,139.51 | 2,465.19 | 19,301.67 | 21901.917 | 21,901.92 | 19,729.43 |
| 19  | 2,353.46 | 2,711.71 | 21,655.13 | 24613.630 | 24,613.63 | 22,092.22 |
| 20  | 2,588.80 | 2,982.88 | 24,243.93 | 27596.515 | 27,596.51 | 24,690.91 |
| LCC | -        | -        | -         | -         | -         | 2905.61   |