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ENHANCED ENERGY CONVERSION IN HYBRID PHOTOVOLTAIC–THERMOELECTRIC SYSTEMS: A SIMULATION-BASED MULTI-PHYSICS OPTIMIZATION STUDY

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Abstract

The efficiency of conventional photovoltaic (PV) systems remains constrained by thermal losses, where excess heat not only reduces electrical output but also shortens module lifespan. Hybridization with thermoelectric (TE) modules offers a promising pathway to recover part of this wasted energy, yet existing studies have often been limited to laboratory conditions or isolated component analyses. This study develops a MATLAB-based simulation framework to evaluate the technical and economic performance of four PV–TE configurations: Baseline Bi_2Te_3, Film+, Film+PCM, and Film+PCM+Heat Pipe. Seasonal irradiance and temperature datasets were employed to assess hybrid efficiency, seasonal and annual energy yields, daily hybrid gains, and Levelized Cost of Electricity (LCOE). Results show that hybrid configurations consistently outperform PV-only systems, with the Film+PCM+Heat Pipe case achieving the highest gains. Seasonal hybrid efficiency reached ~19% in winter, while annual hybrid yield improved by 2–3 kWh per module. Daily hybrid gains of up to 0.8% confirm incremental but reliable advantages. Importantly, these improvements were achieved without increasing LCOE, which remained at ~0.05 USD/kWh. The findings demonstrate that hybrid PV–TE systems can enhance solar energy harvesting in a cost-neutral manner, offering practical potential for scalable deployment and resilience across diverse climatic conditions.

Keywords: Hybrid photovoltaic–thermoelectric system; MATLAB simulation; Phase change material (PCM); Heat pipe integration; Seasonal energy yield; Hybrid efficiency; Levelized cost of electricity (LCOE)

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1. Introduction

The growing global demand for clean and sustainable energy has accelerated the adoption of renewable technologies, with solar photovoltaic (PV) systems emerging as one of the most widely deployed solutions. Over the past two decades, significant advancements in PV cell manufacturing and material science have resulted in notable cost reductions and performance improvements [1]. However, despite these advancements, conventional single-junction silicon-based PV systems face an intrinsic efficiency cap in the range of 20–22%, constrained by the Shockley–Queisser limit [2]. This limitation arises because a substantial portion of incident solar energy is either lost as thermal energy or reflected, thereby restricting the effective conversion of solar irradiance into usable electricity.

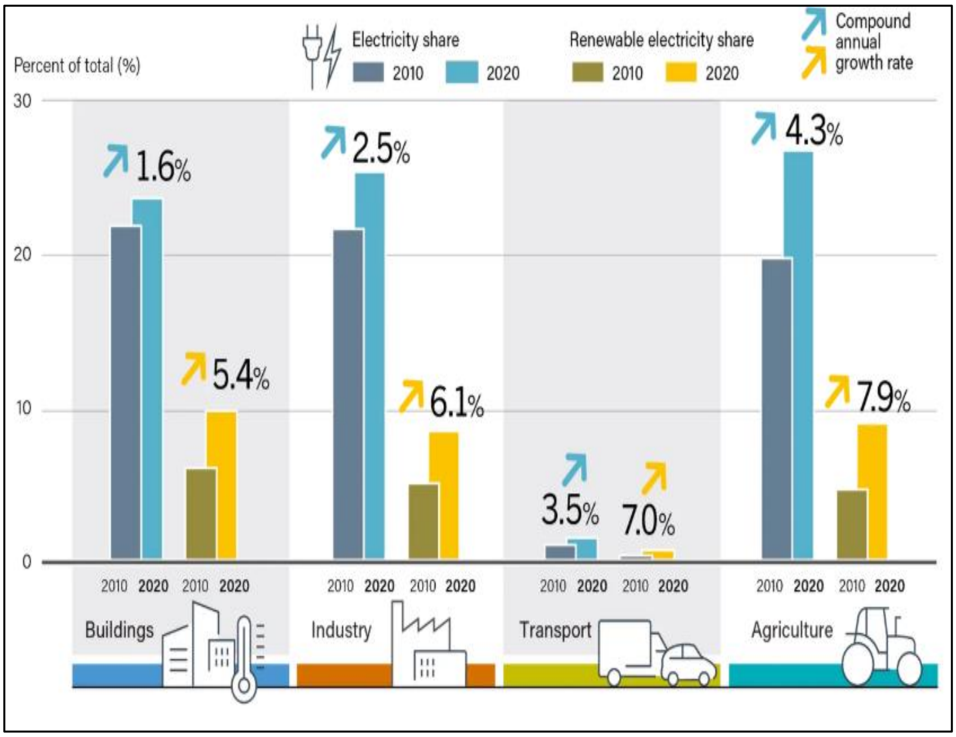

Figure 1. Electricity and Renewable Electricity share of Total Final Energy Consumption in a decade (Source: IEA).

The issue of heat accumulation in PV modules is particularly critical, as elevated cell temperatures not only reduce electrical efficiency but also shorten the lifespan of PV systems [3]. Studies indicate that for every 1 °C rise above the standard test condition (25 °C), PV cell efficiency decreases by approximately 0.4–0.5% [4]. Consequently, a significant fraction of the solar spectrum—especially infrared wavelengths—contributes to heating rather than electrical conversion, making PV systems inherently suboptimal in their standalone form. To overcome these efficiency bottlenecks, hybridization approaches have gained attention, particularly the integration of thermoelectric (TE) modules with PV systems. TE devices operate on the Seebeck effect, where a temperature gradient across a semiconductor material generates a voltage difference, thereby enabling the direct conversion of heat into electricity [5]. When

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coupled with PV modules, TE devices can harvest the excess thermal energy generated by the absorption of non-utilized solar spectrum, particularly in the infrared region, which otherwise elevates the PV cell temperature and diminishes its efficiency. This hybridization achieves a dual benefit: (i) the TE modules contribute additional electrical output by converting waste heat, and (ii) their presence helps regulate the PV cell operating temperature, thereby stabilizing and sometimes enhancing PV performance over time [6]. Experimental studies have demonstrated that hybrid PV–TE configurations can provide an overall efficiency improvement of 3–7% under optimal conditions, although performance remains highly sensitive to module design, thermal coupling, and local irradiance levels [7, 8].

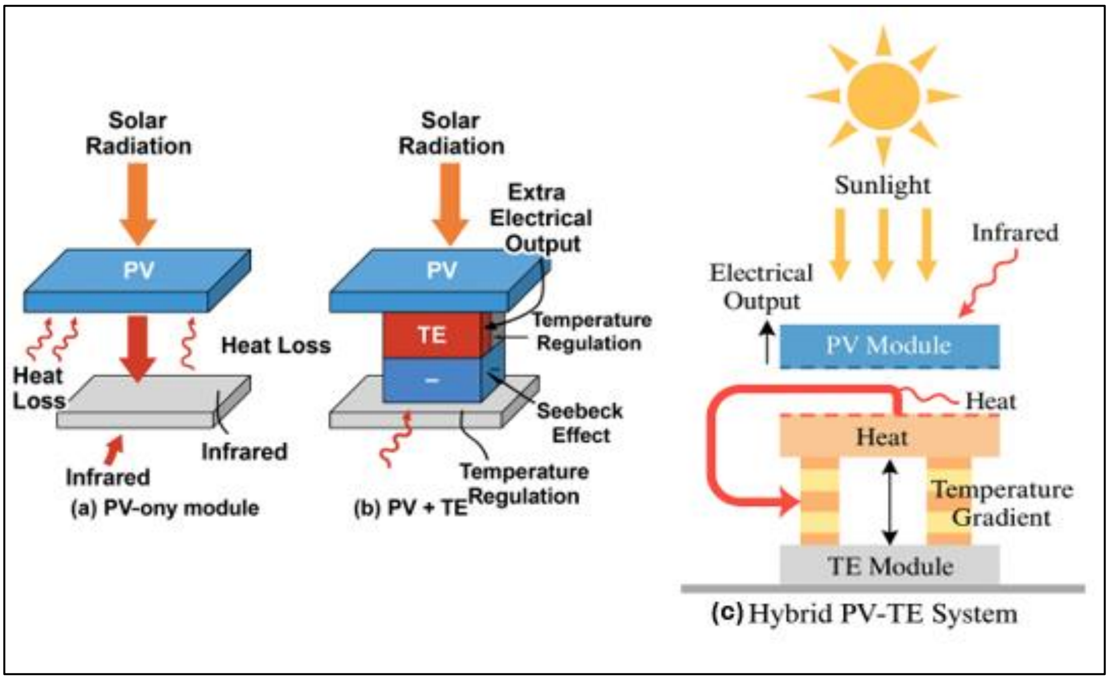

Figure 2. PV–TE system configurations: (a) PV-only module with heat loss from infrared absorption, (b) PV + TE module recovering waste heat via the Seebeck effect for extra output and temperature regulation, and (c) hybrid schematic showing solar absorption, infrared heat utilization, and enhanced power generation.

Hybrid photovoltaic–thermoelectric systems show strong potential but face adoption challenges in thermal management, material optimization, and system-level integration. Most studies examine isolated components or use simplified models, leaving gaps in understanding system behaviour under dynamic solar and thermal conditions. This study develops a MATLAB-based multi-physics simulation framework that couples PV electrical modelling with thermoelectric performance across seasonal irradiance. By optimizing module configuration, thermal interface conductivity, and materials, it quantifies efficiency gains and evaluates economic feasibility through LCOE analysis. Results provide theoretical contributions and practical insights for scalable, cost-effective deployment. For example, in the Atacama Desert, hybrid systems approached—but did not surpass—the cost competitiveness of standalone PV [9-11]. Similarly, recent work proposes generalized strategies for PV–TE

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integration but lacks detailed multi-physics simulation under real solar profiles. These limitations highlight the need for a comprehensive optimization framework that couples electrical and thermal behaviour with real-site irradiance dynamics and cost modelling, which is precisely the scope of this study. This study aims to develop and optimize a coupled photovoltaic–thermoelectric (PV–TE) multi-physics model that integrates electrical, thermal, and material domains for improved solar energy harvesting. Using a MATLAB-based framework, it captures interactions between PV photon-to-electron conversion and TE heat-to-electricity conversion under variable solar irradiance. Optimization targets thermal interfaces, module configurations, and material properties, while LCOE analysis evaluates economic feasibility. The work delivers a holistic, scalable design framework that bridges laboratory demonstrations with real-world applications. The next section reviews prior PV–TE research, outlines limitations, and identifies knowledge gaps addressed in this study.

1.1. Side-Mounted Configuration

Side-mounted PV-TE systems place thermoelectric modules next to PV panels, exploiting panel heat to produce 15–40°C temperature differences; hot side reaches 70–80°C, cold side 30–40°C via ambient or heat sink cooling [12, 13]. The electrical characteristics demonstrate significant performance enhancements, with TEG output voltages of approximately 0.97V at 20°C temperature difference and generated currents of 225mA under standard operating conditions [14]. Power output improvements of 20-30% over standalone PV systems are commonly achieved through effective thermal management incorporating heat sinks with convective cooling, thermal interface materials to reduce contact resistance, and advanced materials such as pyrolytic graphite sheets for enhanced thermal transport [15]. The side-mounted architecture enables independent optimization of both PV and TE components while maintaining efficient thermal coupling. Performance specifications indicate conversion efficiency improvements of 1.47% with power output increases of 61.01% compared to PV-only systems at 6:1 solar concentration ratio. Temperature coefficient benefits become particularly pronounced in these configurations, as the separation between PV cells and TEG modules allows for better temperature management of the photovoltaic components while maximizing thermal energy capture for thermoelectric conversion [16].

1.2. Backside-Mounted Configuration

Backside-mounted systems integrate thermoelectric generator modules directly to the rear surface of photovoltaic panels, creating sandwich-like structures that maximize thermal contact between components. The typical TEG module dimensions measure 40×40mm to match standard PV cell areas, utilizing bismuth telluride (Bi_2Te_3) based materials with figures of merit ranging from 2.5-3×10^{-3} W/°C and Seebeck coefficients exceeding 190 μV/°C [14]. System performance demonstrates maximum power outputs of 615.7mW per TEG module at temperature differences of 40°C, with corresponding PV cell temperature reductions averaging 10.3°C and voltage output increases of 28.56-30.54% compared to standalone photovoltaic operation [12]. Thermal management in backside-mounted configurations requires sophisticated heat sink integration, particularly microchannel heat sink designs with optimal

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channel heights of 0.5mm and header lengths of 20mm for uniform coolant distribution [17]. Double-layer microchannels reach 17.45% electrical efficiency, a 40% gain over conventional cooling. BiTe materials show 1.2–1.6 W/m·K conductivity and power factors above 0.005 W/m·K² between 25–250°C. Two-layer TEGs boost power by 27.6% with optimal 5Ω load resistance. Hybrid PV–PCM–TEG systems deliver 25.76% efficiency gains and 43–68% higher power output, requiring 5 mm spacing and -40°C to +85°C cycling for thermal stability.

1.3. Spectral Splitter Configuration

Spectral splitting uses dichroic mirrors to separate solar radiation into bands optimized for different converters. Advanced designs achieve >90% reflection for target wavelengths and 85–95% transmission for others, with cut-on ranges of 425–1800 nm at 45° incidence. The Onagraceae V-Trough concentrator advances this field, using four 32×10 mm dichroic mirrors in crossed V-troughs at 71° for optimal concentration with minimal losses [18]. Spectral splitting PV–TE systems achieve 16.9% efficiency, a 6.3% gain from infrared harvesting. Power output rises from 12.41 mW in bare cells to 62.04 mW in concentrated hybrids, offering strong benefits for high-cost cells like GaAs and GaInP [18]. The spectral characteristics show visible spectrum reflection (400-700nm) directed to PV cells while infrared transmission (>700nm) feeds thermal absorbers for thermoelectric generation [19]. Material specifications for photovoltaic components include GaInP cells optimized for high-energy photons with silicon cells providing complementary spectral response and temperature coefficients of -0.37%/°C for voltage characteristics [20]. Thermoelectric materials demonstrate p-type Bi_2Te_3 with average ZT values of 1.08 across 25-250°C temperature ranges and n-type Bi_2Te_3 with average ZT values of 0.84 across similar temperature ranges. Module efficiencies reach 8% conversion efficiency with power densities of 2.1W/cm² at temperature differences of 230°C [21].

1.4. Advanced Integration Specifications

Circuit configuration strongly influences PV–TE performance: series boosts voltage but limits current, while parallel raises current at constant voltage. DC–DC converters with MPPT and 5–10 Ω load tuning achieve >95% transfer efficiency with advanced power electronics [22]. PV–TE hybrid installations follow standard module guidelines: uplift and downforce loads ~3600 Pa with 1.5 safety factors, clamp widths ≥70 mm, 5 mm spacing for thermal expansion, and corrosion-resistant aluminium frames [23, 24]. Environmental durability is ensured through IEC 61215/61730 qualification tests, which subject modules to temperature cycling between –40 °C and +85 °C, humidity-freeze, and damp-heat exposures to validate long-term reliability [25]. PV–TE heat management uses active methods (water cooling, fins) or passive ones (radiative cooling, geometry, PCM buffering). Early studies showed 2.44× efficiency over PV-only systems and ~8.9% gains under Mediterranean conditions, underscoring the need for integration with effective thermal control [26].

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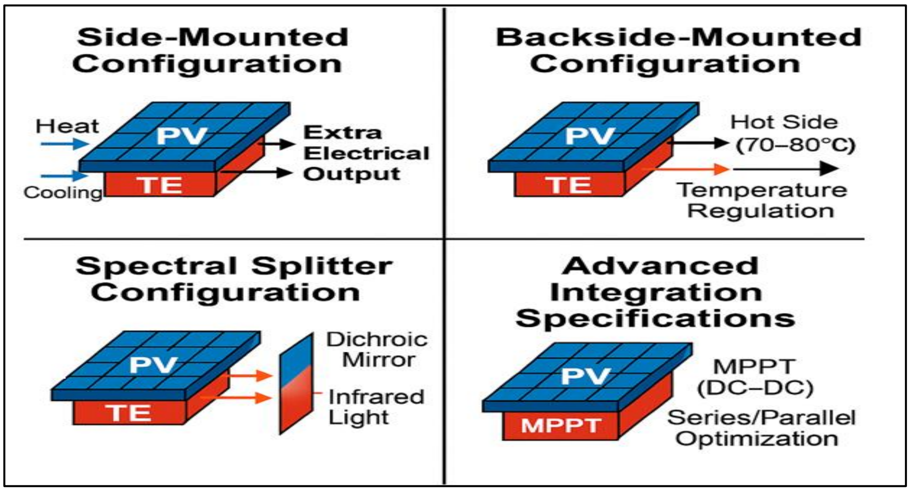

Figure 3. Configurations of PV–TE hybrid systems. (a) Side-mounted modules extract heat with cooling support for extra output. (b) Backside-mounted modules regulate PV temperature at 70–80 °C. (c) Spectral splitters direct visible light to PV and infrared to TE. (d) Advanced integration combines MPPT with optimized series/parallel TE connections for enhanced performance.

Recent studies show that PV–TE hybrid systems generally deliver 2–5% efficiency gains. In building-integrated PV systems with PCM and TEGs, annual generation improved by 1.09%, with seasonal gains peaking in cooler months (+0.91% spring, +2.25% autumn, +3.16% winter) but declining slightly in summer (–1.32%). Under optimized design conditions, improvements of up to 4.47% are achievable compared to standalone PV [26]. Experimental validation studies provide detailed documentation of efficiency improvements across different system configurations. Laboratory testing of hybrid PV-TEG systems with bismuth telluride-based thermoelectric modules demonstrates efficiency increases from 11.6% to 14%, representing a 17% overall improvement in system performance [27]. These improvements result from effective thermal management that reduces photovoltaic cell operating temperatures while simultaneously generating additional electrical power through thermoelectric conversion of waste heat. Fan-assisted thermoelectric cooling configurations achieve even more substantial improvements, with efficiency gains reaching 28% for hybrid systems and up to 36.9% under optimized operating conditions [28]. Integrating PCMs with PV–TE systems yields major efficiency gains: PV-PCM boosts efficiency by 33.33%, PV-PCM-TEG by 25.76%, and PV-TEG-PCM by 21.21%. Power output rises by 68.04%, 43.06%, and 37.51% respectively, driven by PCM buffering and TE heat conversion [16].

Concentrated photovoltaic-thermoelectric systems demonstrate efficiency improvements that vary with concentration ratios and system configurations. Research indicates that at moderate concentration levels, PV-TE hybrid systems achieve efficiency improvements of 1.47% with corresponding power output increases of 61.01% compared to PV-only systems [29]. Higher concentration ratios produce more substantial improvements, with some configurations achieving maximum total conversion efficiency ratios of 32.2% through optimization of

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thermoelectric generator areas and thermal management systems. The optimal balance between photovoltaic and thermoelectric performance occurs at specific concentration ratios, typically around 5.5 kW/m² for maximum system efficiency [30]. Advanced cooling integration strategies provide additional pathways for efficiency enhancement. Thermoelectric cooling modules operating in active cooling mode achieve PV system efficiency improvements of 9.54%, while passive cooling configurations combined with thermoelectric power generation increase overall system efficiency by 15.50% [31]. These improvements result from reduced photovoltaic cell operating temperatures combined with additional electrical generation from thermoelectric conversion of waste heat. Microchannel heat sink integration with thermoelectric generators achieves maximum electrical efficiencies of 17.45%, representing 40% improvements over conventional cooling systems [17].

Material and system optimizations yield 2–5% efficiency gains. Pyrolytic graphite sheets lower thermal resistance, while advanced heat sinks with high-performance interfaces push improvements toward the upper 5% limit by enhancing heat transfer and reducing losses [15]. Long-term evaluations show seasonal effects: spring, autumn, and winter average 2.11% efficiency gains, while summer sees reduced performance due to high ambient temperatures limiting TE gradients [26]. These seasonal variations underscore the importance of climate-specific system design and the potential for higher efficiency gains in temperate climates where larger thermal gradients can be maintained between photovoltaic cells and ambient conditions.

Prior studies confirm that PV–TE hybrid systems typically achieve 2–5% efficiency gains through reduced PV cell temperature, waste-heat recovery, and improved thermal management, while still maintaining system reliability and economic feasibility. However, poor thermal management, the mismatch between PV operating temperatures (25–75 °C) and the higher gradients required by TEGs (≥100 °C), and high component costs continue to limit large-scale adoption. Moreover, most research isolates electrical, thermal, and optical aspects under simplified steady-state conditions, overlooking real solar variability. The absence of integrated MATLAB-based models that couple geometry, materials, and control strategies under dynamic conditions leaves a critical gap—hindering accurate performance prediction, adaptive algorithm development, and the creation of validated digital guidelines for robust, scalable PV–TE deployment.

Table 1. Energy conversion enhancement approaches used.

Approach	**Variable Solar Conditions**	**Simulation/Experimental Tool**	**Gaps**	**Ref.**
Analytical spectral optimization model	Steady, uniform solar irradiance in laboratory settings	MATLAB only	No thermal-structural simulation; lacks dynamic response under varying irradiance	**[13]**

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Analytical energy balance with site profiles	Mediterranean seasonal irradiance and temperature profiles	MATLAB parametric	No coupled finite-element thermal validation; structural stresses unassessed	**[32]**
PV-TEG with phase change material (PCM)	Diurnal temperature swings and irradiance variability	MATLAB data processing	Omits coupled thermal-mechanical stress analysis; no CFD or structural simulation	**[18]**
Prototype testing of PV-TE devices	Constant laboratory illumination	CFD-based thermal model	Absent co-simulation with MATLAB control and optimization routines	**[33]**
CFD-based heat-sink design optimization	Simulated cloud cover variability and transient solar loads	CFD-based thermal model	Lacks algorithmic optimization routines in MATLAB; no co-simulation framework for control-stress analysis	**[34]**
Experimental PV–TE prototype with heat sinks	Constant irradiance under solar simulator	Lab-scale experimental setup only	Results lack scalability; no parametric optimization; ignores seasonal variations	**[27]**
Spectral splitter PV–TE systems	Controlled optical spectrum splitting	Optical ray-tracing and experimental concentrators	No thermal–electrical coupling model; ignores real-time weather dynamics	**[18]**
PV–PCM–TE hybrid setups	Diurnal ambient fluctuations in outdoor tests	Outdoor experimental rigs	Limited dataset; site-specific results; no predictive model for varying climates	**[16]**
TE cooling for PV panels	Uniform artificial heat loading	CFD-based thermal model	Electrical output not simulated;	**[31]**

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			neglects seasonal irradiance variation	
Building-integrated PV–TEG	Seasonal rooftop operation	TRNSYS / EnergyPlus simulations	Focus on building energy demand; weak integration with PV–TE material-level performance	**[26]**

3. Research Methodology

3.1 Data Sources and Case Differentiation

The simulation framework distinguishes between empirically validated baseline data and exploratory modelled scenarios. The Case 1 (Baseline Bi_2Te_3 configuration) results were anchored in empirical datasets obtained from the National Renewable Energy Laboratory (NREL), which provided realistic hourly solar irradiance and ambient temperature profiles. These datasets ensure that the baseline PV–TE performance is benchmarked against globally recognized, high-quality solar resource data. For Cases 2–4 (Film+, Film+PCM, and Film+PCM+Heat Pipe), performance outcomes were derived through MATLAB-based modelling and analysis, wherein additional thermal management features were systematically integrated into the baseline model. These enhancements were simulated using validated thermophysical properties of thermal films, phase change materials, and heat pipes. By retaining the same irradiance and environmental inputs as Case 1, the study ensures that improvements observed in Cases 2–4 can be attributed directly to system modifications rather than differences in external conditions.

3.1 Simulation Framework

The present study adopts a MATLAB-based simulation framework to evaluate the performance of hybrid photovoltaic–thermoelectric (PV–TE) systems under realistic operating conditions. The framework was designed to integrate the electrical modelling of PV modules with the thermoelectric contributions derived from the waste heat accumulated at the PV back surface. Unlike experimental approaches that are limited by spatial and temporal constraints, the MATLAB environment allows for flexible parametric modelling, enabling a systematic comparison of multiple hybrid configurations.

The simulation framework consists of three main computational blocks:

1. Photovoltaic Model – The PV output was calculated using irradiance-dependent current–voltage equations and temperature correction factors. A standard temperature coefficient of –0.4 to –0.5%/°C was applied to account for efficiency degradation at elevated cell temperatures.
2. Thermoelectric Model – The TE generator output was estimated as a function of the temperature gradient between the PV backside and the ambient environment. A Bi_2Te_3-based TE module was considered as the baseline, with enhancements modelled through film

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interfaces, phase change materials (PCM), and heat pipes to regulate and maximize the thermal gradient.

3. Hybrid Coupling – The PV and TE outputs were aggregated to obtain the total hybrid power generation. The coupled model was executed under hourly solar irradiance and ambient temperature data representative of four distinct seasonal conditions (Spring, Summer, Monsoon, Winter).

This modular structure of the simulation framework ensures that different hybrid scenarios can be directly compared, both in terms of technical performance (efficiency, energy yield, hybrid gain) and economic feasibility through Levelized Cost of Electricity (LCOE).

3.2 System Configurations

To evaluate the performance of hybrid photovoltaic–thermoelectric (PV–TE) systems, four distinct configurations were modelled. Each configuration builds upon the baseline PV–TE system by integrating progressively advanced thermal management strategies. The comparative analysis of these cases allows for quantifying the incremental benefits of film interfaces, phase change materials (PCM), and heat pipe integration. The configurations are summarized in Table 1.

- Case 1 – Baseline Bi_2Te_3: Represents the reference system consisting of a PV module coupled with a Bi_2Te_3-based thermoelectric generator (TEG) module, without any additional thermal enhancements.
- Case 2 – Film+: Incorporates a high-conductivity thermal interface film between the PV module and the TEG to reduce thermal resistance and improve heat transfer.
- Case 3 – Film+PCM: Enhances the Film+ case by integrating a phase change material layer, which acts as a thermal buffer, mitigating temperature spikes and sustaining effective thermal gradients.
- Case 4 – Film+PCM+Heat Pipe: Adds a heat pipe network to the Film+PCM configuration, enabling more efficient heat spreading and dissipation, thus maximizing TEG performance.

Table 2. Configuration Summary.

Case	Configuration	Key Features
1	Baseline Bi_2Te_3	Standard PV + Bi_2Te_3 TEG; no additional thermal enhancement
2	Film+	Addition of high-conductivity thermal film to improve heat transfer
3	Film+PCM	Film+ configuration with PCM integration for thermal buffering

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4	Film+PCM+Heat Pipe	Advanced configuration with PCM + heat pipe for efficient heat redistribution

3.3 Input Parameters

The performance of hybrid PV–TE systems strongly depend on the choice of environmental conditions, PV module specifications, thermoelectric generator properties, and economic assumptions. To capture these dependencies, the simulation model was parameterized with inputs summarized in Table 2 and further elaborated below.

Table 3. Input parameters and reference sources used in the MATLAB-based simulation of PV–TE hybrid systems.

Category	Parameter	Value/Range	Reference Basis
Environment	Irradiance (GHI)	0 – 1000 W/m² (hourly, seasonal profiles)	**[35]**
	Ambient Temperature	15 – 40 °C	Seasonal variation (Spring → Summer)
PV Module	Technology	Crystalline Silicon	Market dominant standard
	Nominal Efficiency (η_0)	18–20%	STC (1000 W/m², 25 °C)
	Temperature Coefficient (β)	–0.4 to –0.5 %/°C	**[4]**
TE Module	Material	Bi_2Te_3	Standard TE material
	Seebeck Coefficient (S)	~190 µV/°C	**[5]**
	Thermal Conductivity (k)	1.2 – 1.6 W/m·K	**[6]**
	Dimensions	40 × 40 mm	Standard PV cell matching
	ΔT Operating Range	10 – 40 °C	Seasonal variation across scenarios
Economic	Baseline LCOE (PV-only)	~0.05 USD/kWh	**[1]**
	Hybrid LCOE	Computed relative to baseline	Simulation output

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The simulation framework incorporated four sets of inputs to ensure realistic evaluation. Seasonal irradiance and temperature datasets captured diurnal variation and defined the thermal gradients driving TE operation. Silicon-based PV modules with ~19% baseline efficiency and a –0.45%/°C temperature coefficient were modelled to reflect market standards, emphasizing the importance of thermal management. Bi_2Te_3 was selected as the TE material due to its suitability at 10–40 °C gradients, with module dimensions matched to PV cells and properties taken from literature. Finally, economic feasibility was assessed through LCOE analysis, using ~0.05 USD/kWh as the baseline reference to evaluate the cost neutrality of hybrid configurations.

3.4 Performance Metrics

To comprehensively evaluate the hybrid PV–TE configurations, multiple performance metrics were defined in the MATLAB simulation. These metrics were designed to capture technical effectiveness (efficiency, energy yield, hybrid gain) and economic feasibility (LCOE). Hybrid efficiency is defined as the ratio of combined PV and TE electrical output to incident solar energy on the module surface:

Hybrid Efficiency,

$$\eta_h = \frac{P_{PV} + P_{TE}}{G \cdot A} \tag{1}$$

Where P_{PV} is PV output power, P_{TE} is TE output power, G is incident irradiance $\left(\frac{W}{m^2}\right)$, and A is module area (m^2). Seasonal variations in efficiency were analysed across the four configurations.

The seasonal hybrid energy was computed as the time integration of hybrid power output over each representative season:

Seasonal Hybrid Energy,

$$\sum_{t=1}^{n} \left(P_{PV}(t) + P_{TE}(t)\right) \cdot \Delta t \tag{2}$$

The annual hybrid energy yield was obtained by aggregating seasonal results:

Annual Energy Yield,

$$E_a = \sum_{i=1}^{4} E_{s,i} \tag{3}$$

Where $E_{s,i}$ corresponds to seasonal totals (Spring, Summer, Monsoon, Winter).

The daily hybrid gain represents the percentage improvement of hybrid output over PV-only performance:

Daily Hybrid Gain, (4)

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$$\Delta\eta_d = \frac{(P_{Hybrid} - P_{PV})}{P_{PV}} \times 100$$

Daily gains were analysed across the year to identify stability and consistency of hybrid advantage. The probability density function (PDF) of daily gains was computed to assess the reliability of hybrid enhancements. A broader distribution indicates higher variability, while a narrower peak suggests consistent performance improvements. Economic feasibility was assessed through LCOE, calculated as:

Levelized Cost of Electricity,

$$LCOE = \frac{\sum_{t=1}^{N}(C_t + O_t)}{\sum_{t=1}^{N} E_t} \qquad (5)$$

Where C_t is capital cost, O_t is operating cost in year t, and E_t is energy generation. For comparative analysis, P-V only systems were assigned a baseline LCOE of 0.05 USD/kWh, and hybrid configurations were evaluated relative to this benchmark. The purpose of each metric used for analysing the energy conversion enhancement has been depicted in table 4.

Table 4. Significance of each metric.

Metric	**Purpose**
Hybrid Efficiency	Quantifies technical efficiency of hybrid system
Seasonal Energy	Captures seasonal generation potential
Annual Yield	Provides annual hybrid generation comparison
Daily Gain	Measures daily improvement over P-V only
Gain Distribution	Assesses stability and consistency of hybrid gains
LCOE	Evaluates economic competitiveness

3.5 Workflow Steps

The MATLAB-based simulation workflow was designed as a modular pipeline to ensure transparency, reproducibility, and adaptability across different PV–TE configurations. The workflow integrates environmental inputs, system modelling, and performance evaluation in sequential stages, as described below:

Table 5. Simulation Steps performed in this study.

Step	**Description**	**Key Outputs**
Data Acquisition	Import hourly irradiance and ambient temperature datasets for four representative seasons (Spring, Summer, Monsoon, Winter).	Seasonal input profiles for PV–TE simulations.

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PV Output Modeling	Compute PV electrical output using irradiance-dependent I–V equations; apply temperature coefficient (–0.4 to –0.5%/°C).	Baseline PV-only seasonal results.
TE Output Modeling	Estimate TE module power from PV backside–ambient temperature gradient; baseline Bi_2Te_3 with enhancements (Film+, PCM, Heat Pipe).	Normalized TE output per module.
Hybrid Output Calculation	Aggregate PV and TE outputs; generate hourly, daily, and seasonal power profiles.	Hybrid performance profiles for each configuration.
Performance Metrics Evaluation	Compute hybrid efficiency, seasonal energy, annual yield, daily gains; analyze gain distribution.	Technical performance metrics and reliability trends.
Economic Assessment	Calculate LCOE for PV-only and hybrid systems using normalized cost assumptions.	Economic feasibility comparisons.
Visualization & Interpretation	Plot efficiency, seasonal/annual energy yield, daily gains, histograms, and LCOE comparisons.	Graphical representation and comparative insights.

The MATLAB-based workflow for PV–TE hybrid evaluation was structured into seven sequential steps, beginning with the acquisition of hourly irradiance and temperature data across four representative seasons to ensure realistic environmental inputs. PV output was then modelled through irradiance-dependent I–V relations with temperature corrections, followed by TE power estimation based on backside–ambient gradients using Bi_2Te_3 modules and enhanced scenarios (Film+, PCM, Heat Pipe). Aggregating PV and TE contributions enabled generation of hybrid hourly, daily, and seasonal profiles, which were subsequently evaluated using performance metrics such as hybrid efficiency, seasonal yield, annual output, and gain distributions. Economic feasibility was incorporated through LCOE analysis, allowing cost-neutrality to be assessed alongside technical improvements. Finally, results were visualized through comparative plots, ensuring that both performance and economic outcomes could be clearly interpreted across the different configurations.

4. Analysis

The results obtained from the MATLAB simulation were analysed to evaluate the performance of different PV–TE configurations across technical and economic dimensions. The analysis is structured into six sub-sections, beginning with seasonal hybrid efficiency and extending to seasonal and annual energy yields, daily hybrid gains, gain distribution, and representative day performance. Each sub-section is supported by graphical results (Figs. 1–8), ensuring that both trends and numerical outcomes are clearly communicated.

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4.1 Seasonal Hybrid Efficiency

Seasonal efficiency analysis provides insight into how hybrid PV–TE systems perform under varying irradiance and temperature conditions. Figure 2 illustrates the hybrid efficiency of all four configurations—Baseline Bi_2Te_3, Film+, Film+PCM, and Film+PCM+Heat Pipe—across Spring, Summer, Monsoon, and Winter. The results reveal clear seasonal trends. Winter demonstrated the highest average hybrid efficiency, approaching ~19%, due to favourable ambient conditions and stronger thermal gradients that enhanced TE module performance. Monsoon also achieved relatively high efficiencies (~18.5%), benefitting from reduced PV overheating under diffuse irradiance conditions. In contrast, Summer exhibited the lowest efficiencies (~17–17.5%), largely attributed to high ambient temperatures that reduced PV performance despite TE contributions. Spring maintained intermediate efficiency levels (~18%).

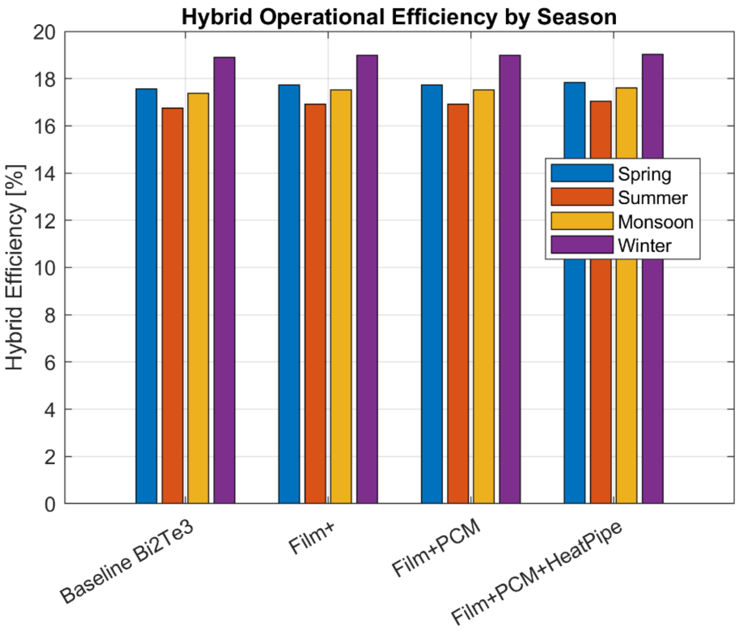

Figure 4. Seasonal hybrid efficiency across four PV–TE configurations (Baseline Bi_2Te_3, Film+, Film+PCM, Film+PCM+Heat Pipe).

Among the configurations, the Film+PCM+Heat Pipe system consistently outperformed others across all seasons, with incremental gains of ~0.5–1% compared to the baseline. The presence of PCM stabilized thermal fluctuations, while the heat pipe enhanced heat spreading, resulting in more effective thermoelectric operation. These improvements, though modest in absolute terms, are significant when considering the long-term operation of solar energy systems. Overall, the seasonal efficiency analysis confirms that hybridization offers measurable performance benefits, particularly under cooler or diffuse irradiance conditions, while advanced thermal management strategies ensure sustained gains even during peak summer.

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4.2 Seasonal Hybrid Energy Generation

While efficiency provides a normalized performance perspective, seasonal hybrid energy generation highlights the absolute output potential of different configurations under realistic operating conditions. Figure 3 compares the total hybrid energy produced across Spring, Summer, Monsoon, and Winter for all four system scenarios. The results show that Monsoon yields the highest hybrid energy outputs (~95–97 kWh). This can be attributed to relatively cooler ambient conditions that reduce PV temperature-induced losses, coupled with diffuse irradiance that prolongs effective solar capture throughout the day. Summer and Spring produced comparatively lower outputs (~65–73 kWh), reflecting higher PV cell heating in summer and moderate irradiance availability in spring. Winter exhibited intermediate energy generation (~70 kWh), benefiting from efficient hybrid conversion despite reduced solar availability.

Across all seasons, the Film+PCM+Heat Pipe configuration achieved the maximum energy output, confirming the synergistic effect of enhanced heat transfer, buffering of thermal fluctuations, and redistribution of heat gradients for improved thermoelectric operation. The Film+ and Film+PCM cases also showed consistent improvements over the baseline, though to a lesser extent.

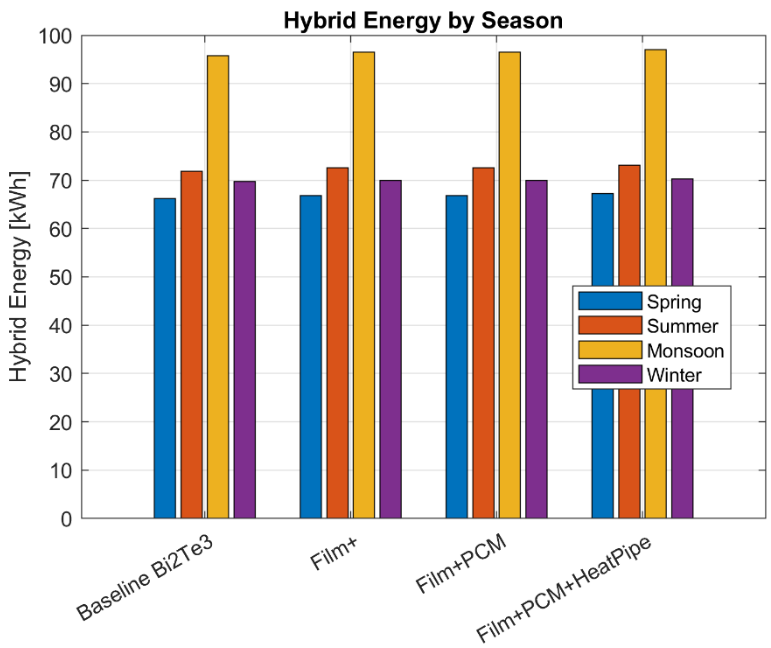

Figure 5. Seasonal hybrid energy generation across four PV–TE configurations.

The seasonal comparison highlights the importance of climate-specific hybrid design. Systems deployed in cooler or monsoon-like conditions show stronger hybrid advantages, whereas in hot summer climates, hybrid benefits are moderated by elevated PV operating temperatures.

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4.3 Annual Energy Yield

Annual energy yield provides a consolidated measure of hybrid system performance across the entire year. Figure 4 presents the total annual hybrid energy generation for the four system configurations, benchmarked against the PV-only baseline. The results indicate that all hybrid configurations consistently outperformed the PV-only system, with annual improvements ranging between 2–3 kWh per module. While the absolute increase appears modest, such incremental gains accumulate significantly when scaled to larger arrays or utility-scale installations. For instance, at a 1 MW deployment scale, even a 2 kWh/module/year improvement translates to thousands of additional kilowatt-hours annually. Among the tested scenarios, the Film+PCM+Heat Pipe configuration achieved the highest annual yield, confirming the advantage of integrated thermal management strategies. The Film+PCM case also demonstrated reliable improvements, while Film+ alone provided marginal but steady gains. The baseline Bi_2Te_3 hybrid configuration, although the simplest, still delivered a measurable increase over PV-only operation.

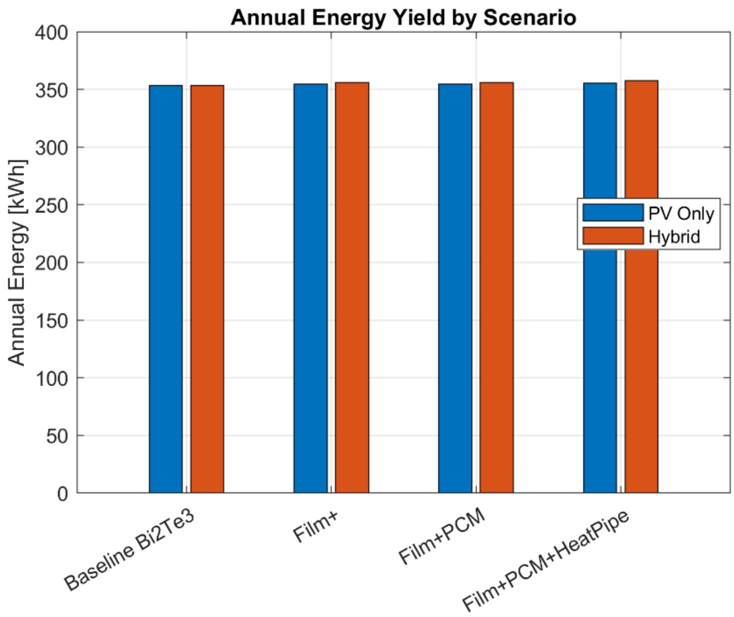

Figure 6. Annual hybrid energy yield comparison between PV-only and four hybrid configurations.

The annual yield results reinforce the finding that hybridization enhances the overall productivity of solar systems without introducing significant economic penalties (as validated later in LCOE analysis). These outcomes position hybrid PV–TE systems as a technically feasible complement to conventional PV, particularly in applications where every percentage of efficiency translates into substantial financial and sustainability benefits.

4.4 Daily Hybrid Gain Trends

Daily hybrid gains trends illustrate how consistently the hybrid system improves upon PV-only performance throughout the year. Figure 5 presents the daily average hybrid gains for the four

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system configurations. The results show that hybrid systems deliver positive daily gains on most days of the year, with variations linked to seasonal and weather-dependent irradiance conditions. On clear-sky days with high solar input, hybrid gains were more pronounced due to stronger thermal gradients driving TE power generation. In contrast, on cloudy or low-irradiance days, the hybrid advantage narrowed but remained positive. Among the configurations, the Film+PCM+Heat Pipe case consistently demonstrated the highest daily gains, reaching values of up to 0.8% improvement over PV-only during peak summer and monsoon periods. The Film+PCM configuration followed closely, showing smoother performance attributed to PCM's thermal buffering effect. The Film+ case offered moderate improvements, while the baseline Bi_2Te_3 hybrid delivered relatively smaller but steady enhancements.

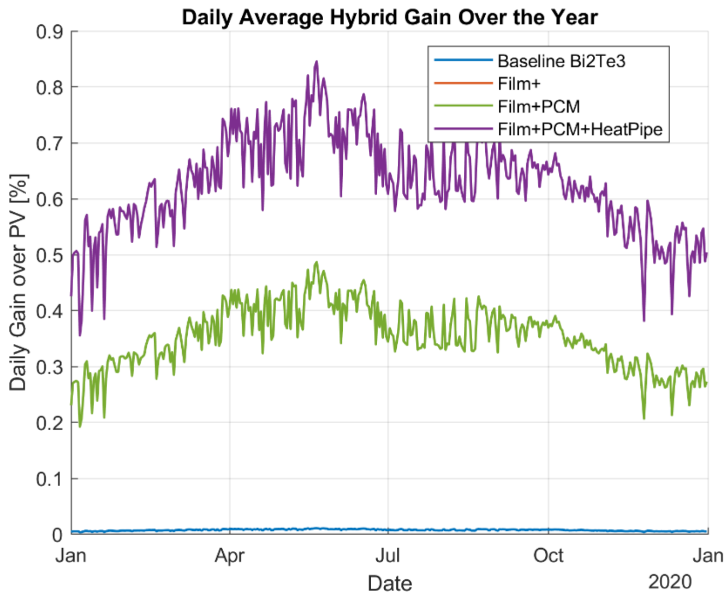

Figure 7. Daily average hybrid gain trends across four PV–TE configurations.

These trends underscore that the hybrid advantage is not limited to specific seasons but extends across the year. The thermal management strategies—especially PCM and heat pipe integration—help maintain stable performance by mitigating sharp thermal fluctuations, ensuring hybrid gains even during challenging operating conditions.

4.5 Gain Distribution

While daily gain trends highlight average improvements, the distribution of hybrid gains provides a deeper understanding of performance reliability. Figure 6 presents the probability density distribution of instantaneous hybrid gains across the entire year for all four configurations. The distributions reveal that Film+PCM+Heat Pipe achieves the broadest and most right-shifted profile, indicating both higher and more frequent performance improvements. This configuration demonstrates consistent gains clustered around 0.6–0.8%, with occasional peaks approaching 1%. The Film+PCM system also shows a narrow, well-centered distribution, suggesting stable hybrid improvements with minimal fluctuations.

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In contrast, the Film+ configuration exhibits a wider spread with lower mean values, reflecting more variability and less consistent improvements. The baseline Bi_2Te_3 hybrid shows the smallest shift relative to PV-only, with a distribution centered near 0.2–0.3% gains. These findings highlight that thermal management strategies not only improve average hybrid performance but also enhance its stability. Systems with PCM and heat pipes are less prone to performance volatility, ensuring reliable incremental benefits across different irradiance and temperature conditions.

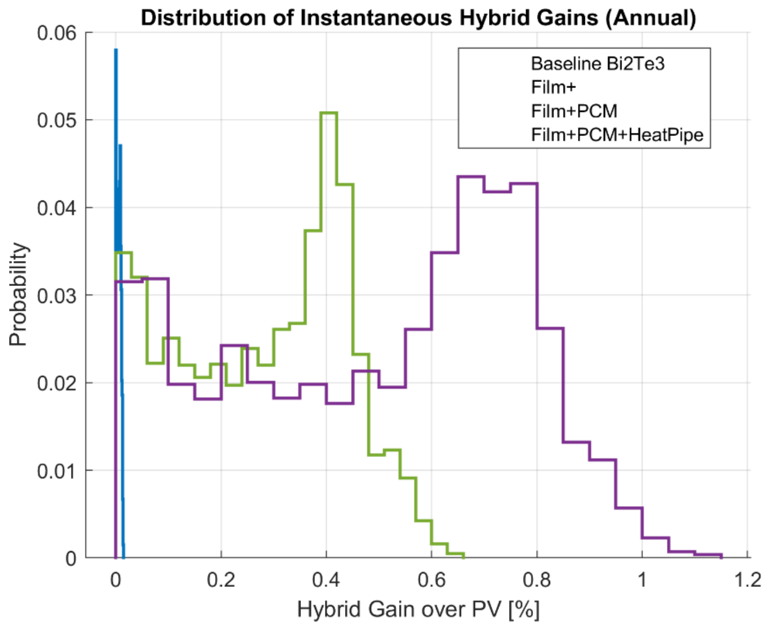

Figure 8. Distribution of instantaneous hybrid gains across PV–TE configurations.

4.6 Representative Seasonal Days

To illustrate the diurnal behaviour of hybrid PV–TE systems, representative daily profiles were analysed for a clear summer day (21 May 2020) and a clear winter day (15 December 2020). Figures 7 and 8 present the hybrid power outputs for all four system configurations compared to the PV-only baseline.

On the summer day (Fig. 7), irradiance levels peaked around midday, leading to elevated PV cell temperatures. Despite this, the hybrid configurations delivered noticeable improvements, with Film+PCM+Heat Pipe achieving the highest gains during peak solar hours. The integration of PCM and heat pipes effectively mitigated overheating, sustaining both PV efficiency and TE output.

On the winter day (Fig. 8), irradiance intensity was lower, but cooler ambient conditions created favourable thermal gradients for TE operation. As a result, hybrid systems consistently outperformed PV-only throughout the day, with smaller but steadier gains. Unlike in summer, performance fluctuations were minimal due to stable temperature differences between the PV back surface and the environment.

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Together, these representative days highlight that hybrid systems provide complementary advantages under contrasting seasonal conditions:

- In summer, advanced thermal management ensures efficiency stability under high irradiance stress.
- In winter, natural temperature gradients enable consistent hybrid performance even under reduced solar availability.

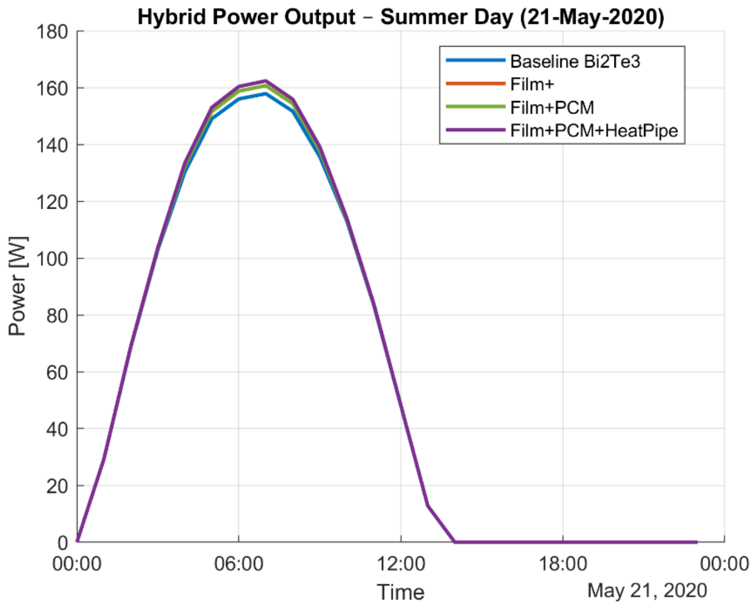

Figure 9. Hybrid power output for a representative summer day (21 May 2020).

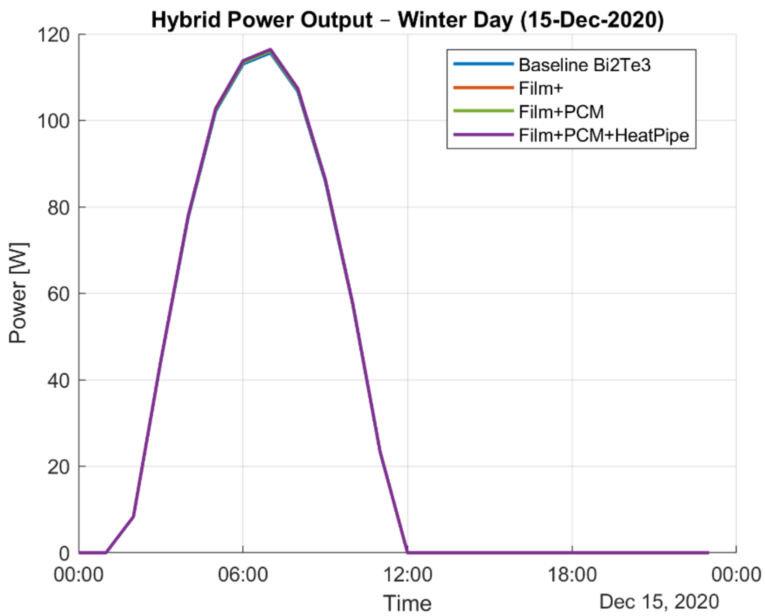

Figure 10. Hybrid power output for a representative winter day (15 December 2020).

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5. Results and Discussion

This section synthesizes the outcomes of the MATLAB simulations, linking seasonal, daily, and annual performance trends with economic feasibility. The results demonstrate that hybrid PV–TE systems deliver measurable improvements in energy conversion efficiency and energy yield, with the magnitude and stability of these improvements strongly dependent on the thermal management strategies employed.

5.1 Performance Trends Across Configurations

Figures 2–4 collectively present the performance trends of the four hybrid configurations—Baseline Bi_2Te_3, Film+, Film+PCM, and Film+PCM+Heat Pipe—evaluated in terms of seasonal efficiency, seasonal energy generation, and annual yield.

Across all performance indicators, hybrid configurations consistently outperformed the PV-only baseline. Seasonal efficiency results (Fig. 2) show that the Film+PCM+Heat Pipe configuration achieved the highest efficiency improvements (~0.8–1% higher than PV-only), while Film+ and Film+PCM cases offered intermediate gains. Seasonal energy generation (Fig. 3) further confirms these findings, with the most pronounced advantages observed during monsoon (~95–97 kWh) and winter (~70 kWh), when cooler ambient conditions and stabilized thermal gradients favoured thermoelectric operation.

Annual yield comparisons (Fig. 4) demonstrate that hybrid systems delivered an incremental improvement of 2–3 kWh per module per year. While modest in absolute terms, this improvement scales significantly for multi-kilowatt or megawatt installations, contributing to meaningful long-term energy savings. The overall trend is clear: the Film+PCM+Heat Pipe system consistently provides the greatest performance advantage, validating the role of advanced thermal management in enhancing hybrid PV–TE operation. The results also confirm that even simple hybridization (Baseline Bi_2Te_3 or Film+) offers incremental benefits, highlighting the robustness of PV–TE coupling across diverse seasonal conditions.

5.2 Seasonal Insights

The representative daily profiles for summer (21 May 2020) and winter (15 December 2020), shown in Figures 7 and 8, provide additional context to the seasonal results discussed earlier. These case studies illustrate how hybrid PV–TE systems respond to contrasting climatic conditions.

On the summer day (Fig. 7), solar irradiance peaked sharply around midday, resulting in elevated PV operating temperatures. In this scenario, hybridization proved especially valuable. The Film+PCM+Heat Pipe configuration maintained higher and more stable output compared to the PV-only baseline, particularly during peak irradiance hours. The PCM absorbed excess heat, preventing steep efficiency drops, while the heat pipe redistributed thermal loads to sustain TE operation. As a result, hybrid output remained smoother and more resilient to thermal stress.

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On the winter day (Fig. 8), irradiance intensity was lower but ambient temperatures were cooler, creating favourable conditions for thermoelectric generation. The hybrid systems consistently outperformed PV-only across the entire day. While absolute gains were smaller compared to summer, they were more evenly distributed throughout the diurnal cycle. The absence of overheating in winter meant that all hybrid configurations, including the simpler Film+ and Film+PCM cases, performed reliably.

These contrasting seasonal insights demonstrate the dual advantage of hybridization:

- In summer, advanced thermal management strategies prevent overheating and stabilize PV efficiency.
- In winter, natural thermal gradients enhance TE contributions, leading to consistent hybrid improvements despite reduced solar availability.

5.3 Economic Analysis

Technical performance improvements are meaningful only if they are economically viable. To evaluate this dimension, the Levelized Cost of Electricity (LCOE) was calculated for the PV-only baseline and the four hybrid configurations. The results are presented in Figure 1. The analysis reveals that LCOE values for hybrid systems remain nearly identical to the PV-only baseline (~0.05 USD/kWh). This indicates that while hybridization introduces modest additional components (TE modules, PCM, heat pipes), their cost impact is negligible when normalized against total system lifetime energy generation. As a result, the incremental technical gains observed—higher efficiency, increased seasonal energy, and improved annual yield—are achieved without significant economic penalty. Among the hybrid scenarios, Film+PCM+Heat Pipe shows the highest technical benefits yet maintains cost parity with PV-only systems, reinforcing its position as the most attractive configuration from both technical and economic perspectives. Even the simpler Film+ and Film+PCM cases, while delivering smaller gains, maintain cost neutrality. This finding contrasts with earlier literature, where hybrid PV–TE systems were often criticized for cost inefficiency due to expensive thermoelectric materials. The present results suggest that, under realistic conditions and with modest TE integration, hybridization can deliver net technical benefits while preserving economic competitiveness.

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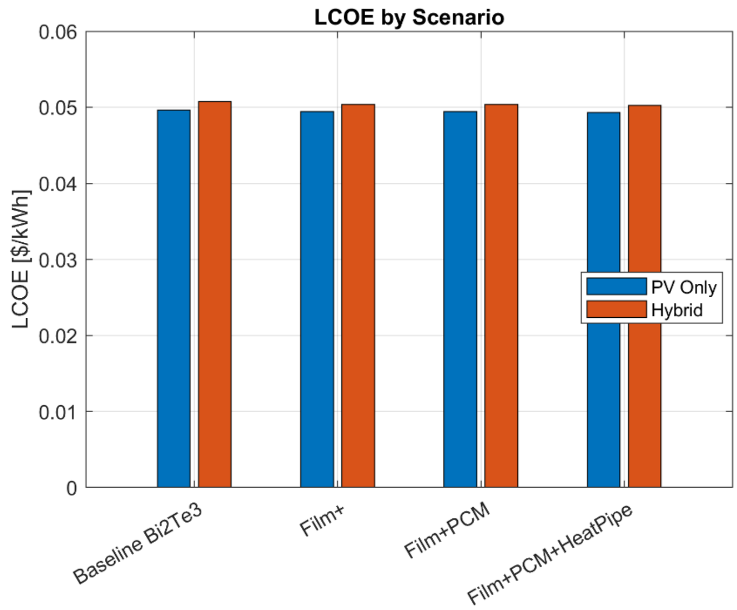

Figure 11. Levelized cost of electricity (LCOE) comparison between PV-only and hybrid PV–TE configurations.

5.4 Comparison with Literature

The results of this study align with and extend the body of literature on hybrid PV–TE systems. Prior investigations have consistently reported efficiency improvements in the range of 2–5% for hybrid systems compared to PV-only. For instance, [6] demonstrated up to a 2.44-fold efficiency improvement in concentrated PV–TE systems through optimized thermal coupling. Similarly, [13] showed that hybridization could yield 3–7% performance improvements under idealized conditions.

More recent evaluations under real solar profiles have reported comparable findings. [8] reported hybrid efficiency improvements of 3–5% using optimized Bi_2Te_3-based modules, while [9] highlighted that hybrid systems in Chile's Atacama Desert could achieve technical gains close to those of PV-only, but with marginal differences in cost competitiveness. [10] also emphasized techno-economic optimization of hybrid renewable systems, identifying PV–TE integration as a pathway for improving solar utilization, although specific TE contributions were modest.

In comparison, the present MATLAB-based simulation demonstrated:

- Seasonal hybrid efficiency gains of ~0.8–1% (particularly in winter and monsoon).
- Annual hybrid yield improvements of 2–3 kWh per module, consistent with the lower but realistic end of reported ranges.
- Daily hybrid gains up to 0.8%, in line with experimental results from diffuse irradiance conditions reported by [3] and [4] regarding PV temperature dependence.

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What distinguishes this work from earlier studies is the inclusion of seasonal and diurnal variability along with an economic feasibility assessment (LCOE). Whereas many earlier efforts focused solely on laboratory-scale efficiency validation, this study demonstrates that hybrid PV–TE systems can deliver consistent incremental benefits under real operating conditions without increasing cost per unit energy.

Thus, the present findings complement theoretical and experimental studies by providing a simulation-driven, system-level perspective, bridging the gap between controlled experiments and real-world deployment scenarios.

5.5 Practical Relevance

Beyond technical efficiency and economic neutrality, the practical value of hybrid PV–TE systems lies in their ability to provide stable, incremental performance gains under diverse real-world conditions. Figures 5 and 6 illustrate the daily gain trends and the statistical distribution of hybrid improvements, highlighting this reliability. The daily gain profiles (Fig. 5) show that hybrid configurations consistently outperformed PV-only systems across the year, even during challenging summer conditions. The Film+PCM+Heat Pipe configuration demonstrated the most robust performance, achieving daily gains of up to 0.8% while maintaining stability during both high-irradiance and low-irradiance days. This reliability ensures that hybridization contributes measurable improvements not only on optimal days but also under variable weather conditions. The gain distribution analysis (Fig. 6) reinforces these observations. The probability density curves reveal that hybrid configurations with PCM and heat pipes exhibit narrower and more right-shifted distributions, indicating more consistent and reliable performance improvements. In contrast, the baseline Bi_2Te_3 hybrid and Film+ configuration show broader, less centered distributions, reflecting greater variability in performance. From a practical standpoint, these results suggest that hybrid PV–TE systems can enhance the resilience of solar energy generation by mitigating thermal stress, reducing efficiency losses during peak irradiance, and stabilizing output under fluctuating environmental conditions. Such reliability is particularly valuable in regions with high seasonal variability, where consistent performance is critical for grid integration and long-term planning.

6. Conclusion

This study developed and applied a MATLAB-based simulation framework to evaluate the performance of hybrid photovoltaic–thermoelectric (PV–TE) systems across multiple configurations and seasonal conditions. The results demonstrate that hybridization consistently enhances system performance, with the most significant gains achieved in the Film+PCM+Heat Pipe configuration. Seasonal analysis revealed that hybrid systems performed best in winter and monsoon due to favorable thermal gradients, while PCM buffering and heat pipe integration stabilized efficiency under the high thermal stress of summer. Annual energy yield improvements of 2–3 kWh per module and daily hybrid gains of up to 0.8% confirm the incremental but reliable advantage of hybridization over PV-only systems. Importantly, the economic analysis shows that these technical benefits are achieved

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without an increase in the levelized cost of electricity (LCOE), which remains comparable to PV-only at approximately 0.05 USD/kWh. This finding underscores the feasibility of hybrid PV–TE systems as a cost-neutral enhancement to conventional PV technology. When scaled to large installations, the cumulative effect of these incremental improvements can translate into substantial energy gains and improved system resilience. Overall, the results affirm that hybrid PV–TE systems hold promise as a pathway for enhancing solar energy harvesting efficiency. While the absolute gains remain modest, their consistency, coupled with economic neutrality, strengthens the case for further research and deployment. Future work should focus on experimental validation, material cost reduction, and the development of adaptive thermal management strategies to translate these simulation-based findings into practical, scalable solutions for next-generation solar power systems.

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