Evaluating of DC-DC Buck-Boost Converter implementation for Integrated Solar Photovoltaic and Thermoelectric Cooler System

Priyo Adi Sesotyo
Department of Electrical Engineering, Semarang University, Semarang, Indonesia

La Ode Muhamad Idris
Department of Electrical Engineering, Semarang University, Semarang, Indonesia

Taufik Dwi Cahyono
Department of Electrical Engineering, Semarang University, Semarang, Indonesia

Ery Sadewa
Department of Electrical Engineering, Semarang University, Semarang, Indonesia

Abstract: The growing demand for compact, efficient, and eco friendly cooling solutions has driven research into integrating thermoelectric coolers (TECs) with solar photovoltaic (PV) systems, where solar irradiance variability impacts cooling efficacy and energy efficiency. This challenge is addressed using DC-DC Buck-Boost converters whose performance is heavily influenced by control strategies such as Proportional Integral Derivative (PID) controllers employing tuning approaches that balance performance and prioritize disturbance rejection. This study investigates the implementation and performance of a DC-DC buck-boost converter in a solar photovoltaic and thermoelectric cooling (PV-TEC) system. Simulation-based analysis compared tuning methods for their ability to maintain thermal stability, reduce electrical input fluctuations, and enhance the TEC's Coefficient of Performance (COP). Results show that the PID controller significantly improves responsiveness and energy efficiency in dynamic solar conditions, achieving a 23% reduction in power consumption and a 36% increase in COP, highlighting the importance of adaptive control strategies.

Keywords: Coefficient of Performance, DC-DC Buck-Boost Converter, Proportional-Integral Derivative controller, Solar Photovoltaic, Thermoelectric Cooler

Correspondents Author:

Priyo Adi Sesotyo, Department of Electrical Engineering, Universitas Semarang, Indonesia
Email: psesotyo@usm.ac.id

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Introduction

The escalating global energy demands coupled with growing concerns about climate change necessitate the development of efficient and sustainable energy systems. Indonesia has established ambitious renewable energy targets, aiming for a 23% renewable energy share in its energy mix by 2025, rising to 31% by 2050 (PT PLN (Persero), 2021). Nevertheless, renewable energy sources comprised merely 13.9% of the total energy production as of December 2024, signifying a substantial deficit in achieving the 2025 target. Given its abundance and environmentally sound nature, solar energy is a prominent renewable energy resource. The consistent and intense solar radiation received by Indonesia is a direct consequence of its location on the equator. The country's average falls within the range of 4.8–5.0. The consistent performance of solar energy reduces seasonal variability in power production, thus ensuring its reliability as a renewable source. Solar PV systems are the standard method for direct conversion of sunlight to electricity in residential and industrial contexts. The efficiency of PV systems is significantly impacted by high temperatures, which substantially reduce their performance (Adeeb et al., 2019). Given the primary function of PV modules is electricity generation, the sun's thermal energy is exchanged through convection and radiation (Sesotyo et al., 2022).

Research Gap and Motivation

Integrating Thermoelectric Coolers (TECs) into PV systems addresses the limitation by managing heat and improving energy conversion efficiency. PV panels and TECs in combination make a hybrid system (Morais et al., 2020). This system uses a TEC to actively remove excess heat from the PV module and maintain optimal operating temperature, offering potential performance benefits through precise parameter optimization, though its effectiveness is limited by the TEC's relatively low coefficient of performance compared to conventional cooling methods (Yu & Wang, 2009), prompting researchers to seek ways to enhance efficiency. To maximize overall system efficiency, the hybrid PV-TEC system employs Proportional Integral (PI) controllers for the temperature control of the PV module via a TEC cooling mechanism (Kane et al., 2017).

Enhanced TEC performance in terms of heat absorption and cooling capacity can be achieved by increasing input voltage, which raises current flow, amplifies the temperature difference between the cold and hot sides, and improves cooling effectiveness, though optimal operation requires careful consideration of system limitations (Prasetyo et al., 2022). While higher voltage can enhance cooling, each TEC module has an optimal voltage range beyond which efficiency declines due to factors such as increased internal resistance and Joule heating, where electrical energy is converted into heat rather than cooling (Kiran & Prakash, 2023). In a TEC, since internal resistance remains constant, increasing the voltage directly raises current flow and, consequently, power consumption necessitating enhanced cooling capabilities due to the greater thermal load (Muchlis et al., 2023). DC–DC converters are the main pillars of renewable energy equipment and are used to adjust their voltage and deliver to the DC-AC inverter, where the continuous output current leads to a reduction in input current and output voltage ripples (Hosseinpour et al., 2024). DC-DC converters utilize a PID controller to achieve regulated voltage from the solar PV's supply voltage (Kunigar et al., 2023). Stable output voltage and current are achieved by integrating the battery to create Dual Input Single Output (DISO) for the DC-DC Buck-Boost Converter (Reddy et al., 2022).

The output which is proportional to the input voltage divided by 1-Duty Cycle, while the DC-DC buck converter to degrade the output voltage, which is proportional to the input voltage multiplied by 1-Duty Cycle (Rashid, 2014). Altering the duty cycle changes the reference voltage; a duty cycle below 0.5 lowers the output voltage, while one above 0.5 raises it (Corapsiz & Kahveci, 2019). Compared to a standard PID controller, the FOPID controller combined with DISO resulted in approximately twice as fast rise time and ten times faster settling time, producing a similar voltage output (Aseem & Selva Kumar, 2020). Although higher voltage can enhance heat transfer in a thermoelectric cooler (TEC), its overall efficiency measured by the Coefficient of Performance (COP), the ratio of thermal energy transferred to electrical input may decline at high voltages, as increased power consumption does not always yield proportional gains in COP (Prasetyo et al., 2024). Parallel and cascade converters were enhanced by combination to resolve voltage imbalances among loads of different values (Mesbah et al., 2024). Parallel and cascade buck-boost converters function similarly; however, the parallel converter displays on-off control and experiences harmonic oscillation (Tolga Altınöz, 2025). Voltage optimization was the primary focus of earlier research on DC-DC buck-boost converters using PID controllers and a solar PV energy source. This paper presents a novel approach to cooling Solar PV systems by integrating TECs, increasing the COP.

The main contribution of the study below includes : (1) Identifying key design and operational parameters influencing system efficiency, such as thermoelectric configuration, heat sink effectiveness, and environmental factors, (2) Developing a simulation-based model is needed to assess the impact of these parameters on energy output and temperature control, (3) Recommend optimization strategies designed to improve the performance and reliability of the integrated system in various environmental contexts. Researchers will conduct a comprehensive analysis to identify and evaluate key parameters affecting system efficiency.

The structure of this paper is as follows: Section 2 details the operational principles and mathematical model of TEC. Section 3 details the integrated TEC and Buck-Boost Converter design methodology and simulation. Section 4 presents the findings, while Section 5 details the study's principal conclusions.

Research Method

A solar PV module's performance is defined by several important parameters, as found in Table 1, including peak power (P_{max}), open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), and maximum power point (MPP). The peak power represents the highest electrical power the module can produce under standard test conditions, indicating its maximum energy output. The open-circuit voltage is the voltage measured across the module's terminals when no current is flowing, essentially the maximum voltage the module can generate. The short-circuit current is the current that flows when the module's terminals are directly connected, representing the maximum current output under ideal conditions. The maximum power point is the combination of voltage and current at which the module produces its greatest power output; this point is critical for optimizing energy harvesting through maximum power point tracking (MPPT) systems.

Table 1 Solar PV Parameters

Parameters (STC = Standard Test Conditions)	**Unit**	**Value**
Pmax (Peak Power)	Wp	100
V_{oc} (Voltage Open Circuit)	V	115.8
I_{sc} (Current Short Circuit)	A	1.27
V_{mpp} (Voltage Maximum Power)	V	94.4
I_{mpp} (Current Maximum Power)	A	1.06
Number of Series	Pcs	1
Number of Parallel	Pcs	1

Voltage supplied to the TEC, is from the output of the Solar PV, which fluctuated, depends on the daily irradiance. Variations in solar irradiance lead to fluctuations in the electrical output of the PV panel, which directly impacts the power available to drive the TEC. Reduced or unstable power supply can degrade the TEC's cooling performance or cause it to operate intermittently. As irradiance increases, the PV panel absorbs more heat, raising its temperature. Without sufficient TEC operation due to power limitations, the system struggles to dissipate this heat effectively, leading to thermal inefficiencies and potential performance degradation of the PV module.

Enhancing photovoltaic (PV) cell output necessitates addressing the cooling impact of heat dissipation. Heat transfer via conduction involves the passage of heat through a solid medium. Elevated temperatures inversely correlate with the power generated by PV cells. Heat conduction, governed by the heat equation, proceeds from regions of higher to lower temperature as described below:

$$q_x = -kA\frac{dT}{dx} \quad (4)$$

Where: q_x represents heat flux (watts) and k represents thermal conductivity (W/m/^{o}C). Applying the Fourier equation, the heat flow (Q) is given by the formulation

$$Q_{out} = k * A * \frac{(T_H - T_C)}{L} \quad (5)$$

Where: A denotes area (m^2), T_H and T_C represent the hot and cold temperatures (^{o}C), respectively, and L represents length (m), where the bottom PV temperature (T_H) and ambient temperature (T_C) within a day, can be found in the Table 2 below:

Table 2 Irradiance & Temperature in the PV Panel (Sesotyo et al., 2022)

Time	Irr (W/m^2)	T_H (^{o}C)	T_C (^{o}C)
08.00	525.7	47.5	34.8
09.00	777	47.6	34.7
10.00	944.5	43.9	34
11.00	830.5	47.9	35.7
12.00	765.8	47.5	38.3
13.00	609.8	44.4	37.5
14.00	439.5	38.9	36.8
15.00	276.5	35	34.8
16.00	288	35.2	33.8

The TEC's proposed power supply, derived from a solar PV system, exhibits inherent fluctuations in DC voltage and current output, which required to be stabilized with DC-DC converter. The TEC is affixed to the PV module's rear surface via a thermal transfer compound, its cold side contacting the PV. Heat dissipation from the TEC's hot side to the ambient air is achieved using a heat sink with a thermal transfer compound, as shown in Fig. 1.

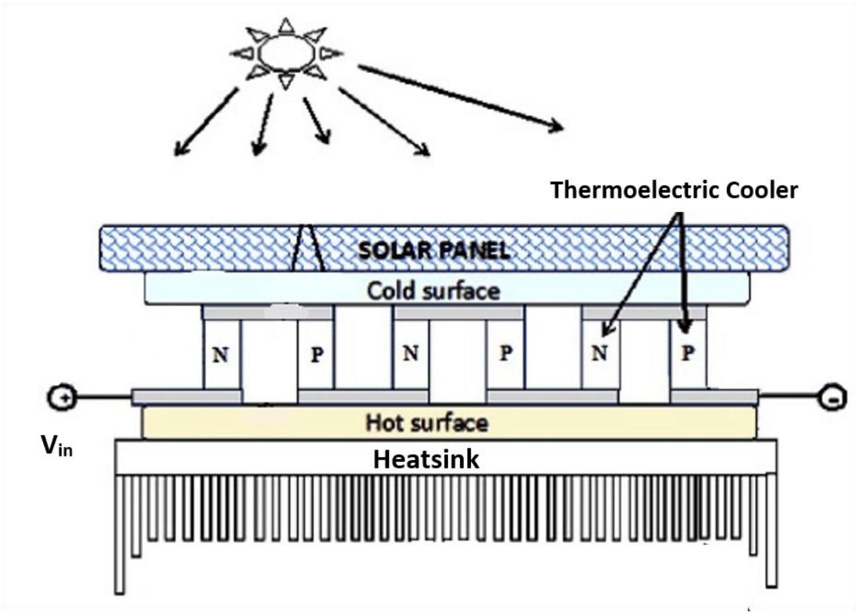

Figure 1 Solar PV Cooling using a TEC (Mooko & Kusakana, 2018)

The heat balance from both sides are written for steady state which include Peltier Heat, Conduction Losses and Joule Losses (Tsai & Lin, 2010). The temperature of PV panels is calculated by :

$$T_p = \frac{Q_{in}-Q_{out}}{m*c_{pp}} \tag{6}$$

Where T_p is the mean temperature of the PV panel, Q_{in} is the heat input to the PV panel, Q_{out} is the heat output of the panel, m the mass of the panel, and c_{pp} is the average specific heat of the panel. The panel receives its thermal energy input from incident solar radiation. A fraction of the incident radiation is photoelectrically converted; however, the resultant energy increase is predominantly manifested as sensible heat, causing a temperature elevation within the panel, which can be expressed as:

$$Q_{in} = GA * (1-\in) \tag{2}$$

Here, G denotes the incident solar irradiance on the panel surface, A represents the panel surface area, and ∈ signifies the panel's electrical conversion efficiency. The equation Q = m*c*ΔT quantifies heat removal. This equation is fundamentally based on thermodynamic and heat transfer principles.

The heat removal factor (FR) represents the ratio of actual useful energy gain to the maximum potential gain, assuming uniform collector surface temperature at the fluid inlet. Accurate quantification of heat removal efficiency critically depends on this parameter. The rate of heat removal exhibits a mathematical correlation with the fluid properties and collector area, as well as the FR, considering conduction, convection, and radiation as primary heat removal mechanisms (Abdel-Khalik, 1976).

$$FR = \dot{m} * c_p * A_c * U * \left[1 - e^{\frac{-A_C * U * F'}{\dot{m} * c_p}}\right] \quad (3)$$

Where $\dot{m}$ is the mass flow rate of the cooling fluid, c_p is the specific heat capacity of the cooling fluid (J/kg.K), A_c is the area of the plate (m^2), U is the heat transfer coefficient (W/(m^2.K), F' is the plate efficiency factor, and e is the base of the natural logarithm.

The Peltier module's efficiency is quantified by the COP, which is calculated as follows:

$$COP = \frac{Q_E}{P_{in}} \quad (6)$$

The TEC's hot side temperature (T_H) must be maintained to ensure a constant heat flux (Q_R) in W for cooling effect generation (Bayendang et al., 2021). The heat removal Q_R by TEC can be calculated by :

$$Q_R = (SM * T_H * I) - (0.5 * I^2 * RM) - (KM * \Delta T) \quad (7)$$

Where SM is the Peltier coefficient (V), T_C is the cold side temperature (°C), I is the electric current (A), RM is the internal resistance of the Peltier module (Ω), KM is the internal thermal conductivity of the Peltier module (S/m) and ΔT is the delta temperature of hot and cold sides (°C).

Since the Peltier module require the input powered (P_{in}), then

$$P_{in} = V_{in} * I \quad (8)$$

$$V_{in} = (SM * \Delta T) + (I * RM) \quad (9)$$

Where V_{in} is the input voltage to the Peltier module (V).

While the heat rejected (emitted) Q_E by the module, calculated by

$$Q_E = P_{in} + Q_R \quad (10)$$

The equivalent circuit diagram of the TEC module, powered by a DC voltage source, is presented in Fig. 2., where T_H>T_C. In this case, the measured current and voltage signs are '-' and '+' respectively as shown in the figure.

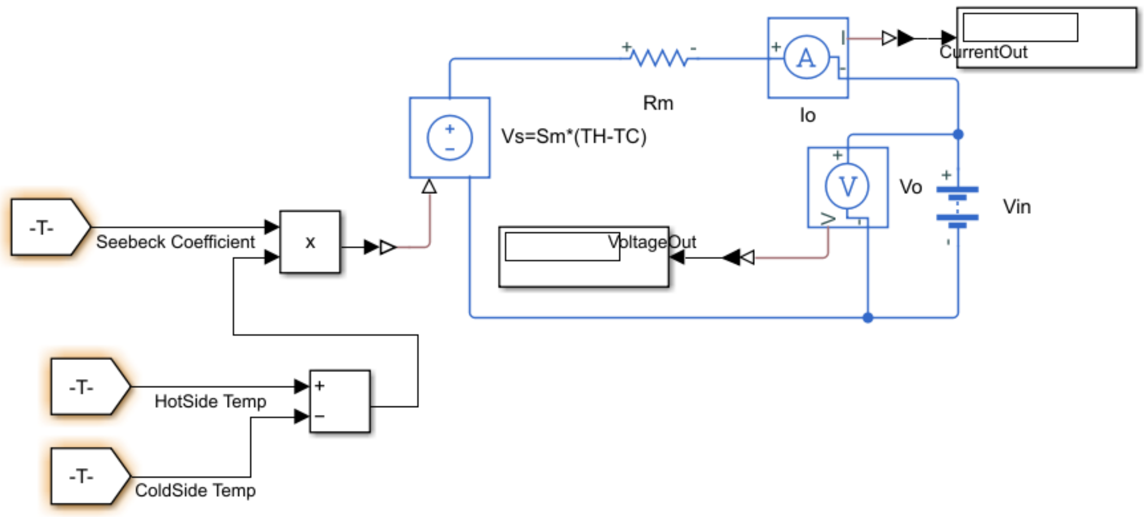

Figure 2 Equivalent circuit of the TEC module for -I and +V (Yilmaz et al., 2022)

The heat and power equations are calculated as follows:

The heat of the removal side is,

$$Q_R = -Q_H = -[(SM * T_H * I) + (KM * (T_C - T_H)) + (0.5 * I^2 * RM)] \qquad (11)$$

The heat of the emitting side is,

$$Q_E = -Q_C = -[(SM * T_C * I) + \left(KM * (T_C - T_H)\right) - (0.5 * I^2 * RM)] \qquad (12)$$

And the power consumed by the TEC is,

$$P = Q_R - Q_E = Q_C - Q_H = -[SM * I * (T_H - T_C) + I^2 * RM] \qquad (13)$$

A TEC module's performance is primarily characterized by three key parameters: the Seebeck coefficient, electrical resistance, and thermal conductance. The Seebeck coefficient represents the voltage generated per unit temperature difference across the module's thermoelectric materials and indicates the efficiency of converting thermal gradients into electrical energy; higher values mean better conversion efficiency. The electrical resistance reflects how much the module resists electric current flow; it influences power loss within the device through Joule heating (I^2R losses), so lower resistance is preferable for better performance. Lastly, the thermal conductance describes how readily heat passes through the TEC module by conduction between its hot and cold sides. A lower thermal conductance helps maintain a greater temperature difference by minimizing unwanted heat transfer, thereby enhancing cooling efficiency. Together, these parameters, as found in Table 2, determine the overall cooling capacity, efficiency, and electrical requirements of a TEC module in practical applications.

Table 2 TEC Parameters

Parameters	Unit	Value
Seebeck Coefficient (SM)	V/K	$220*10^{-6}$
Electrical Resistance (RM)	Ohm	0.005
Thermal Conductance (TM)	W/K	$1.5*10^{-3}$

The integration of Solar PV and TEC can be found in Fig. 3, where all the parameters from the TEC and the Solar PV are calculated and simulated.

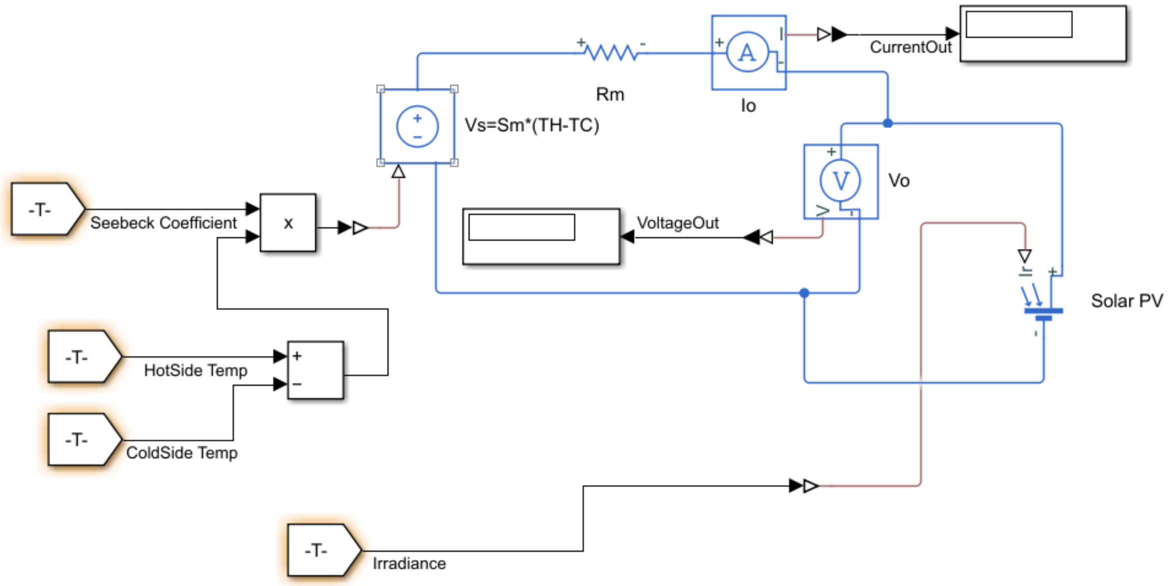

Figure 3 Equivalent circuit of the integrated PV & TEC module for -I and +V

A DC-DC converter comprises two components: the circuitry and the regulatory/control mechanism (Dokić & Blanuša, 2015). The constituent elements of DC–DC converters, as depicted in Fig. 1, are an inductor, a capacitor, a diode, and a switch. The deployment of DC-DC converters is prevalent in switch-mode power supplies, electric vehicles, electric motor drives, electric braking systems, and solar and wind-based microgrids (Momoh, 2018). The power converter topology's fundamental architecture necessitates a minimal number of electrical components. The operational versatility and structural elegance of this power converter are the primary considerations justifying its selection for this research.

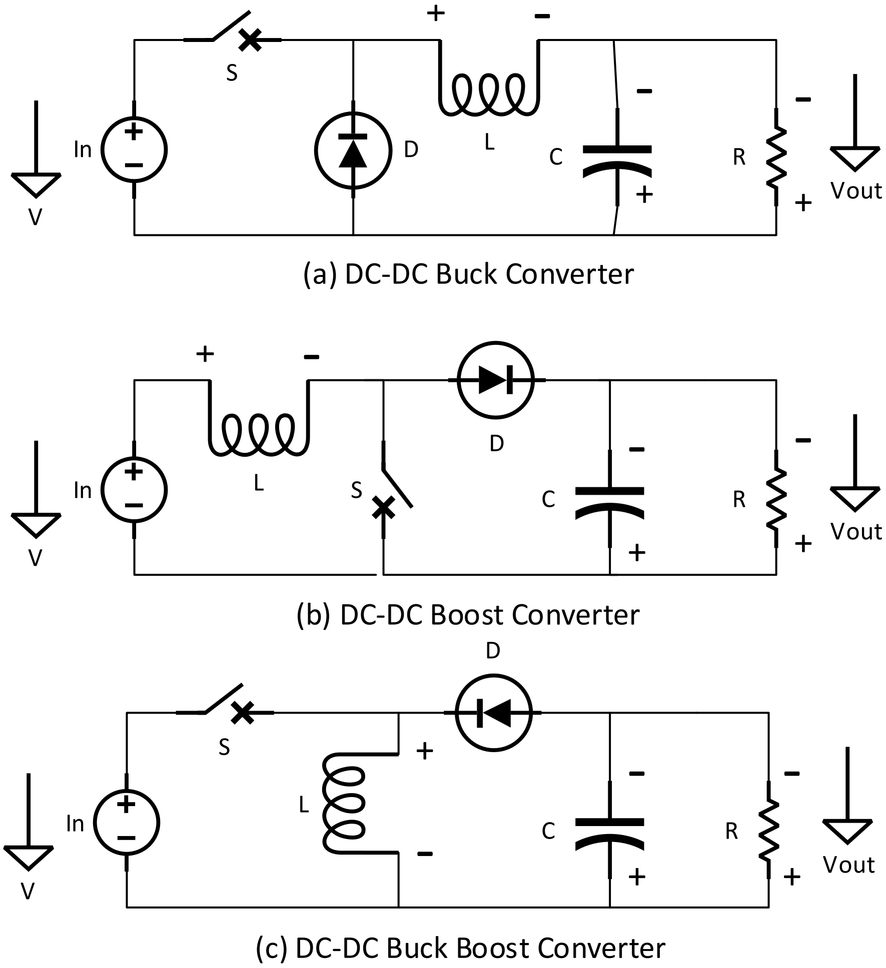

Figure 4 DC-DC Converter with three different configurations (Bhattacharjee & Saharia, 2014)

An idealised DC-DC buck–boost power converter's topology is presented in Fig. 4c. The depicted device makes up a second-order system with a single input and a single output (SISO). In Fig. 4, L denotes the inductance of the power inductor incorporated in the converter. In this circuit, C symbolises the capacitance of the integrated capacitor. This circuit configuration necessitates the use of diode D. Switch S serves as the control mechanism for the device's operational status. The output voltage (Vo) produced by this converter exhibits reverse polarity with respect to the input voltage (V_{in}).

The circuit employs a single switch with a 0.5 duty cycle, yielding a negative output voltage when the input voltage is negative; this behaviour aligns with the constraint $0 < D < 1$. This component serves to stabilize the output voltage, compensating for variations in the input voltage by acting as a voltage step-up or step-down converter. Variations in load and line voltage affect the average load current. Fluctuations in solar irradiance considerably affect the output voltage generated by PV systems. Buck-boost converters offer the capability of regulating system output to the desired level.

$$V_o = V_s * \frac{D}{(1-D)} \tag{14}$$

$$D = \frac{V_o}{V_o - V_s} \tag{15}$$

$$L = \frac{V_s * D}{F * \Delta L} \tag{16}$$

Where L is the inductor, Vs is the input voltage, D is the Duty Cycle, F is the switch frequency and ΔL is the inductor current ripple value.

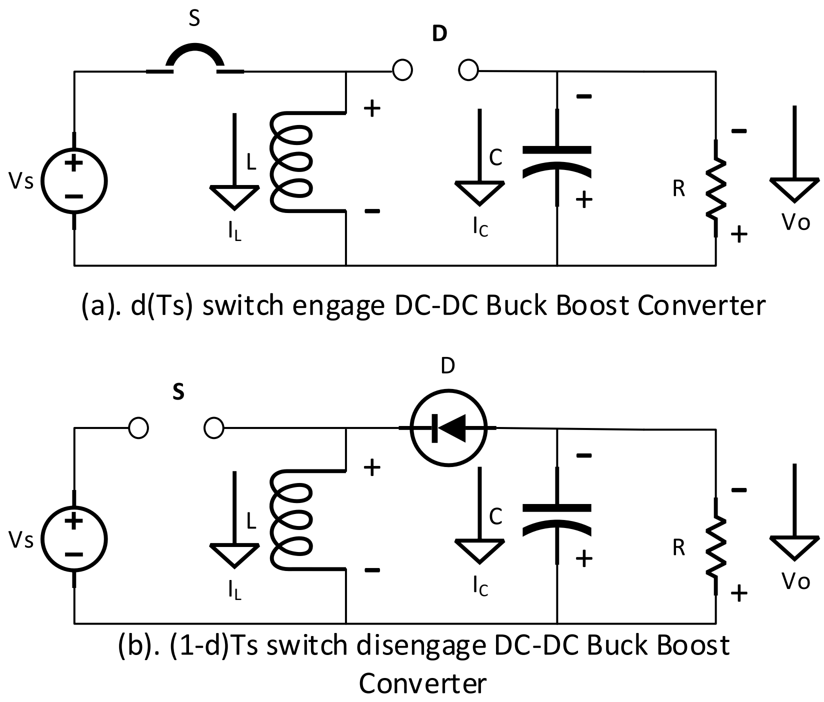

Figure 5 DC-DC Buck-Boost Converter in operational states (Molina-Santana et al., 2023)

The various states of operation for the power converter are shown schematically in Fig. 5. These are employed to construct a model representing the ideal power converter. The circuit represented by Fig. 5 (a) is valid during the converter's on-state, whereas Fig. 5 (b) governs the off-state. Each switching time (Ts) necessitates two operational modes. The primary switch remains engaged for a duration of (dTs) during the initial operational phase, subsequently transitioning to the disengaged state for a period of (1-d) Ts.

The proposed model, as found in Fig. 8, expected to have the D changes according to the output voltage, therefore validation from (Corapsiz & Kahveci, 2019) also confirm that if D < 0.5, the output voltage is lower than the input voltage; conversely, if D > 0.5, the output voltage is higher. The model illustrated in Fig. 8 is further supported by the research of (Soheli et al., 2018), demonstrating an increase in voltage gain with the value of D.

The buck-boost converter maintains output voltage stability despite input voltage fluctuations. Buck-boost DC-DC power converters possess the capability to convert various input voltage polarities and magnitudes to a consistent output voltage. Their significant value in various power electronics fields is well-established, particularly within renewable energy systems. The control method represents an area in need of enhancement. A PID (Proportional, Integral, Derivative) control algorithm is implemented in the proposed research.

PID controllers are systems that combine proportional, integral, and derivative control mechanisms. The classic PID parameters typically remain constant during operation, which means the controller may become ineffective in managing the system in the presence of unforeseen disturbances or environmental changes.

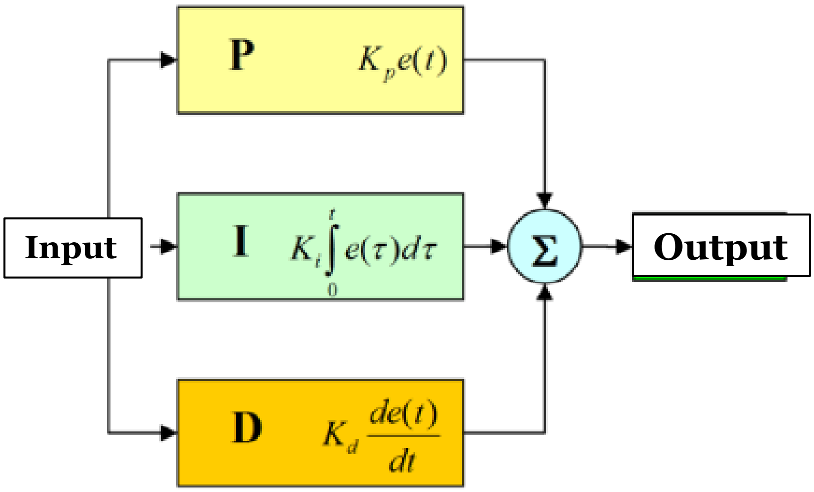

Figure 6 PID Controller with Kp, Ki and Kd parameter setting (UNC Charlotte, 2022)

One method to establish PID parameters is the open loop Ziegler-Nichols approach as seen in Fig. 6. The Kp is the proportional gain, whose controls how much the controller output responds proportionally to the current error (the difference between the desired setpoint and the actual process variable). The Ki is the integral gain, whose controls the reaction based on the accumulation (integral) of past errors over time. And the Kd is the derivative gain, whose controls the reaction based on the rate of change (derivative) of the error.

Research on buck-boost DC-DC converter control utilizes pulse width modulation. Numerous controllers have been utilized in conjunction with pulse-width modulation (PWM) techniques; among these, proportional-integral-derivative (PID) controllers have proven particularly effective (Qadir & Ati, 2024). A dynamic compensator, constituted by PID control elements, is a characteristic feature of nearly all PWM DC-DC controllers, as found in Fig. 7. The system's nonlinearity necessitates a departure from the conventionally accepted linear-invariant PID control structure. In a buck-boost control system employing pulse-width modulation (PWM) with a time-varying duty cycle, fluctuations in output inductance and capacitance are observed. Consequently, the buck and boost inductors contribute to a non-standard proportional-integral component.

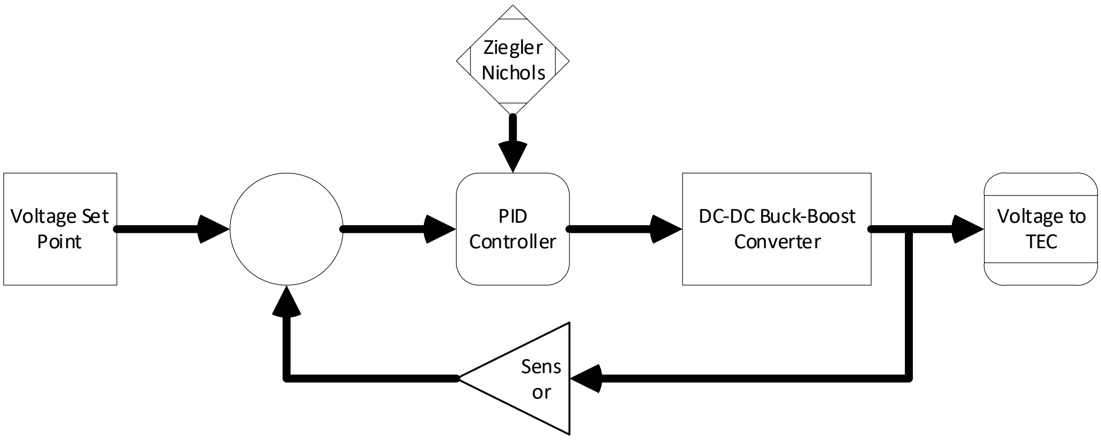

Figure 7 PID Controller implemented on DC-DC Buck-Boost Converter (Pratama Putra et al., 2023)

PID controllers constitute a common element within the architecture of industrial control systems. The system boasts benefits such as reduced maintenance requirements and improved stability. Proportional, integral, and derivative control mechanisms are integrated to achieve optimal performance. Their straightforward implementation and simplicity allow for application across diverse fields. Proportional-Integral-Derivative (PID) controllers are implemented across various industrial applications, including electrical, thermal, and mechanical engineering. The accurate setting of PID parameters is critical to ensure both optimal performance and stability. Optimization of equalizer settings is critical for consistent plant system functionality. Control system output behavior may be improved through the application of diverse tuning methods, such as manual and automated tuning (Pathiran, 2019).

Simulation significantly benefits prototype development, offering cost-effective and efficient design, development, and testing. The simulation platform furnishes an ideal setting for evaluating the designed PID controller's performance. Implementing closed-loop control in PV-powered TEC systems introduces a feedback mechanism to regulate the TEC's cooling output, thereby enhancing stability, efficiency, and adaptability under fluctuating solar irradiance. A closed-loop control system continuously monitors system parameters, including temperature, current, and voltage, and dynamically adjusts the TEC module's power supply to meet cooling demands.

Result and Discussion

Unlike prior studies, this research uses variable irradiance for more realistic simulations. Real-world PV system behaviour is modeled via simulated solar irradiance changes. Solar PV output voltage and current, and thus system performance, are impacted by these variations. Accurate PV system assessment and optimization are enabled within these scenarios below.

Scenario 1: PV-TEC with DC-DC Buck-Boost without PID controller.

The integration of MPPT controllers within closed-loop control systems is common practice to guarantee that PV modules operate at their maximum power point, thereby maximizing power generation under the present irradiance conditions. Adequate power supply to the Peltier module is essential, especially under conditions of low light or fluctuating irradiance. Optimize the PV modules' operating point to maximize energy harvesting, subsequently directing this energy to the Peltier system via optimized PV output.

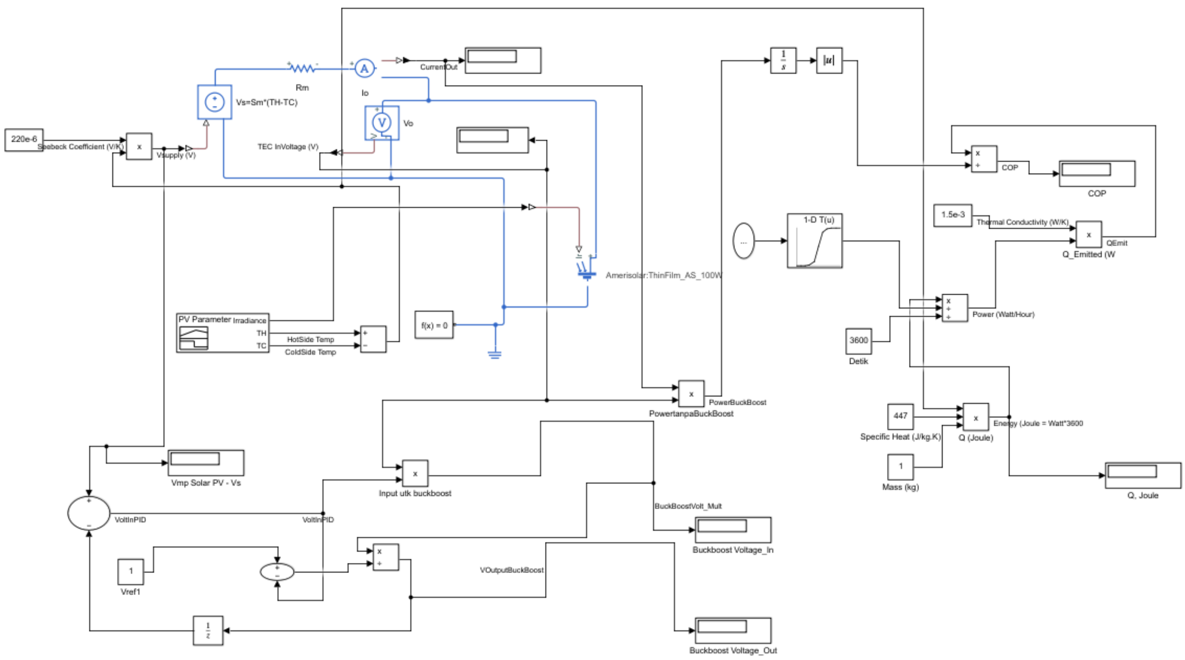

Figure 8 Simulink model of the integrated PV-TEC system and DC-DC Buck-Boost converter without PID controller

The integration of PV-TEC model, as found in Fig. 8, involves simultaneous thermal and electrical interactions between the two components. The PV module's electrical output depends on both the incident solar irradiance and its temperature, while the TEC's cooling performance depends on electrical input and the temperature difference it maintains between its hot and cold sides. Modeling this integrated system requires accounting for the heat generated by the PV module, the electrical power drawn by the TEC for cooling, and the resulting changes in the PV module's temperature and efficiency. Optimizing this interaction allows for improved total system efficiency, making integrated PV-TEC systems promising for applications where maximizing solar energy harvesting and thermal management are critical.

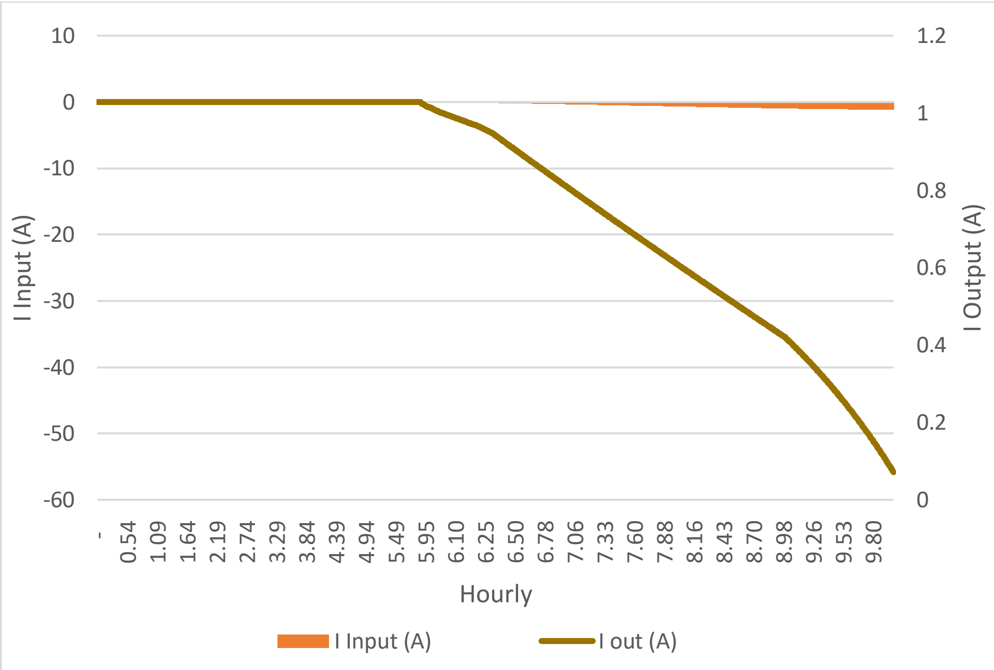

Figure 9 I input and I output of integrated PV-TEC system and DC-DC Buck-Boost converter without PID controller

As seen in the Fig. 9, the current indication of input, shows negatively small, in the end of simulation duration, shows -1.2 A, but for the current indication of output, shows negatively great, which is approximately -55.8 A. The negatively indication for the input, is because there is a reverse connection of the TEC supplied by the Solar PV power. But for the output, the negatively indication, it is not the actual current flow indication, but the heat transfer flow. The principal function of a TEC, when employed for cooling, is heat transfer from the cold side to the hot side. The Peltier effect accounts for this heat transfer. The passage of current across a junction formed from disparate semiconductor materials (P-type and N-type) results in the absorption of heat at one junction and its release at the other. There is a direct proportional relationship between the input current and the heat pumped (Q_R). The output is not an electrical current; rather, it is a thermal differential and heat dissipation. Heat dissipation, alongside electrical power consumption, is typically achieved via a heatsink on the component's hot side. Current output strongly indicates improper implementation of TEC for cooling, with a likely reversal of heat flow.

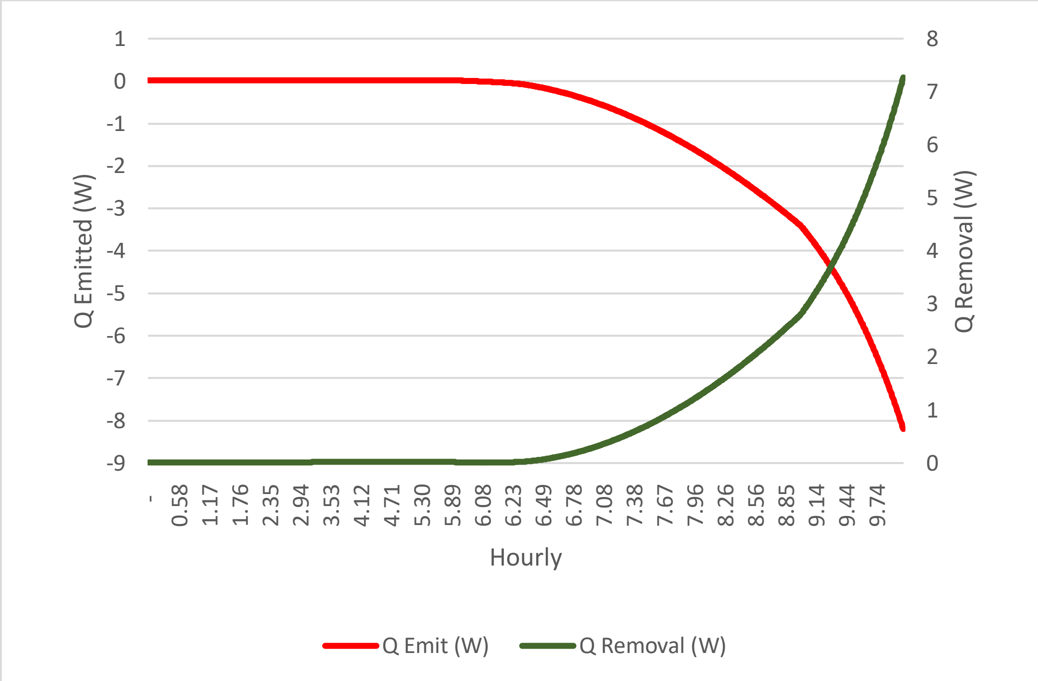

Figure 10 Q emitted (Q_E) vs Q removal (Q_R) of integrated PV-TEC system and DC-DC Buck-Boost converter without PID controller

The TEC module actively pumps heat away from the PV panel's surface, thereby lowering its temperature. The heat absorbed by the TEC at the cold side (from the PV module) and the heat rejected at the hot side (to the ambient environment) are key thermal parameters. The heat absorbed, Q_R, represents the cooling load and is the amount of heat the TEC removes from the PV panel, while the heat emitted, Q_E, includes both the absorbed heat plus the electrical power input to the TEC, which is dissipated at the hot side. As illustrated in Fig. 10, the Q_R value represents heat extraction from the hot side, while the Q_E value, displaying a negative sign, signifies heat emission to the heat sink, indicating improper heat flow within the TEC. The data presented in Figure 10 is concurrently has the same indication from the Fig. 9, the problem stems from the inadequate heat flow within the TEC and its improper execution.

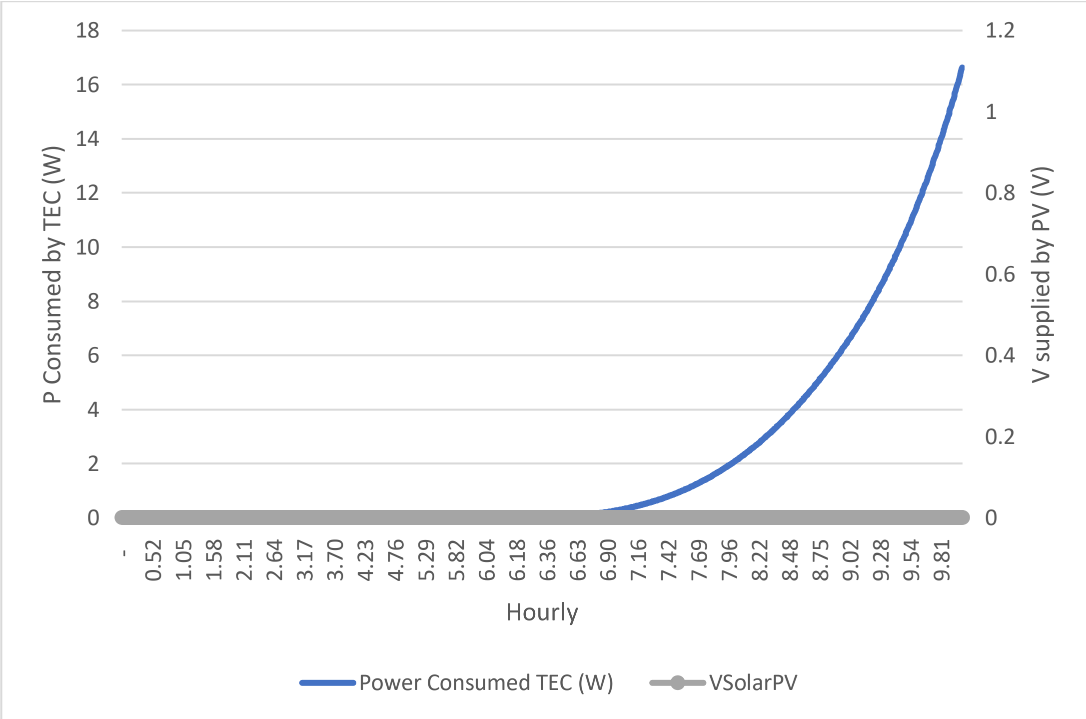

Figure 11 Power Consumption by TEC (W) vs Voltage Supplied by Solar PV of integrated PV-TEC system and DC-DC Buck-Boost converter without PID controller

TEC power consumption's relationship with applied voltage is characterized by both electrical and thermal power considerations, contingent upon the TEC's current draw and voltage differential. The electrical power (P) consumed by the TEC facilitates its primary function: heat transfer from the cold side to the hot side. Heat transfer capacity is a function of both the electric current and the temperature gradient across the hot and cold surfaces; this gradient varies according to the electrical input and prevailing operating conditions. The efficacy of a TEC is determined by its ability to conduct heat away from the cold side and reject it from the hot side. The elevated temperature on the hot side, a consequence of poor heat dissipation, negatively impacts overall efficiency. Inefficient heat dissipation on the TEC's hot side compromises cold-side cooling efficacy and increases power consumption to maintain a constant temperature differential, as found in Fig. 11, while the voltage supplied is relatively the same.

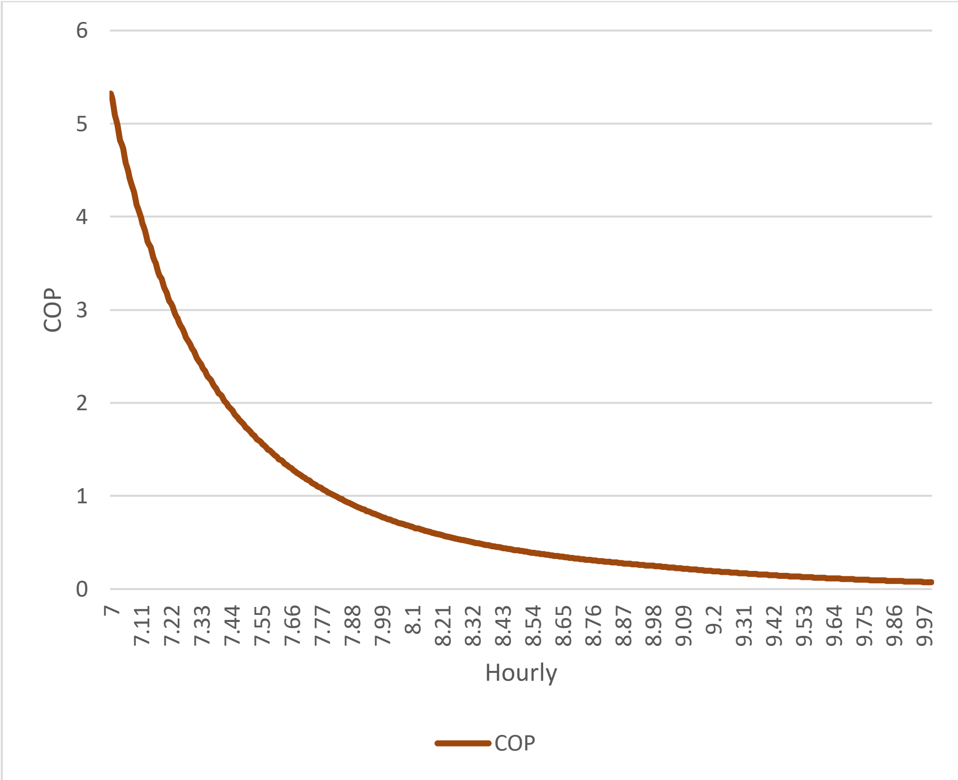

Figure 12 COP of integrated PV-TEC system and DC-DC Buck-Boost converter without PID controller

The COP of the TEC is a crucial metric that defines its cooling efficiency and is given by the ratio of the heat removed from the PV module (Q_R) to the electrical power input to the TEC (Pin). By carefully balancing the electrical power supplied to the TEC and the cooling effect it provides, the integrated PV-TEC system can improve the overall energy conversion efficiency beyond what a standalone PV module can achieve. A higher COP, as shown in Fig. 12, indicates a more efficient TEC, meaning it can remove more heat per unit of electrical power consumed. In the integrated system, optimizing the COP is essential to ensure that the energy spent on cooling does not outweigh the gain in PV efficiency from temperature reduction.

Scenario 2: PV-TEC with DC-DC Buck-Boost, equipped with PID controller and Balanced focused tuning.

A PV system model, as found in Fig. 13, integrated with a TEC and a PID-controlled DC-DC buck-boost converter, provides a robust simulation platform for analyzing energy conversion, thermal management, and power control within a renewable energy system. This model, as found in Fig. 13, integrates PV power generation, thermoelectric cooling and heating, and DC-DC power conversion and control, all regulated by a PID controller to ensure system stability.

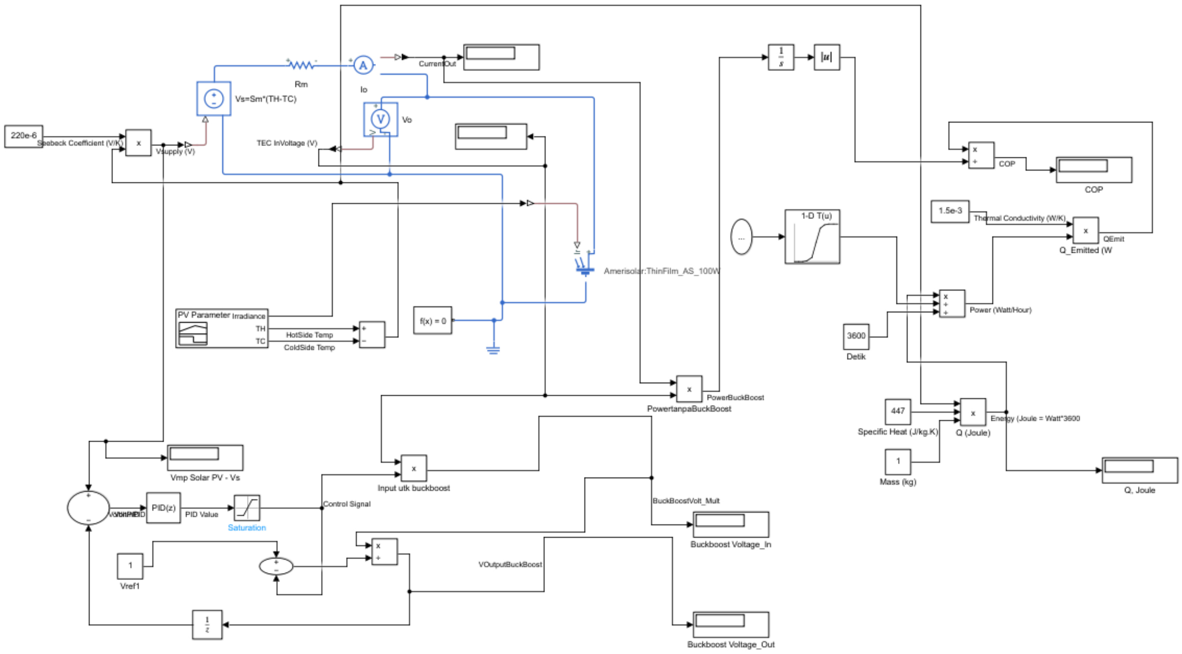

Figure 13 Simulink model of the integrated PV-TEC system with PID-controlled DC-DC Buck-Boost converter, emphasizing current feedback for balance tuning

Balanced tuning is crucial for achieving the optimal balance between system responsiveness and stability, ensuring consistent performance under variable conditions while avoiding negative consequences such as overshoot or energy inefficiency. Achieving a "balanced focus" in PID controller tuning of a TEC necessitates determining a set of PID gains (Kp, Ki, Kd) that represents a suitable compromise among multiple desirable performance characteristics, preventing overemphasis on any single characteristic, as found in Fig. 14, to consider certain parameters such as : (i) Ensuring the system does not oscillate uncontrollably or become unstable, (ii) Minimal Overshoot/Undershoot, (iii) Efficiency/Minimizing Power Consumption, otherwise can lead to excessive power consumption and reduced COP.

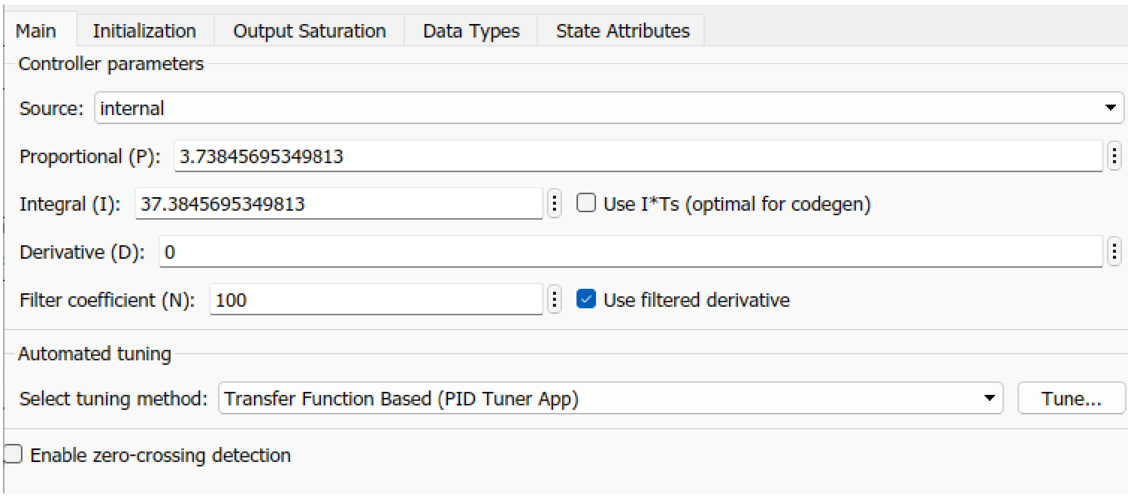

Figure 14 PID pop up window with balance tuning

The temperature differential and the applied current significantly influenced the COP. Utilizing a high proportional gain may result in rapid convergence to the setpoint, but this approach may induce substantial overshoot and oscillations. Fluctuations of this nature negatively impact TEC efficiency and may lead to rapid transitions between heating and cooling modes, compromising the device's operational longevity. Alternatively, a system with low gain may exhibit stability but demonstrate inadequate responsiveness to dynamic changes, thereby compromising precise temperature regulation ([Ibikunle et al., 2022](#)).

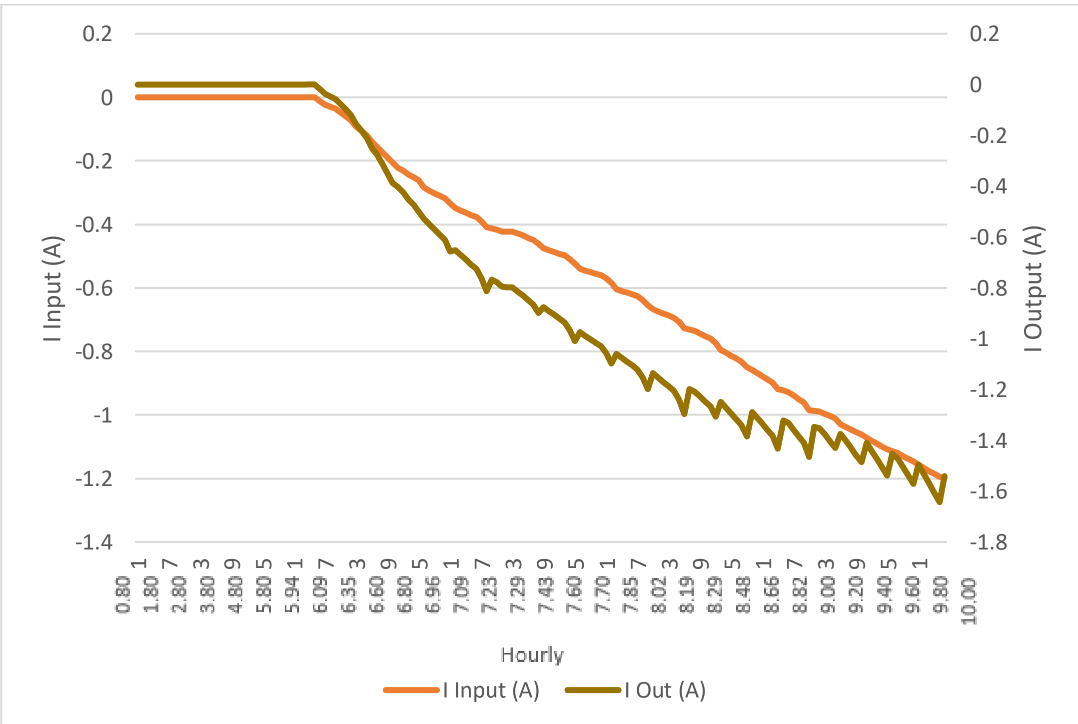

Figure 15 I input and I output of the integrated PV-TEC system with PID-controlled DC-DC Buck-Boost converter, emphasizing current feedback for balance tuning

As seen in the Fig. 15, the current indication of input, shows negatively small, in the end of simulation duration, shows -1.2 A, but for the current indication of output, shows negatively small also, which is approximately -1.54 A.

The negative input reading is due to a reversed connection in the TEC's solar PV power supply. However, the output's negative indication does not reflect actual current flow but rather heat transfer. The primary role of a TEC in a cooling system is heat transfer from the cold junction to the hot junction. The Peltier effect explained this heat transfer. A directly proportional relationship exists between input current and heat pumped (Q_R). The output is not electrical; instead, it is a thermal differential and heat dissipation. A heat sink applied to the component's heated surface commonly addresses heat dissipation and electrical power consumption. Analysis of the current output indicates a significant flaw in the TEC cooling system's implementation, likely causing an inversion of heat flow, although is not as high as the one without the PID controller, as seen in Fig. 9.

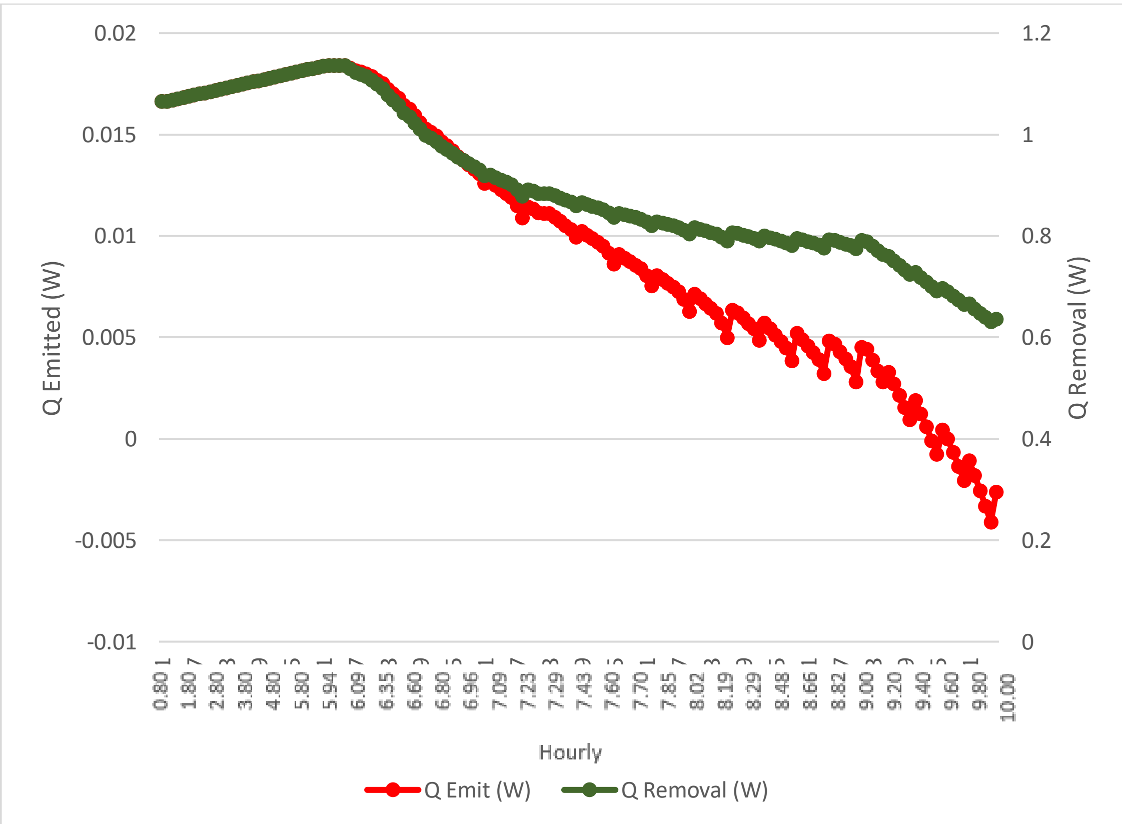

Figure 16 Q emitted (Q_E) vs Q removal (Q_R) of the integrated PV-TEC system with PID-controlled DC-DC Buck-Boost converter, emphasizing current feedback for balance tuning

The TEC module actively facilitates heat dissipation from the PV panel's surface, resulting in a decreased temperature. Heat absorption at the cold side (from the PV module) and heat rejection at the hot side (to the ambient environment) are critical thermal parameters for the

TEC. The absorbed heat, Q_R, quantifies the cooling load; this represents the heat removed from the PV panel by the TEC. The heat emitted, Q_E, is the sum of the absorbed heat and the electrical power input to the TEC, which is dissipated at the hot side. As shown in Fig. 16. Q_R signifies heat extraction from the hot side; conversely, the negative Q_E value indicates heat release to the heatsink, thereby suggesting a malfunction in the TEC's thermal pathway. The data illustrated in Fig. 16 somehow aligns with the data shown in the Fig. 15, inadequate heat transfer within the TEC, compounded by its improper execution, constitutes the root cause; heat generation trends show a reduced magnitude relative to the Fig. 10, a downward trend in Q_R usage is observed throughout the simulation.

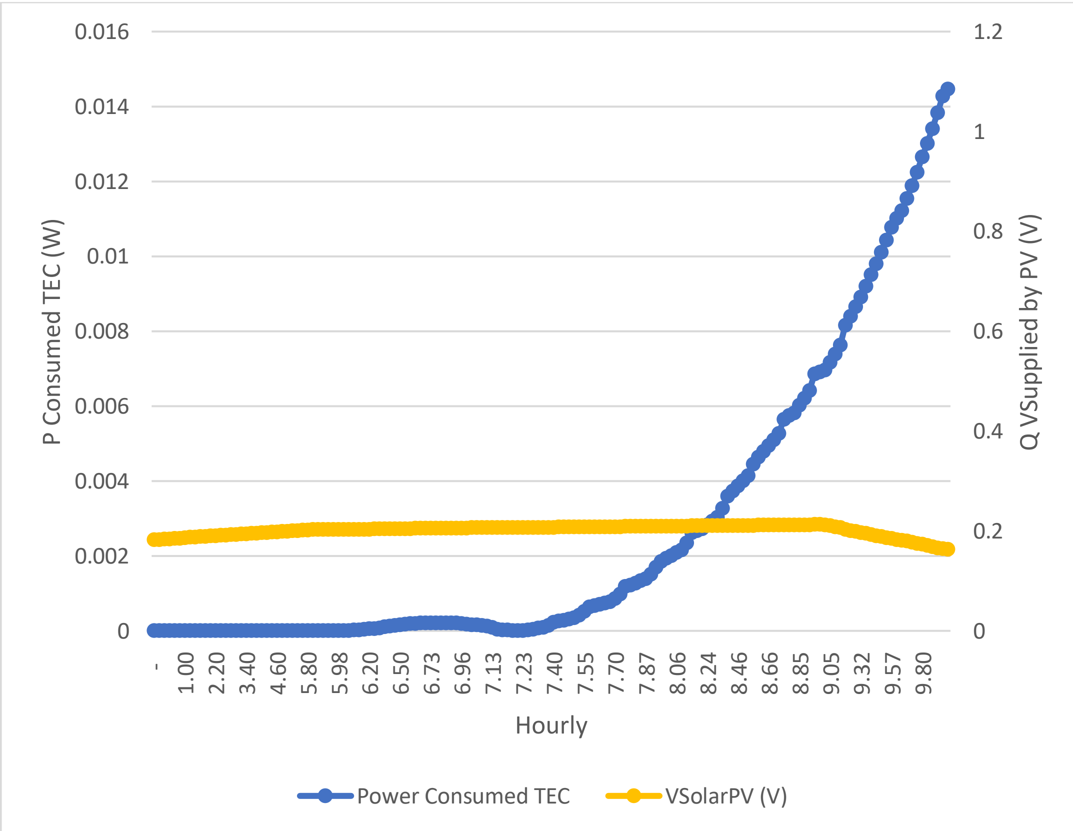

Figure 17 Power Consumption by TEC (W) vs Voltage Supplied by Solar PV of the integrated PV-TEC system with PID-controlled DC-DC Buck-Boost converter, emphasizing current feedback for balance tuning

TEC power consumption's relationship with applied voltage is characterized by both electrical and thermal power considerations, contingent upon the TEC's current draw and voltage differential. The electrical power (P) consumed by the TEC facilitates its primary function: heat transfer from the cold side to the hot side. Heat transfer capacity is a function of both the electric current and the temperature gradient across the hot and cold surfaces, this gradient varies according to the electrical input and prevailing operating conditions. The efficacy of a TEC is determined by its ability to conduct heat away from the cold side and reject it from the hot side. The elevated temperature on the hot side, a consequence of poor heat dissipation, negatively impacts overall efficiency. Inefficient heat dissipation on the TEC's hot side compromises cold-side cooling efficacy and increases power consumption to maintain a constant temperature differential, as found in Fig. 17, while the voltage supplied is relatively the same. However, the level of TEC power consumption in the Fig. 17. Substantially below the trend shown. Fig 11. Implementing a PID controller has demonstrably contributed to this outcome; tuning could further reduce TEC power consumption.

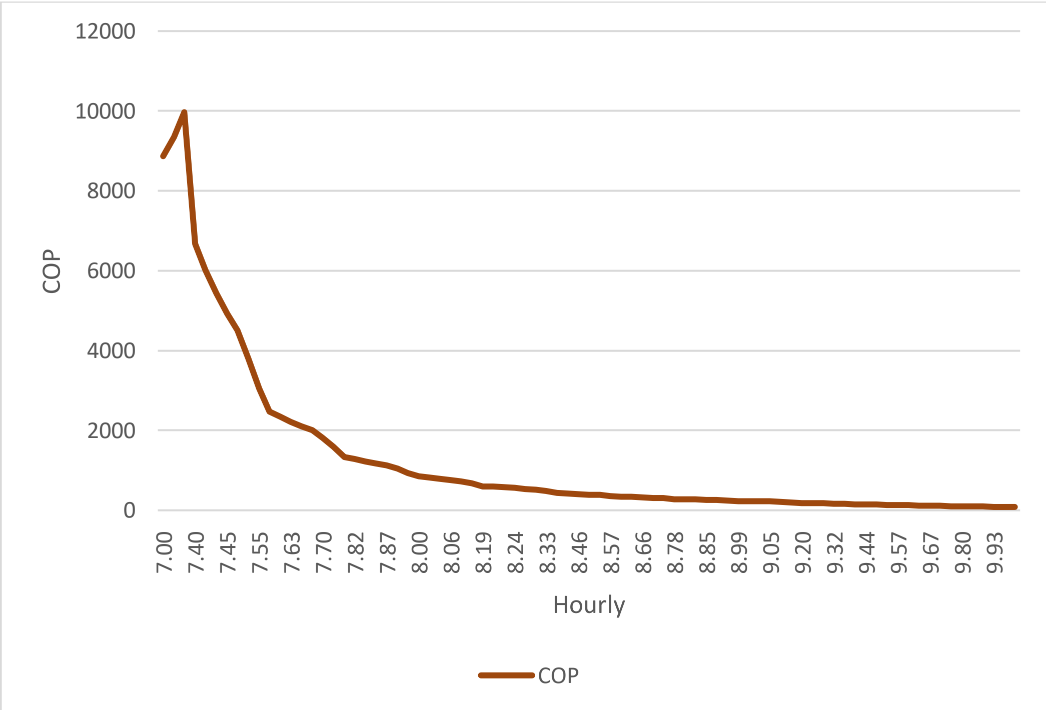

Figure 18 COP of the integrated PV-TEC system with PID-controlled DC-DC Buck-Boost converter, emphasizing current feedback for balance tuning

TECs exhibit an optimal operating point that maximizes their COP. Operating a TEC at its peak power output (unregulated) frequently surpasses its optimal performance parameters, resulting in significant Joule heating and diminished COP. Fig. 18 demonstrates that the COP for the balanced-focus PID controller is substantially greater than that shown in the Fig. 12. Utilizing a PID controller enables the TEC to operate with only the necessary power to achieve the setpoint, resulting in optimized efficiency and reduced energy consumption.

Scenarion 3: PV-TEC with DC-DC Buck Boost equipped with PID controller and Input Disturbances rejection focused tuning.

A PV system integrated with a TEC and a DC-DC buck-boost converter, incorporating a PID controller with input disturbance rejection focused tuning, is modeled to achieve high-performance, energy-efficient temperature control. The system effectively mitigates real-world challenges, including variations in solar irradiance (input disturbances), thereby ensuring stable power delivery to the TEC irrespective of environmental fluctuations and consequently affecting the TEC's cooling efficiency.

This model employs a disturbance rejection tuning strategy to improve the PID controller's capacity, for mitigating the effects of disturbances, such as abrupt fluctuations in sunlight intensity or temperature, on the TEC's temperature regulation. The PID controller for a TEC necessitates a balanced selection of gains (Kp, Ki, Kd) to achieve satisfactory performance across multiple characteristics, avoiding over-optimization of any single attribute, see Fig. 19. This method provides a more robust and reliable system that is capable of consistently maintaining temperature stability despite widely fluctuating inputs.

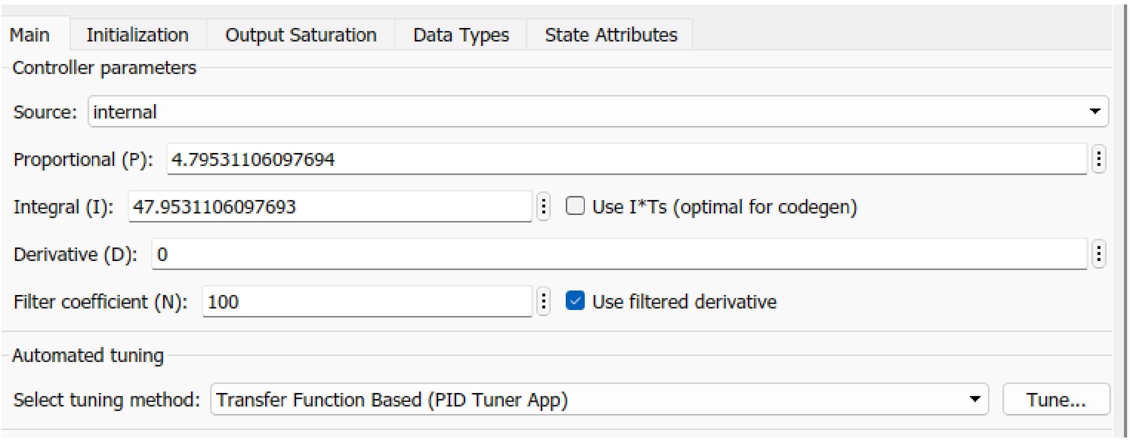

Figure 19 PID pop up window with Input Disturbances rejection tuning

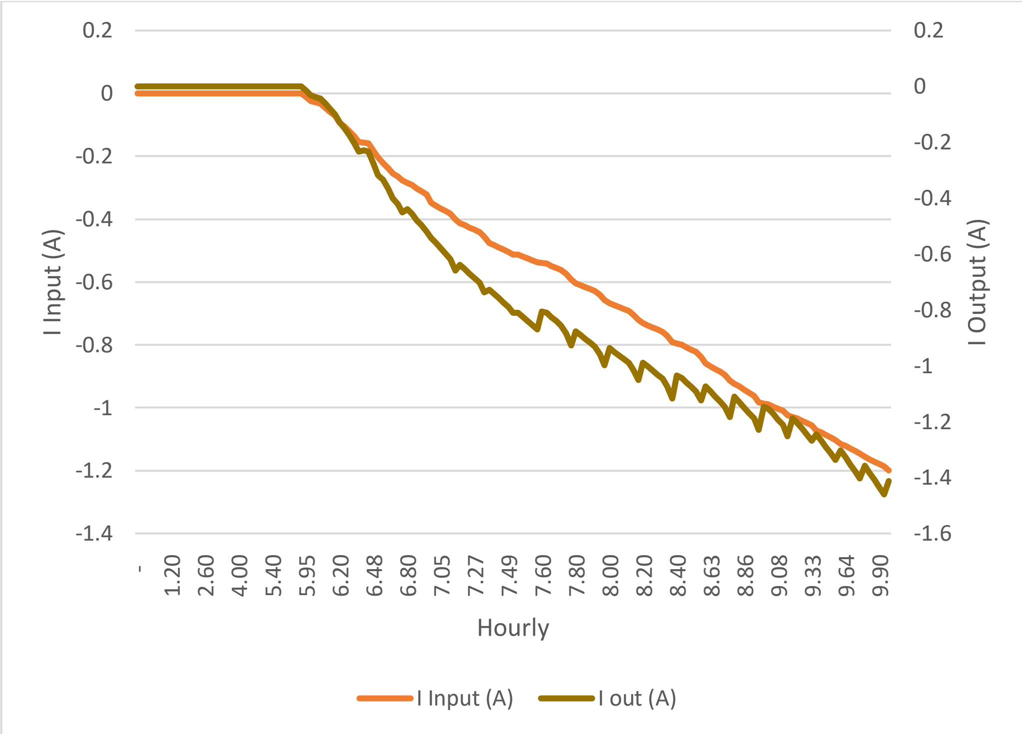

Figure 20 I input, and I output of the integrated PV-TEC system with PID-controlled DC-DC Buck-Boost converter, emphasizing current feedback for input disturbance rejection tuning

Fig. 20 reveals a slightly negative output current reading of approximately -1.41 A. This suggests a substantial deficiency in the TEC cooling system's design, potentially resulting in reversed heat flow; however, this effect is less pronounced than that observed in Fig. 15 concerning the balanced focus PID controller. This phenomenon indicates that the thermal energy retained within the TEC is ostensibly less than the equilibrium focal point. A reduction in trapped internal heat improves TEC performance.

Fig. 21 illustrates positive QE values, signifying heat emission from the TEC, in contrast to the insignificant negative values presented in Fig. 16. The PID controller, designed for input disturbance rejection, exhibited a more pronounced effect on the TEC, particularly concerning heat dissipation to the heatsink.

Figure 21 Q emitted (Q_E) vs Q removal (Q_R) of the integrated PV-TEC system with PID-controlled DC-DC Buck-Boost converter, emphasizing current feedback for input disturbance rejection tuning

Since heat dissipation on the TEC's works properly, as found in Fig. 20, the hot side compromises cold-side cooling efficacy and decrease power consumption, as found in Fig. 22 while maintain a constant temperature differential. The supplied voltage exhibits relative stability. The level of TEC power consumption in the Fig. 22, substantially below the trend shown. Fig 17. Implementing a PID controller of input disturbance rejection focused tuning has demonstrably contributed to this outcome.

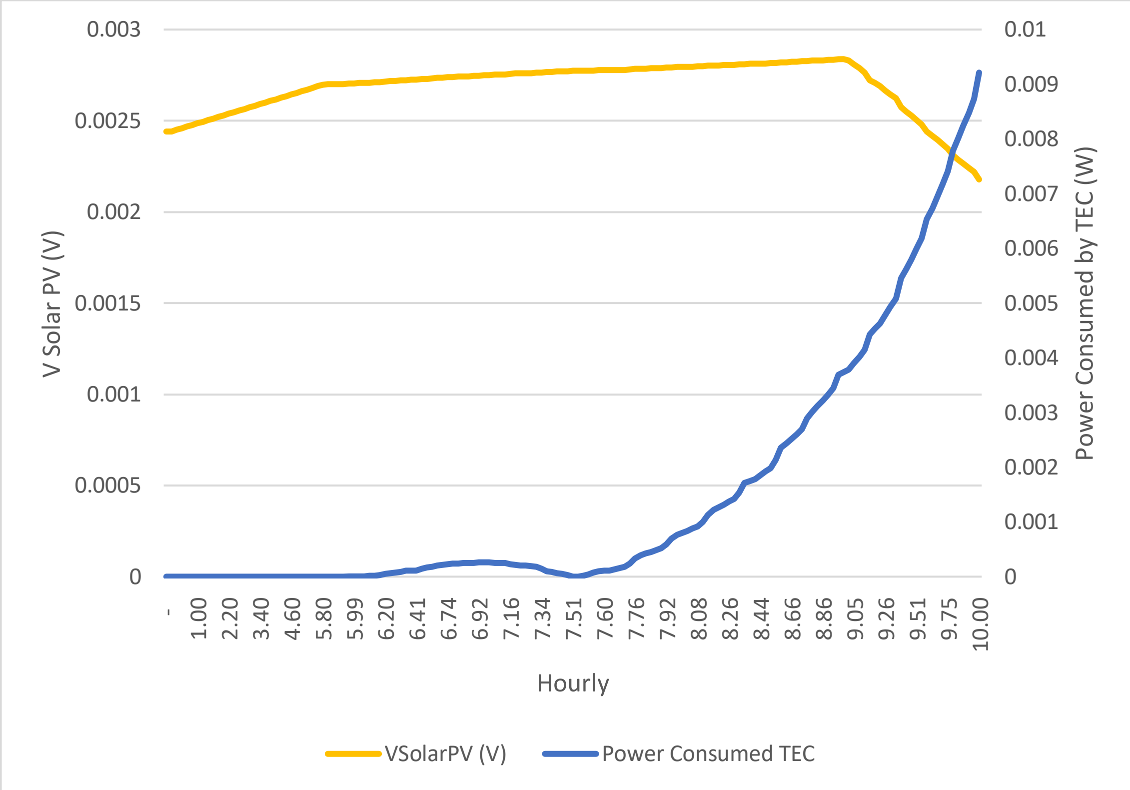

Figure 22 Power Consumption by TEC (W) vs Voltage Supplied by Solar PV of the integrated PV-TEC system with PID-controlled DC-DC Buck-Boost converter, emphasizing current feedback for input disturbance rejection tuning

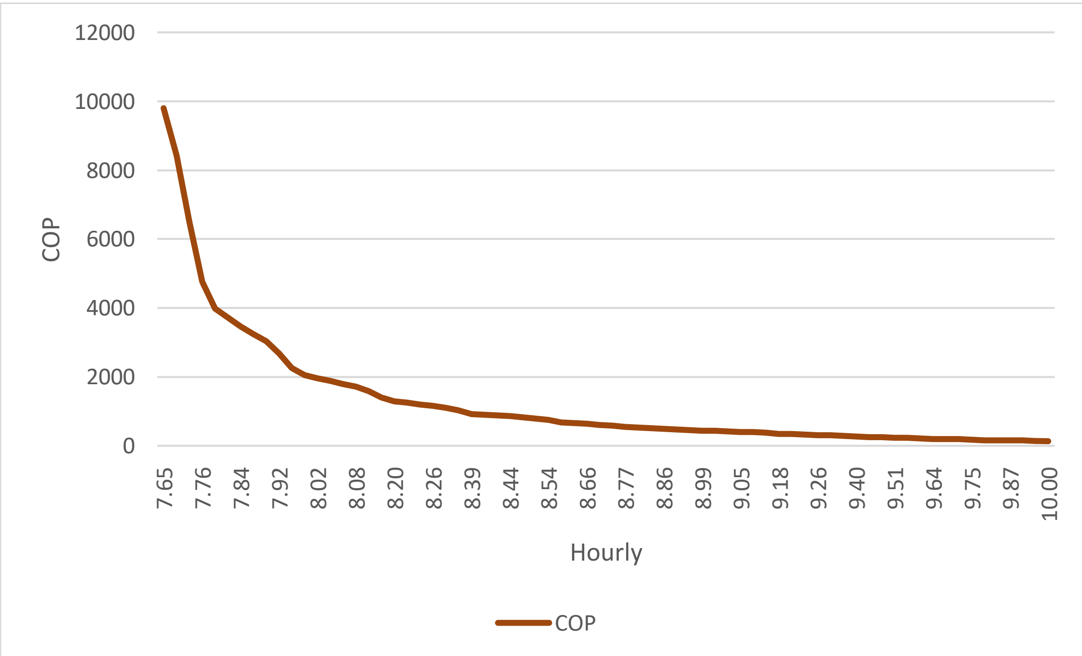

Figure 23 COP of the integrated PV-TEC system with PID-controlled DC-DC Buck-Boost converter, emphasizing current feedback for input disturbance rejection tuning

Thermoelectric converters (TECs) attain peak coefficients of performance (COPs) at their optimal operational parameters. Fig. 23 indicates a significantly higher COP for the Input Disturbanced rejection focused PID controller compared to Fig. 18. Implementation of a PID controller, incorporating input disturbance rejection tuning, mitigates joule heating, ensuring optimal system efficiency. The TEC's operation is thus limited to the power level necessary for setpoint achievement, resulting in optimized efficiency and reduced energy consumption. A disturbance-rejecting PID controller mitigates fluctuations in solar PV input power, thereby ensuring the TEC operates at its optimal steady state. Improved voltage tracking is achieved, ensuring optimal TEC performance within its peak coefficient of performance range. Table 4 presents a rigorous performance analysis of a DC-DC buck-boost converter, both with and without PID control, integrated within a solar PV panel and TEC system across three distinct scenarios.

In the absence of a PID controller, the DC-DC buck-boost converter functioned in an open-loop configuration. Despite exhibiting basic voltage regulation, the system's performance remained susceptible to fluctuations. With this configuration, the TEC's cooling capacity exhibited a significant lack of control, reacting passively to fluctuations in solar irradiance, load conditions, and ambient temperatures. Substantial temperature oscillations, prolonged settling times, and suboptimal performance were observed, often resulting from TEC operation outside its ideal current range. The absence of precise control mechanisms presented a significant challenge in achieving consistent temperature regulation for the intended application, underscoring the limitations inherent in a purely open-loop approach within dynamic operational contexts. The system's performance underwent a substantial transformation upon integration of the PID controller. Utilizing a robust feedback mechanism, the PID controller continuously monitored and regulated the TEC temperature by dynamically adjusting the buck-boost converter's output current and voltage.

Table 4 Result comparison from each approach

Parameters	**Scenario 1**	**Scenario 2**	**Comparison Scenario 1 and 2**	**Scenario 3**	**Comparison Scenario 2 and 3**
Buck-Boost V Out (V)	0.0001755	0.006361	97%	0.006939	8%
I output (A)	-55.89	-1.542	-3525%	-1.413	-9%
P Consumed by TEC (W)	15.5	0.008525	-181718%	0.006908	-23%
QH (W)	7.285	0.005903	-123312%	0.006194	5%
QC (W)	-8.213	-0.002623	-313015%	-0.0007141	-267%
COP	0.07304	84.7	100%	133	36%

The balanced-focused PID controller offers stable and smooth control, effectively maintaining temperature setpoints with moderate current variations. This approach minimizes thermal and electrical stress on the TEC and converter, making it suitable for systems with relatively stable solar input and predictable cooling demands. As found in Table 4, the voltage increments from scenario 1 to scenario 2, has reach up to 97%, and the I output has decreased more than 100%. Along with power consumed by the TEC, has decrease more than 100%, and the last is the COP, has increased up to 100%.

However, its slower response to input disturbances can result in short periods of energy inefficiency and suboptimal cooling performance, particularly under dynamic solar or thermal conditions. In contrast, the input disturbance rejection-focused PID controller demonstrates superior adaptability to fluctuating solar irradiance and thermal loads. It enables faster voltage and current compensation through the Buck-Boost converter, thereby maintaining more stable operating conditions for the TEC. This leads to lower electrical power consumption and improved system COP, especially under real-world conditions where PV output is variable. As found in Table 4, the voltage increments from scenario 2 to scenario 3, has reach up to 8%, and the I output has decreased more than 9%. Along with power consumed by the TEC, has decrease more than 23%, and the last is the COP, has increased up to 36%. Despite introducing slightly higher current peaks, this tuning strategy proves more effective in enhancing overall energy efficiency and thermal stability.

Conclusions

Diverging from earlier research, this study incorporates variable irradiance for the purpose of generating more realistic simulations. A simulation of fluctuating solar irradiance models the performance of photovoltaic systems in real-world conditions. These variations affect the voltage and current produced by the solar PV system, consequently impacting its performance. Simulation scenarios facilitate precise PV system assessment and optimization, enabling a comparative analysis of systems with and without PID controllers, highlighting the significance of balance and input disturbance rejection tuning. Solar irradiance variability compromises consistent cooling performance and energy efficiency in systems utilizing DC-DC buck-boost converters; their effectiveness is heavily reliant on PID control algorithms.

PID control provides better temperature stability, accuracy, and efficiency than maximum power. A PID controller is crucial for optimizing the performance of an integrated solar photovoltaic and thermoelectric cooler system. Through PID control, a passive, fluctuating cooling system is transformed into a precise, stable, and responsive temperature control solution, enabling the viability of integrated systems in applications requiring consistent and accurate thermal regulation under varying environmental conditions. The evaluation confirms the critical importance and substantial advantages of implementing closed-loop PID control for the dependable and efficient operation of these emerging green technologies.

Integrated PV-TEC systems operating under dynamic conditions benefit from a PID controller designed for input disturbance rejection, exhibiting enhanced performance and a higher COP, making it the superior control strategy when maximizing cooling efficiency and energy use is paramount. Based on the performance evaluation of the DC-DC Buck-Boost Converter with PID controller tuning strategies specifically balanced focus and input disturbance rejection focus, the following recommendations are proposed: (i) Real-time adaptive PID implementation, (ii) Hardware-in-the-loop testing, and (iii) Integration into IoT-based smart PV system.

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