

Performance optimization of nanofluid-cooled photovoltaic-thermoelectric systems: A study on geometry configuration, steady-state and annual transient effects

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ABSTRACT

In this study, we explored Photovoltaic-Thermoelectric (PV-TE) systems in-depth, addressing complexities in both steady-state and annual transient performance under realistic conditions. The analysis involved twelve distinct PV-TE configurations featuring diverse thermoelectric designs incorporating various semiconductors, multi-staging, non-uniform cross-sections, and material segmentation. Model 6, the PV-TE system with a multi-stage segmented rectangular design, emerged as the top performer, exhibiting a remarkable 12% increase in electric power output during peak sunlight compared to the base model, despite a marginal decrease in efficiency. Furthermore, this research delved into the potential of advanced nanofluid cooling, investigating options such as distilled water, titanium oxide, aluminum oxide, iron oxide, and graphene. The results underscored graphene nanofluid's superiority, demonstrating a significant enhancement in thermal management at an optimal flow velocity of 2 m/s. This improvement in thermal management refers to the effective heat dissipation and temperature control within the PV-TE system. This study underlines the critical role of strategic system design and component selection in optimizing the performance of PV-TE systems. By providing a comprehensive foundation for future developments in effective and sustainable energy solutions, this research contributes to advancing the understanding and implementation of PV-TE technology.

1. Introduction

With an escalating global population inching toward 7.9 billion, the energy sector finds itself in a predicament as it strives to meet the soaring demands. The gradual depletion of conventional energy sources and the environmental toll they exact highlight the urgency to transition towards more sustainable alternatives. Solar energy, a bountiful and environmentally benign resource, has emerged as a frontrunner in this endeavor. Harnessing the sun's energy has been an area of interest since the 7th century B.C., when magnifying glasses were used to concentrate

the sun's rays to make fire [1]. Today, solar energy has evolved exponentially and has been recognized as pivotal in tackling not only energy scarcity but also in combating climate change. The potential of solar energy is immense; the sunlight that reaches Earth in just 1 h is sufficient to meet global energy needs for an entire year [2]. The evolution of solar technology has been remarkable, and its significance in the contemporary energy landscape cannot be overstated.

As the global community marches towards adopting solar energy, the role of innovation in solar technologies becomes paramount. The development of solar technology has historically been guided by efforts to increase efficiency and reduce costs. The first silicon solar cell,

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Nomenclature	
<i>Abbreviations</i>	
PV	Photovoltaic
TE	Thermoelectric
PV – TE	Photovoltaic-Thermoelectric
Si-PV	Silicon Photovoltaic
TEG	Thermoelectric Generator
EVA	Ethylene Vinyl Acetate
TPT -	Tedlar Polyester Tedlar
W	Watt
K	Kelvin
IoT	Internet of Things
CPV	Concentrated Photovoltaic
SiO ₂ -	Silicon dioxide
Fe ₃ O ₄	Iron oxide
TiO ₂	Titanium oxide
Al ₂ O ₃	Aluminum oxide
ND-Co3O4	Nanodiamond-cobalt oxide
FEM	Finite Element Model
Model 1	Photovoltaic single-stage rectangular bismuth-telluride thermoelectric generator
Model 2	Photovoltaic single-stage rectangular skutterudite thermoelectric generator
Model 3	Photovoltaic single-stage segmented rectangular thermoelectric generator
Model 4	Photovoltaic multi-stage rectangular bismuth-telluride thermoelectric generator
Model 5	Photovoltaic multi-stage rectangular skutterudite thermoelectric generator
Model 6	Photovoltaic multi-stage segmented rectangular thermoelectric generator
Model 7	Photovoltaic single-stage trapezoidal bismuth-telluride thermoelectric generator
Model 8	Photovoltaic single-stage trapezoidal skutterudite thermoelectric generator
Model 9	Photovoltaic single-stage segmented trapezoidal thermoelectric generator
Model 10	Photovoltaic multi-stage trapezoidal bismuth-telluride thermoelectric generator
Model 11	Photovoltaic multi-stage trapezoidal skutterudite thermoelectric generator
Model 12	Photovoltaic multi-stage segmented trapezoidal thermoelectric generator
SSR –	Single-stage rectangular
BiTe –	Bismuth-telluride
SKT –	Skutterudite
SST –	Single-stage trapezoidal
MSR –	Multi-stage rectangular
MST –	Multi-stage trapezoidal
SSSR –	Single-stage segmented rectangular
SSST –	Single-stage segmented trapezoidal
MSSR –	multi-stage segmented rectangular
MSST –	Multi-stage segmented trapezoidal
NASA -	National aeronautics and space administration
MERRA -	Modern-era retrospective analysis for research and applications
GEOS -	Goddard earth observing system
CAMS -	Copernicus atmosphere monitoring service
<i>Symbols</i>	
T_{PV} –	PV cell temperature
P_{TE} –	Thermoelectric power efficiency
P_{PV} –	PV Power
(P_{PV-TE}) –	PV – TE power
$\eta_{(PV-TE)}$ –	PV – TE efficiency
α –	Seebeck coefficient
η_{TE} –	Thermoelectric Efficiency
κ -	thermal conductivity ($W \cdot m^{-1} K^{-1}$)
ν -	kinematic viscosity ($m^2 \cdot s^{-1}$)
ρ –	density ($kg \cdot m^{-3}$)
C_p -	specific heat ($J \cdot kg^{-1} K^{-1}$)
Nu -	Nusselt number
h -	Heat transfer coefficient
Pr -	Prandtl number
Re -	Reynolds number
l -	Characteristic length
C -	Solar concentration ratio

invented in 1954, had an efficiency of about 6% [3]. Modern solar panels, thanks to relentless innovation, can now convert more than 20% of sunlight into electricity [4]. Such innovations have been pivotal in making solar energy increasingly cost-competitive with conventional energy sources. This competitive edge is essential as it influences policy-making, promotes investment in solar projects, and paves the way for a more sustainable energy infrastructure globally. Advancements in materials, manufacturing processes, and system designs have proven to be crucial in this regard. Furthermore, integration with emerging technologies like energy storage, smart grids, and the Internet of Things (IoT) lends solar energy systems the agility and responsiveness required in a dynamic energy market.

While solar energy holds a promise for a greener future, it is not without its challenges. One of the inherent limitations of solar photovoltaic cells is their sensitivity to temperature. As the temperature rises, the efficiency of solar cells tends to decline [5]. This is particularly concerning in regions with high solar insolation, where the solar cells can get exceedingly hot during peak hours. Furthermore, the intermittent nature of solar energy necessitates effective energy storage and management solutions to ensure a reliable power supply. Additionally, optimizing the conversion of solar energy is paramount to extracting the maximum possible energy from the available sunlight. Innovative approaches such as Concentrating Solar Photovoltaic-Thermoelectric

(PV-TE) systems have emerged to tackle these challenges. By combining photovoltaic cells with thermoelectric materials, these systems aim to harness both electrical and thermal energy from sunlight, potentially overcoming some of the limitations of conventional solar cells.

Over the last few years, the confluence of PV and TE technologies has gained considerable scholarly attention as a potential strategy for enhancing solar energy conversion efficiency. Hybrid PV-TE systems, with their unique ability to concurrently generate electricity and heat, have become the focus of numerous pioneering investigations. For instance, Zhang and Xuan [6] constructed a PV-TE system that prioritized minimizing heat losses, a strategy that precipitated a marked improvement in overall system efficiency. In a separate investigation, Alghamdi et al. [7] scrutinized the implications of employing a variety of thermoelectric materials in hybrid PV-TE systems, highlighting the significant role that material selection plays in these systems' performance. Further contributing to this dynamic field of study, Shittu et al. [8] embarked on the optimization of the geometrical configurations of PV-TE systems (focusing specifically on rectangular and trapezoidal designs) and evaluated their performance under an entire day's weather conditions. Such studies typically employed the direct coupling method, wherein the Thermoelectric Generator (TEG) module is directly affixed to the PV module's backplate using a thermally conductive material,

thereby enabling maximum thermal energy transfer from the PV to the TEG. This configuration capitalizes on the PV module's ability to utilize visible light and ultraviolet components of solar energy, while directing the infrared component straight to the TEG. Adopting a divergent approach, Yin and Li [9] addressed the pressing issue of significant electrical loss in PV-TEs by implementing a parallel connection strategy. Similarly, Liu et al. [10] explored the bending stresses in curved PV-TEs and optimized the power output and efficiency of these flexible systems, designed for various curved surfaces. Wang et al. [11] developed an intelligent, multiplex thermal management system for high-efficiency PV-TE solar energy conversion. Lastly, Azimi et al. [12] sought to bolster PV-TE performance by employing ultrasonic TEGs that used ultrasound technology to induce cold vapor on the TEG's cold junction, thereby enhancing its thermal gradient.

Nanofluids, which are engineered colloidal suspensions of nanoparticles in a base fluid, have gained prominence as a thermal management solution in energy systems, particularly solar technologies [13]. Their enhanced thermal properties, such as high thermal conductivity and heat transfer coefficients, make them well-suited for cooling applications in photovoltaic and thermoelectric systems [14]. The incorporation of nanofluids into PV-TE systems presents a unique opportunity to combat the heat-related performance issues that traditionally plague these systems [15]. For instance, nanofluids can help in reducing the photovoltaic cell temperature, thus mitigating efficiency losses that arise from increased temperatures [16]. Furthermore, by enhancing heat absorption and transfer capabilities, nanofluids can contribute to augmenting the thermoelectric side of PV-TE systems [17]. In recent years, researchers have directed significant investigative energy towards optimizing the thermal performance of nanofluids within hybrid systems [18]. A pivotal part of these explorations involves the meticulous examination of a variety of nanoparticle materials and concentration levels. In one noteworthy study, Rejeb et al. [19] performed a comparative performance analysis between a stand-alone Concentrated Photovoltaic (CPV) and a CPV-Thermoelectric (TE) hybrid system, both cooled with graphene nanofluid. Remarkably, the systems operated under the peculiarities of London's daily transient weather data, facilitating a more nuanced understanding of their performance under real-world conditions. In another distinctive inquiry, Soltani et al. [20] conducted indoor environmental tests on a PV-TE system cooled by different nanofluids, including water, air, SiO_2 , and Fe_3O_4 . Their research underscored the superior thermal management capabilities of the SiO_2 blend, which yielded the maximum energy efficiency at a solar irradiance of 900 W/m^2 , whereas air cooling trailed behind as the least effective cooling agent. Khalili and Sheikholeslami [21] examined the impact of a confined jet impingement heat sink on PV-TE efficiency while utilizing $\text{ND-Co}_3\text{O}_4$ nanofluids, broadening the scope of nanofluid-related investigations. Furthermore, Ahmadi et al. [22] undertook an experimental study of a PV-TE system integrated with carbon nanotubes nanofluids. This system operated under the Iranian climate's unique conditions, and its performance was evaluated on a transient basis from 10 a.m. to 4:30 p.m. in November. In a more recent experimental investigation, Praveenkumar et al. [23] assessed the thermo-enviro-economic performance of various systems, namely solar PV, PV/Thermal with water, and a PV/Thermal-TE system employing Al_2O_3 nanofluid. This comprehensive analysis concluded that the PV/Thermal-TE system with nanofluids outperformed the others, resulting in a 41.2% temperature drop in the reference PV, while simultaneously increasing its efficiency by 8.5%. Such findings underscore the promising potential of nanofluids in enhancing the performance of PV-TE systems.

An essential component of PV-TE systems is the thermoelectric device, whose configuration significantly affects the performance and efficiency of the system. In literature, researchers have examined various configurations including semiconductor diversification [24], segmentation [25], multi-staging [26], and non-uniform cross-sections [27]. Segmentation involves dividing the thermoelectric legs into sections

with different thermoelectric materials [28], which can be optimized for different temperature ranges [29]. Multi-staging is another approach where several thermoelectric modules are stacked on top of each other to handle a wide range of temperature differences, often leading to enhanced performance [30]. On the other hand, employing non-uniform cross-sections/variable area leg geometry involves changing the cross-sectional area of the thermoelectric legs, which can be optimized for improved performance under different operational conditions [31]. However, each of these configurations comes with its own set of challenges, and finding an optimal configuration for specific applications and environments remains an area of active research. Recent advancements in the structural optimization of Thermoelectric Generator (TEG) configurations within Photovoltaic-Thermoelectric (PV-TE) systems for maximum performance are multifaceted and intriguing. He et al. [32] have made significant strides in this area, conducting a comprehensive structural parametric analysis to discern optimal conditions for peak PV-TE performance, particularly when incorporated with phase change materials in space applications. Cui et al. [33] delved into the efficacy and lifespan of a PV-TE system featuring a segmented materials design in the TEG. Their findings pointedly underscored the superiority of the segmented design over conventional bismuth-telluride based modules when incorporated in PV-TE systems. Taking cues from these insights, Maduabuchi et al. [34] utilized a synthesis of three-dimensional finite element models and multi-layered neural networks to optimize and predict the power and efficiency of segmented PV-TE systems under the monthly-average transient real weather conditions of South-Eastern Nigeria. Zhao et al., in their seminal work [35], demonstrated the remarkable potential of hybrid PV-TE systems with multi-stage designs. Their research indicated a significant enhancement of power density and energy efficiency, outperforming the traditional model by 4.33% and 64.25% respectively. Responding to these compelling results, Maduabuchi et al. [36] extended their investigation, revealing the thermal stress increase in PV-TE systems induced by the adoption of multi-stage designs. However, their research also elucidated a promising mitigation strategy: implementing circular cross-section thermoelements could significantly alleviate these detrimental stresses. Overall, these studies represent an exciting evolution in the understanding of PV-TE system optimization.

The existing body of literature in the field of photovoltaic-thermoelectric (PV-TE) systems, while expansive, reveals significant areas of opportunity that remain relatively unexplored. Three principal gaps emerge that limit the understanding and subsequent optimization of these systems: (1) the role of thermal management in PV-TE systems, specifically nanofluid-cooled ones, (2) the oversight of diverse thermoelectric generator (TEG) designs and their impacts on the system's performance, and (3) the scarcity of robust assessments conducted under realistic annual environmental conditions.

- First, the majority of current research into PV-TE systems focuses primarily on power generation, often overlooking the critical role of thermal management. Despite recent expansions in nanofluid-cooled PV-TE system research, there is a substantial deficiency in exploring the potential benefits of nanofluids in augmenting thermal performance and subsequently, the overall efficiency of the systems.
- Second, the evaluation of TEG designs and their effects on the performance of PV-TE systems is limited in scope. Most studies focus on commercially available TEG modules, predominantly bismuth-telluride semiconductors with a uniform cross-section. This approach neglects the latest advancements in TEG designs, including multi-staging, semiconductor diversification, segmentation, and non-uniform cross-section arrangements. Furthermore, a comprehensive investigation into the combined effects of these novel TEG architectures on the overall performance of the system is glaringly absent.
- Finally, the underrepresentation of real-time environmental impact evaluations is palpable. Most studies offer analyses under idealized

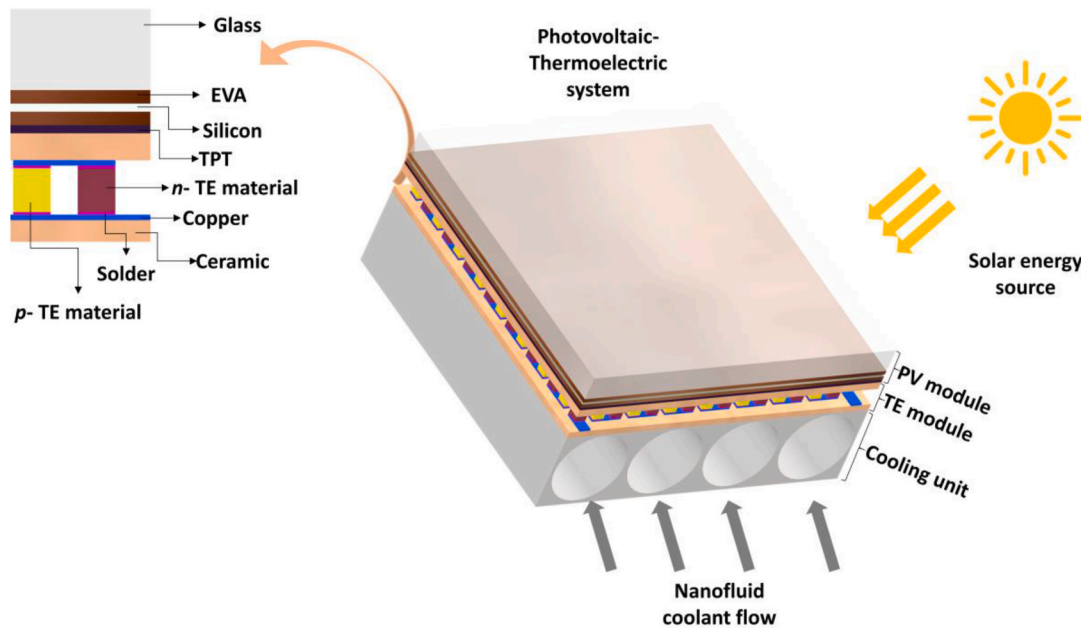


Fig. 1. Pictorial description of the solar PV-TE.

or simplified conditions, failing to account for the influence of real-time environmental dynamics on system performance. Thus, a pressing need exists for comprehensive analyses that not only examine the material properties but also consider the real-time environmental conditions on an annual basis.

This study addresses these gaps by integrating comprehensive explorations and assessments into a cohesive research approach:

- ✓ First, the study delves into the realm of thermal management by examining the use of nanofluids in the cooling of PV-TE systems, offering a nuanced understanding of their potentials and challenges.
- ✓ A systematic investigation on multiple TEG designs, incorporating advancements such as multi-staging, segmentation, non-uniform cross-section, and variant semiconductor architectures is carried out. The work evaluates the separate and combined impacts of these designs on power generation and energy efficiency, thereby offering a comprehensive understanding of PV-TE system performance.
- ✓ Moreover, this approach places considerable emphasis on practical applicability. An annual assessment of transient real-weather performance is undertaken for a nanofluid-cooled concentrating solar PV-TE system. By considering twelve possible combinations of state-of-the-art TEG models, the analysis not only provide a comprehensive performance assessment but it also establishes the groundwork for further exploration into hybrid designs.

In summary, this study bridges the current gaps in the literature by providing a comprehensive examination of the PV-TE systems. It offers new insights into thermal management with nanofluids, extensively investigate the impacts of various TEG designs on system performance, and provide a comprehensive performance analysis under realistic environmental conditions.

The observed literature gaps and this study contributions are summarized as:

1. **Gap:** Limited focus on thermal management in PV-TE systems.

Contribution: Explores the use of nanofluids for thermal management, offering an in-depth analysis of their benefits and challenges.

2. **Gap:** Overlook of diverse TEG designs and their impact on system performance.

Contribution: Comprehensive evaluation of multiple state-of-the-art TEG designs, including multi-staging, segmentation, non-uniform cross-section, and variant semiconductor arrangements.

3. **Gap:** Scarcity of robust assessments conducted under realistic annual environmental conditions.

Contribution: Conducts an annual transient real-weather performance evaluation of a nanofluid-cooled concentrating solar PV-TE system with various device designs.

This paper is organized as follows: [Section 2](#) presents a detailed description of the concentrating solar PV-TE system, the various thermoelectric device configurations, and the nanofluids used for cooling. It also elucidates the mathematical models and simulation techniques employed. Further, the annual transient real-weather conditions and the methodology used for simulating the performance of the PV-TE system under these conditions are delineated. The performance results and analysis, with a focus on elucidating how different device designs and thermoelectric configurations influence the performance of the system, are discussed in [Section 3](#). Additionally, a critical analysis, comparing the results obtained in this study with those from existing literature and highlighting the novel contributions of this work is presented. Finally, [Section 4](#) concludes the paper with a summary of key findings, practical implications, and suggestions for future research in this domain.

2. Methodology

The upcoming Methodology section outlines the intricate procedures and robust analyses implemented in this in-depth study of the hybrid photovoltaic-thermoelectric (PV-TE) systems.

The section initiates with a thorough description of the diverse PV-TE models that serve as the basis for this study. It elucidates the unique architecture of each model, providing a framework to understand the different scenarios of energy conversion and heat transfer.

Thereafter, diving into the mathematical underpinnings of this study explaining the essential physics of the PV and TE systems by outlining the equations and conditions that control them, establishing the basis for

Table 1

Components of the PV-TE and their respective dimensions [36–38].

S/N	Component	Thickness (mm)
TEG module		
1.	Ceramic	0.8
2.	Copper	0.2
3.	Solder	0.1
4.	TE leg	1.62
PV module		
1.	Glass	3
2.	EVA	0.5
3.	Silicon	0.3
4.	TPT	0.3

the computational method.

This is followed by the exposition of the computational strategies, including Finite Element Modeling (FEM) and mesh generation techniques. The purpose is to highlight the precision of numerical methods and the convergence study, thereby assuring the reliability of these simulations.

The section then progresses to an analysis of the cooling systems, addressing both passive and active cooling approaches. It elaborates on the role of nanofluids and airflow velocity, acknowledging their significant impact on the heat management and overall performance of the PV-TE system.

Finally, the method employed to investigate the impact of transient weather conditions on the system's performance is introduced. This analysis enables the understanding of the system's adaptability to environmental variations.

In essence, the Methodology section presents a comprehensive blueprint of the techniques and analyses employed in the exploration of PV-TE systems, offering a pathway to replicate or further advance this research.

2.1. Design and construction of the nanofluid-cooled PV-TE system

Fig. 1 presents a comprehensive three-dimensional visualization of the photovoltaic-thermoelectric (PV-TE) system under exploration in this study. Modeled after the commercially available Kryotherm TGM 127-1.4-2.5 module, the thermoelectric generator (TEG) module's dimensions replicate the 40 mm × 40 mm surface area characteristic of the conventional module. Each component of both the TEG and PV systems

boasts thicknesses as detailed in Table 1.

The TEG structure encompasses a total of 127 thermocouples in each stage, adhering to a uniform cross-sectional area of 1.4 mm × 1.4 mm for all semiconductors. In contrast, the non-uniform cross-sectional area is realized through a reduced cross-section of 0.7 mm × 0.7 mm at the opposing surface.

The heat source originates from solar energy, amplified by suitable concentration technology—such as an optical concentration ratio or a Fresnel lens—which effectively magnifies the solar irradiance. This concentrated solar irradiance subsequently impinges on the surface of the PV top glass.

The PV system assimilates the ultraviolet and visible light components of the solar irradiance, transforming it into electrical energy through the photovoltaic effect. However, the unutilized infrared components, which typically induce heating and subsequently reduce the system's efficiency, are redirected to the TEG's top ceramic plate via a conductive layer.

The TEG then utilizes this redirected infrared energy, converting it into electrical energy via the Seebeck effect, which refers to the direct conversion of temperature differences into electricity. This conversion process enhances the system's power generation and efficiency by tapping into an energy stream usually considered waste.

Nanofluids serve as the backbone of the TEG's thermal management strategy, being strategically attached to the TEG's cold junction. These nanofluids provide enhanced cooling for the TEG, augmenting its rate of heat extraction from the PV cell's backplate. This heat management strategy contributes to the concurrent improvement of the power generation rate and overall efficiencies of the PV-TE system.

For a comprehensive understanding of the PV-TE system's structural parameters, refer to Table 1, which details the thickness of each integral component of the system. This documentation serves as a pivotal resource in elucidating the structure-function relationships that drive the system's performance.

2.2. Unveiling novel system architectures for enhanced PV-TE performance

This portion of the methodology unveils a thorough investigation into the plethora of TEG system architectures. Motivated by recent advancements and the proliferation of bespoke modules in the literature, the endeavor involves embarking on a journey that embraces an array of

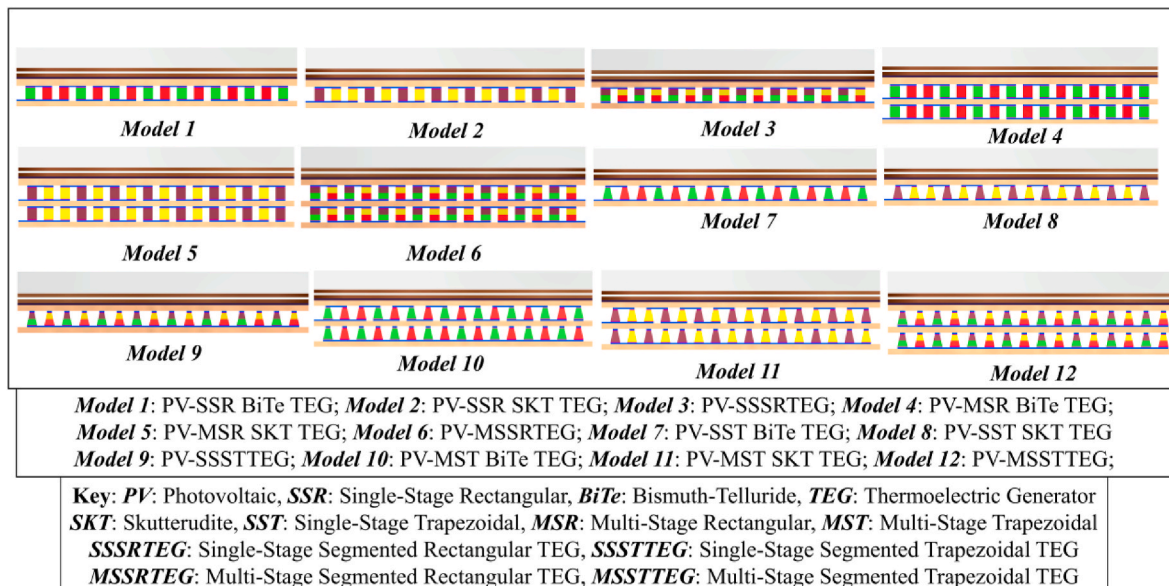


Fig. 2. Visual representation of the systems considered in this study.

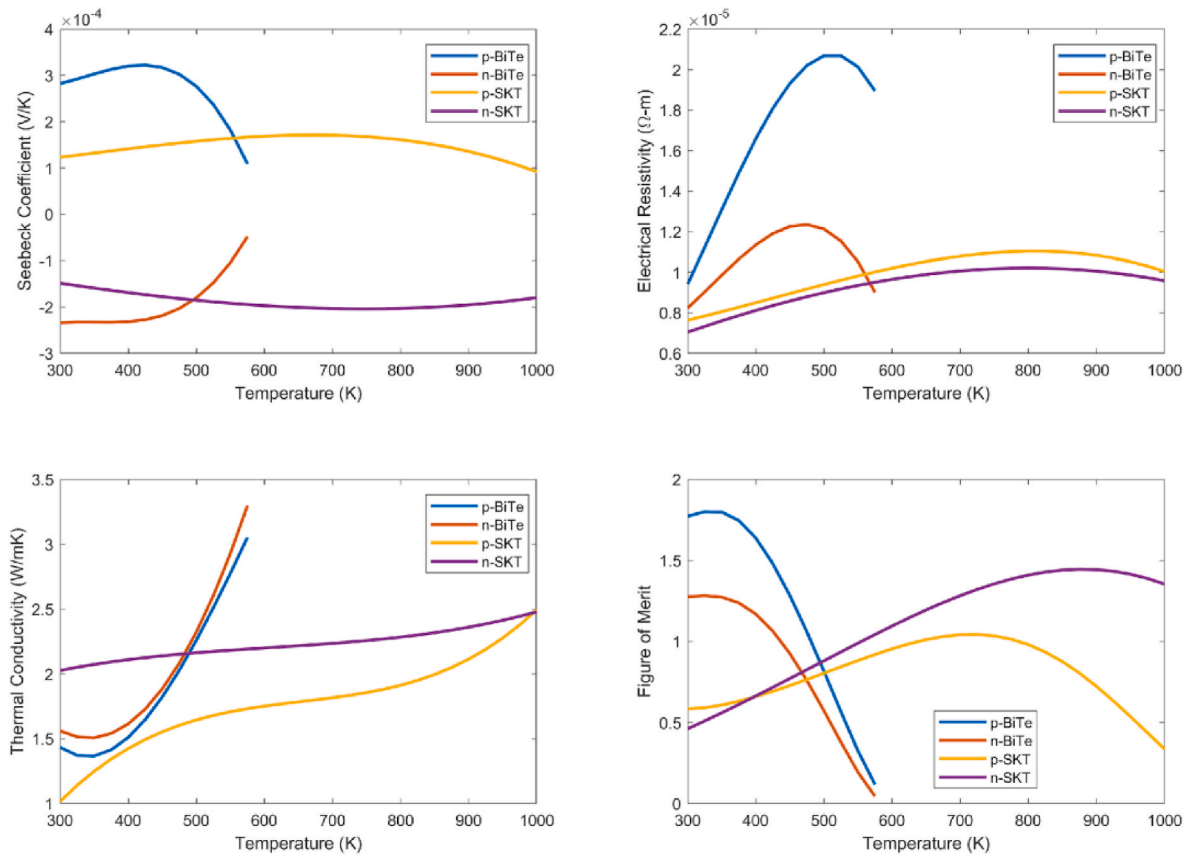


Fig. 3. Temperature-dependent material properties of the TE semiconductors [29].

Table 2

Material properties used in simulation [29,41].

Material	Density (kg/m ³)	Specific Heat Capacity (J/(kg·K))	Thermal Conductivity (W/(m·K))	Electrical Conductivity (S/m)
TEG module				
Ceramic	3970	800	25	1×10^{-12}
Solder	7240	210	55	2×10^7
Copper	8930	386	385	5.9×10^7
Bi ₂ Te ₃	7740	154.4	$\lambda(T)$	$\sigma(T)$
Skutterudite	6800	225	$\lambda(T)$	$\sigma(T)$
PV module				
Silicon	2330	2090	130	—
TPT	1200	1250	0.15	—
EVA	960	2090	0.311	—
Glass	2450	500	2	—

pioneering designs. This extensive exploration encompasses architectures utilizing a diversity of thermoelectric (TE) semiconductors, non-uniform cross-section semiconductors [39], segmented TE semiconductors [40], as well as multi-staged or cascaded system designs.

This research shows a group of twelve different TEG system designs, including uniquely conceived designs such as models 6 and 12, which amalgamate features like material segmentation, multi-staging, and non-uniform cross-sections, clearly depicted in Fig. 2. These models explore new areas that haven't been fully explored in existing literature.

Exploring new and different directions that have not been explored in past research, this study, bolstered by robust computational servers, allows the examination of a multitude of thermocouples. The interactions between the temperature and electric fields of the 127 thermoelectric semiconductors in each stage are meticulously analyzed across all TEG models. This exhaustive approach generates a holistic and real-life simulation of the PV-TE, offering an unprecedented level of

understanding.

The TE materials selected for this study include bismuth-telluride and skutterudite, serving as the high and low-temperature segments, respectively. To closely mimic the real-world behavior of TEG modules, consideration is given to temperature dependency across all thermoelectric couples within the module. The evolution of the TE material properties with temperature is lucidly plotted and illustrated in Fig. 3. For the sake of transparency and reproducibility, the thermal properties of all components of the PV-TE system are provided in Table 2.

The pursuit of these novel system architectures serves a dual purpose. Initially, it allows a comprehensive thermal analysis, evaluating the cooling impacts on the Silicon-based PV cell. Concurrently, it affords one the opportunity to assess their individual contributions to the overarching power and efficiency of the PV-TE system. Through this rigorous, detail-oriented approach, the objective is to augment the comprehension of the intricate interplay within these complex hybrid systems.

2.3. Annual environmental climatic parameters

In this methodology section, the examination focuses on the climatological parameters shaping the South-Eastern Nigerian environment, as depicted in Fig. 4. The climatological factors of interest, namely solar irradiance, wind velocity, and ambient temperature, are under microscopic scrutiny.

These parameters, meticulously recorded every 5 min throughout the entirety of the year 2022, serve as the raw data for this analysis. Leveraging sophisticated data analytics tools, these continuous observations are effectively condensed into average 24-h profiles for each month. However, this analysis does not stop there.

In an effort to capture an even more representative picture of the region's climate conditions, statistical methodologies were further

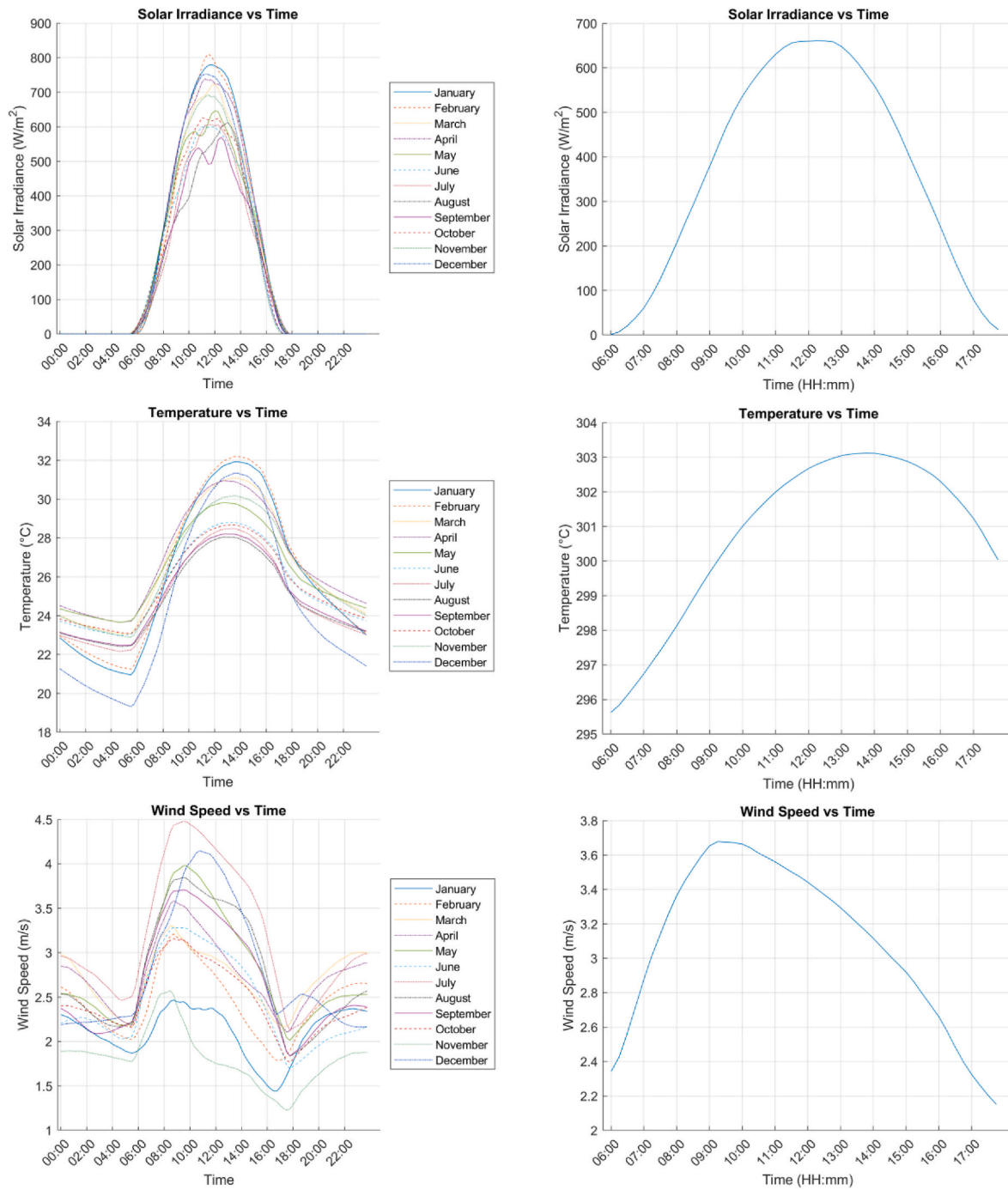


Fig. 4. Monthly and annual average representation of the environmental weather parameters – solar irradiance, temperature, and wind speed for South-Eastern Nigeria in 2022.

employed to distil these monthly profiles into a 12-h snapshot truly emblematic of the region's year-round conditions. The selection of a 12-h window aligns with the diurnal solar cycle in the region, encompassing the hours between sunrise and sunset. The comprehensive approach put forth asserts a more authentic representation of climatic conditions than the selection of a single day or month from the calendar year, as concurred by Nyarko et al., [42].

Regarding the sources of the data, solar irradiance measurements were procured from the Copernicus Atmosphere Monitoring Service [43], an initiative under the European umbrella devoted to cultivating European capabilities for Earth Observation in areas of land, marine, atmospheric monitoring, emergency management, security, and climate

change. Meanwhile, the recordings for air temperature and wind velocity were obtained from the Modern-Era Retrospective Analysis for Research and Applications [44], version 2 (MERRA-2). This platform enhances NASA's prior satellite-era reanalysis system, incorporating additional observations and improvements via the Goddard Earth Observing System, version 5 (GEOS-5), Earth system model.

2.4. Nanofluid cooling in PV-TE systems

To refine the efficacy of the PV-TE system, The cooling performance of the TEG was analyzed through the prism of various nanofluids. The distilled Water, TiO_2 , Fe_3O_4 , Al_2O_3 , and Graphene, was compared

Table 3
Thermophysical properties of coolant fluids [45–47].

Fluids	Thermal Conductivity (W·m ⁻¹ K ⁻¹)	Kinematic Viscosity (10 ⁻⁷ m ² ·s ⁻¹)	Density (kg·m ⁻³)	Specific Heat (J·kg ⁻¹ K ⁻¹)
Distilled Water	0.6	7.47797	997	4181.7
TiO ₂	0.607	9.2143	1048	3502
Fe ₃ O ₄	0.6274	8.174939	1003.06	4178.485
Al ₂ O ₃	0.661	10.07544	1007.4	4154.7
Graphene	0.752	9.97062	1123.3	3343.188

deriving their thermophysical properties - thermal conductivity (κ), kinematic viscosity (ν), density (ρ), and specific heat (C_p). The details of these properties are consolidated in Table 3.

To enrich the accuracy of this analysis, a convective boundary condition was established based on the nanofluid's thermophysical properties on the TEG's cold side, the side through which the nanofluid traverses. The fundamental assumption made was of laminar fluid flow with minimal influence from different physical properties.

Using the Sieder-Tate correlation for the Nusselt number (Nu), the heat transfer coefficient (h) was computed using [48]:

$$Nu = 1.86 \times \left(\frac{Re \times Pr}{l/d_e} \right)^{\frac{1}{3}} \quad (1)$$

where Pr is the Prandtl number ($Pr = \rho \nu C_p / \kappa$), Re is the Reynolds number ($Re = u d_e / \nu$), d_e is the equivalent diameter ($d_e = 4A_f / B$), and l is the characteristic length (0.052 m [49]). The Reynolds number (Re) was computed using different velocities ' u ' ranging from 0.5 m/s to 2.0 m/s in steps of 0.5 m/s. A_f is the flow area and B is the wet perimeter of the TEG module.

With the Nusselt number calculated, the heat transfer coefficient (h) was obtained by:

$$h = \frac{\kappa Nu}{l} \quad (2)$$

These calculations were navigated with a set of underlying assumptions:

- The nanofluid flow remains laminar.
- The nanofluids' thermophysical properties are constant.
- The nanofluid traverses through an area equivalent to the TEG's substrate area.
- The Prandtl number, Reynolds number, and heat transfer coefficient remain constant across the entire flow area.
- The system operates in a quasi-steady state.
- The nanofluid maintains a well-mixed state with no sedimentation.
- Heat losses due to radiation and conduction are negligible.

Through this methodical evaluation of various nanofluids, the study endeavor to optimize the cooling performance of the TEG, thereby bolstering the overall efficiency of the PV-TE system.

2.5. Governing equations

This section explores the fundamental equations governing the performance of both the photovoltaic (PV) and thermoelectric (TE) components. To conduct simulations that capture the transient behavior of the model over time, we employ the ANSYS software. ANSYS serves as the platform for constructing a three-dimensional numerical model, allowing us to simulate how the PV-TE system performs dynamically under changing environmental conditions throughout the year. The use of ANSYS in this context highlights its capability to handle transient simulations, providing a robust framework for analyzing the complex interactions within the PV-TE system.

Table 4
Optical properties of PV [50].

Material	Reflectivity	Absorptivity	Transmissivity	Emissivity
Glass	0.04	0.04	0.92	0.85
EVA	0.02	0.08	0.9	–
Silicon	0.08	0.9	0.02	–
TPT	0.86	0.128	0.012	0.92

2.5.1. In-depth thermal distribution analysis for photovoltaic module

Key to analyzing the efficiency of photovoltaic (PV) module is comprehensively mapping the temperature across the various layers. This is achieved by solving a tri-dimensional energy equation, as proposed by Ref. [34]:

$$\rho C_p \frac{\partial T}{\partial t} = \kappa \nabla \cdot (\nabla T) - Q_{sun} + P_{PV} \quad (3)$$

Here, ρ , κ , and C_p denote the density, thermal conductivity, and specific heat capacity for each layer of the PV module, respectively. The variable Q_{sun} represents the volumetric solar energy absorption, and T stands for the temperature. P_{PV} is the power produced from the polycrystalline silicon layer, with zero power generation assumed for all other layers.

The absorbed solar energy in each PV module layer is treated as an internal heat generation source and can be expressed as [38]:

$$Q_{sun,i} = \frac{(I_{rec,i} \times \alpha_i \times A_i \times C)}{V_i} \quad (4)$$

where:

$$I_{rec,i} = I_{rec,i-1} [(1 - \alpha_{i-1}) - r_{i-1}] \quad (5)$$

In these equations, C represents the solar concentration ratio, while α_i , r_i , and V_i symbolize the absorptivity, reflectivity, and volume of the i th layer, respectively. Moreover, $I_{rec,i}$ and A_i represent the intensity of solar radiation and the area of each layer. Table 4 presents the optical properties of all components in the PV model.

The heat loss due to convection in this hybrid system is accounted for only on the top glass layer of the PV module. The heat transfer coefficient accounting for this heat loss is calculated as [51,52]:

$$h_{conv,t} = 5.7 + 3.8v \quad (6)$$

$$h_{conv,b} = 0.5h_{conv,t} \quad (7)$$

Here, v represents wind speed (m/s), and $h_{conv,t}$ and $h_{conv,b}$ are the heat transfer coefficients at the top glass layer and the bottom Tedlar layer, respectively.

The model also accounts for the radiative heat loss at the photovoltaic glass surface. The radiative heat transfer coefficient (h_{rad}) is given by Ref. [53]:

$$h_{rad} = \varepsilon \sigma \left[(T_{PV}^2 + T_{sky}^2) (T_{PV} + T_{sky}) \right] \quad (8)$$

where σ is the Stefan-Boltzmann constant and ε is the emissivity.

The sky temperature (T_{sky}) plays a key role in this equation and it is computed as [54]:

$$T_{sky} = 0.0552(T_a^{1.5}) \quad (9)$$

where T_a is the ambient temperature.

2.5.1.1. Model implementation blueprint. To facilitate the numerical simulations and mathematical modeling, certain assumptions were made for simplification [55]:

- The thermophysical attributes of the PV/TE system are held constant.

- The radiative heat loss from the backside of the thermal collector is not considered.
- Fluid flow is described as laminar, non-compressible, and transient.
- Fluid's mass flow rate remains constant throughout the numerical simulations and mathematical modeling.

2.5.1.2. Mathematical representation for photovoltaics. The energy generated and the operational efficiency of the photovoltaic silicon cell layer can be quantified using the given equations [56]:

The power generated by the cell (P_{PV}) is the product of the volumetric solar energy absorption of the silicon layer ($q_{sol,3}$) and the efficiency of the photovoltaic system (η_{PV}):

$$P_{PV} = \eta_{PV} q_{sol,3} \quad (10)$$

The photovoltaic efficiency is derived from the reference efficiency (η_{ref}) at a reference temperature ($T_{ref} = 298.15K$), taking into account the temperature coefficient ($\beta = 0.00451 K^{-1}$) and the actual operating temperature of the photovoltaic cell (T_{PV}) [57]:

$$\eta_{PV} = \eta_{ref} [1 - \beta(T_{PV} - T_{ref})] \quad (11)$$

The aforementioned equations are numerically resolved in a simultaneous fashion utilizing the finite element method.

2.5.2. Computational modeling of thermoelectric generator performance

To ascertain the performance characteristics of the thermoelectric generator (TEG), the modeling approach includes the utilization of key governing equations. These equations describe the relationship between heat transfer and electric current in the TEG.

Firstly, the null divergence conditions for the vectors representing electric current density ("J") are established and reversible heat transfer due to the Peltier effect ("q"). This is done using the expressions [58]:

$$\nabla \bullet J = 0 \quad (12)$$

$$\nabla \bullet (q + \dot{Q}) = 0 \quad (13)$$

Here, J represents the electric current density vector, q symbolizes reversible heat transfer resulting from the Peltier effect, and $\dot{Q}$ is the internal heat generation rate.

By integrating Fourier's law, q is defined as [59]:

$$q = -\kappa \nabla T + \alpha T J \quad (14)$$

This equation encompasses the flow of heat energy inside the TEG, where κ signifies the thermal conductivity, α represents the Seebeck coefficient, and T is the temperature.

Additionally, combining the Seebeck and Ohm's law effects, leads to the derivation of the electric field density (E) at any location within the TEG, expressed as [60]:

$$E = \alpha \nabla T + \frac{J}{\sigma} \quad (15)$$

where σ represents electrical conductivity.

Then calculating the power generated per unit volume ($\dot{Q}$) as [61]:

$$\dot{Q} = E \bullet J \quad (16)$$

By integrating the equations presented, the distribution of temperature (T) within the TEG was obtained [62]:

$$\nabla \bullet (k \nabla T) - J \bullet \left(\frac{d\alpha}{dT} \right) \nabla T + J \bullet J = 0 \quad (17)$$

In this equation, $\left(\frac{d\alpha}{dT} \right)$ denotes the Thomson coefficient.

The electrical power generated by the TEG can be computed using [63]:

$$P_{TE} = \left(\frac{V_S \sqrt{R_L}}{R_{el} + R_L} \right)^2 \quad (18)$$

The efficiency of the TEG (η_{TE}) is then obtained as:

$$\eta_{TE} = \frac{P_{TE}}{Q_h} \quad (19)$$

In these equations, V_S represents the Seebeck voltage, R_{el} is the internal electrical resistance, R_L symbolizes the external load resistance, and Q_h is the power input to the TEG's top surface.

This mathematical model provides a comprehensive representation of the heat transfer, electrical current, and performance indicators within a thermoelectric generator system.

2.5.3. Photovoltaic-thermoelectric performance

With individual models of the Photovoltaic (PV) and Thermoelectric (TE) modules established, the analysis of the comprehensive performance of the hybrid PV-TE system can proceed. Essentially, the cumulative performance of the PV-TE system arises from the interplay between the behaviors of the PV and TE modules.

This presents an intriguing subject of investigation as it aims to quantify how various system configurations influence the TE module's power output, and consequently, the temperature of the Si-PV cell. Changes in this temperature directly impact the PV's efficiency and power, thus affecting the combined PV-TE power and efficiency.

Therefore, the hybrid PV-TE system's power (P_{PV-TE}) and efficiency (η_{PV-TE}) are calculated as follows:

$$P_{PV-TE} = P_{PV} + P_{TE} \quad (20)$$

$$\eta_{PV-TE} = \eta_{PV} + \eta_{TE} \quad (21)$$

These relations illuminate the complex interdependencies within the hybrid PV-TE system, offering insights for potential optimization.

2.6. Defining the thermal boundary conditions in a hybrid PV-TE system

To create a comprehensive and accurate model of the PV-TE system, the need to describe the thermal behavior within and between its various layers. For this purpose, a series of thermal boundary conditions is set up to mirror the heat transfer mechanics present in each layer and at each interface.

• Boundary Condition at the Glass-Air Interface (Glass Surface):

Starting at the top of the PV module, where the glass layer faces the external environment (Ambient Air and Sky). The thermal behavior here is influenced by three different modes of heat transfer: solar radiation absorption, convective heat exchange with the wind, and radiative heat loss to the sky. This can be expressed as:

$$E_1 = \alpha_g I_{solar} + h_{wind} \Delta T_{ga} + \epsilon_{radiation} \Delta T_{gs} \quad (22)$$

Here, α_g is the solar absorptance of the glass, I_{solar} is the incident solar radiation, h_{wind} is the convective heat transfer coefficient due to wind, ΔT_{ga} is the temperature difference between the glass and the ambient air, $\epsilon_{radiation}$ is the radiative heat transfer coefficient, and ΔT_{gs} is the temperature difference between the glass and the sky.

• Boundary Conditions at Material Interfaces within the PV Module:

For the interfaces between the glass, EVA, solar cell, Tedlar, and TEG layers, the continuity of heat flux is employed (i.e., the heat entering a layer is equal to the heat leaving it). This principle leads to the following conditions at the respective interfaces:

$$E_2 = k_{glass} \nabla T_{glass} = k_{EVA_{top}} \nabla T_{EVA_{top}} \quad (23)$$

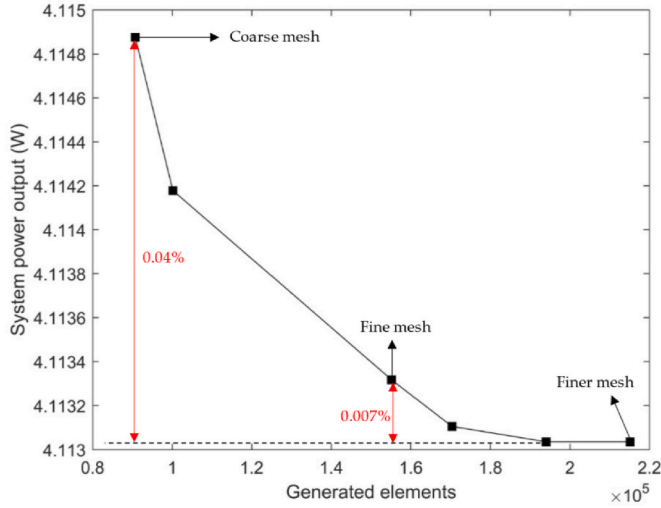


Fig. 5. Mesh convergence result – Sensitivity of the system electric power output to the number of generated mesh elements.

$$E_3 = k_{\text{cell}} \nabla T_{\text{cell}} = k_{\text{EVA}_{\text{top}}} * \nabla T_{\text{EVA}_{\text{top}}} \quad (24)$$

$$E_4 = k_{\text{cell}} \nabla T_{\text{cell}} = k_{\text{EVA}_{\text{bottom}}} \nabla T_{\text{EVA}_{\text{bottom}}} \quad (25)$$

$$E_5 = k_{\text{EVA}_{\text{bottom}}} \nabla T_{\text{EVA}_{\text{bottom}}} = k_{\text{Tedlar}} \nabla T_{\text{Tedlar}} \quad (26)$$

$$E_6 = k_{\text{Tedlar}} \nabla T_{\text{Tedlar}} = k_{\text{TE}} * \nabla T_{\text{TE}} \quad (27)$$

Here, k_{glass} , $k_{\text{EVA}_{\text{top}}}$, k_{cell} , $k_{\text{EVA}_{\text{bottom}}}$, k_{Tedlar} , and k_{TE} are the thermal conductivities of the glass, EVA (top), solar cell, EVA (bottom), Tedlar, and TEG, respectively. ∇T represents the temperature gradient within each layer.

- **Boundary Condition at the TEG-Air Interface (TEG Surface):** At the bottom surface of the TEG, the boundary condition is set by the convective heat exchange with the nanofluids:

$$E_7 = k_{\text{TE}} \nabla T_{\text{TE}} = h_{\text{nano}} \Delta T_{\text{TEG}_{\text{nano}}} \quad (28)$$

Here, $\Delta T_{\text{TEG}_{\text{nano}}}$ is the temperature difference between the TEG and the nanofluids.

2.7. Model accuracy verification

A critical step in this study is ensuring the veracity of the numerical model used to generate the optimization results for the system. This involves two main stages: a mesh refinement analysis for numerical accuracy and a comparison with established experimental and theoretical studies for external validation.

2.7.1. Mesh refinement analysis

Beginning with a mesh convergence study conducted within the ANSYS modeling interface. The goal is to determine an optimal mesh size that strikes a balance between computational cost and model accuracy. This is done by gradually transitioning from a coarse mesh (larger element size) to a refined mesh (smaller element size).

The study (as depicted in Fig. 5) shows an inverse relationship between system electric power output and the number of mesh elements - power output decreases as we increase the mesh density. The largest discrepancy observed is about 0.04% between the coarse and refined mesh settings. However, as the mesh refinement increases, the difference shrinks to just 0.007%. Further refinement leads to a negligible difference. For this study, the more refined mesh is chosen to prioritize numerical accuracy.

2.7.2. Model benchmark validation

To substantiate the accuracy of the finite element model used in this study, a comprehensive cross-referencing of results was conducted with various works in the literature, focusing on both PV-TE and TEG models. Key studies encompass those conducted by Shittu et al., which investigated under varying weather conditions [64], Motiei et al., who focused on unsteady state performance analysis [65], and Alghamdi et al., who explored exergo-economic and thermo-mechanical optimization [66]. Additionally, we considered studies by Kraemer et al. on flat-panel solar [67] and Alghamdi et al. [68] on 4E performance. Employing Autodesk Inventor, we generated digital twins of the 3D models presented in these studies and imposed the respective boundary conditions within ANSYS. The outcomes of the replication effort are visually presented in Fig. 6. The model output closely aligns with the findings from prior studies, underscoring the fidelity and reliability of the finite element model in the comprehensive evaluation of PV-TE performance.

This rigorous approach to mesh refinement and model validation ensures that this study's outputs are both accurate and reliable, providing a strong foundation for the further analysis of hybrid PV-TE systems.

3. Results and Discussions

In the forthcoming section on Results and Discussion, a deep dive is taken into the fundamental findings derived from the meticulous assessment and detailed simulations of the hybrid photovoltaic-thermoelectric (PV-TE) systems.

The section unfolds with an analysis of how heat flux dynamics impact the effectiveness of various PV-TE models. This exploration sets the foundation for understanding the interplay of heat and energy conversion in these hybrid systems.

Following this, an exploration is undertaken of the intertwined influences of nanofluids and fluid flow velocity on PV-TE system performance. This step-by-step approach helps us narrow down the most optimal models in terms of power output and efficiency, providing key insights for future applications of these hybrid systems.

Subsequently, focus is shifted to the impact of annual transient weather conditions on the system's overall performance across different models. This comprehensive analysis underscores the critical role of external climatic factors in the operational efficiency of PV-TE systems, underscoring the importance of environmental adaptability in their design.

The final phase of this section showcases the distribution of temperature and Seebeck voltage across all models under identical operating conditions. This comparative assessment gives a visual understanding of the system's behavior, providing crucial clues to improve their design and operation.

In essence, this section presents a rigorous exploration of various aspects influencing PV-TE system performance, offering insights that can inform improvements in design, operation, and efficiency.

3.1. Heat flux comparisons

In this section, the impact of different degrees of concentrated solar heat flux on the performance metrics of the 12 distinctive PV-TE models is meticulously analyzed. The solar heat flux values, in this context, span from 1 kW/m² to 20 kW/m², changing in steps of 1 kW/m². The lower limit mirrors conditions under standard AM 1.5G irradiance [73], reflecting everyday, unconcentrated solar environments. On the contrary, the upper threshold of 20 kW/m² symbolizes high-intensity, concentrated solar scenarios that are typically achieved using Fresnel lenses [74] or compound parabolic concentrators [75].

This examination is carried out under the conditions where distilled water is employed as the base coolant, flowing at a constant velocity of 0.5 m/s. The rationale behind the selection of distilled water is two-fold: one, its universal availability making it a prevalent choice in commercial

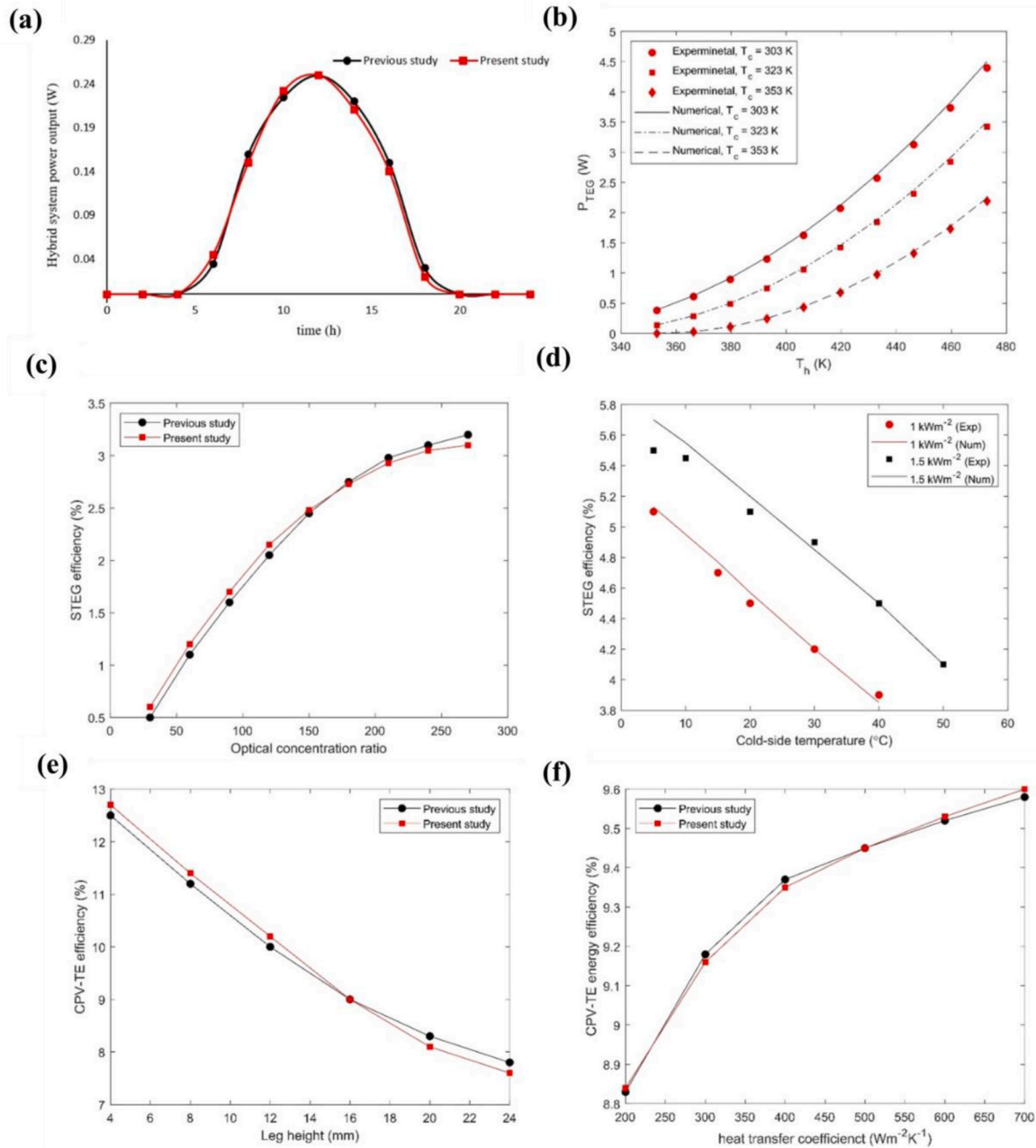


Fig. 6. Validation results of the numerical model (a) transient unconcentrated PV-TE [69] (b) stand-alone TEG [70] (c, d) solar concentrating TEGs [67,71] (e, f) concentrated PV-TE [8,72].

applications [76], and two, its widespread usage in related research [77], enabling this work to serve as a valuable reference for future studies. Moreover, the flow velocity of 0.5 m/s is selected considering it as a common benchmark in similar investigations [78], thus facilitating useful cross-comparisons.

The study evaluates various performance indicators, encompassing PV cell temperature, TE power output and efficiency, PV power output and efficiency, and combined PV-TE power output and system efficiency. The analysis offers a comprehensive view of the hybrid system's performance under diverse solar heat fluxes. It aims to provide nuanced insights for researchers and practitioners in renewable energy, ensuring clarity and detail without ambiguity.

3.1.1. PV cell temperature

Fig. 7 illustrates the impact of heat flux on the twelve PV-TE models

in this study. It shows a positive correlation between concentrated solar irradiance and Silicon PV cell temperature, resulting from increased heat flux absorption. However, temperature increases vary among models. At 20 kW/m^2 , models 10, 11, and 12, employing multi-stage systems with BiTe, SKT, and segmented geometries, record the highest temperatures (517.26 K, 512.38 K, and 514.55 K). These geometries enhance heat retention at the hot junction. In contrast, models 1, 2, and 3, single-stage systems with uniform BiTe, SKT, and segmented semi-conductors, exhibit lower temperatures (420.56 K, 416.98 K, and 419 K) due to their structural characteristics.

3.1.2. TE power and efficiency

The plot illustrates the correlation between TE power generation and concentrated solar flux on the PV top glass. Increased heat flux on the PV cell leads to higher heat extraction by the TEG hot junction, raising the

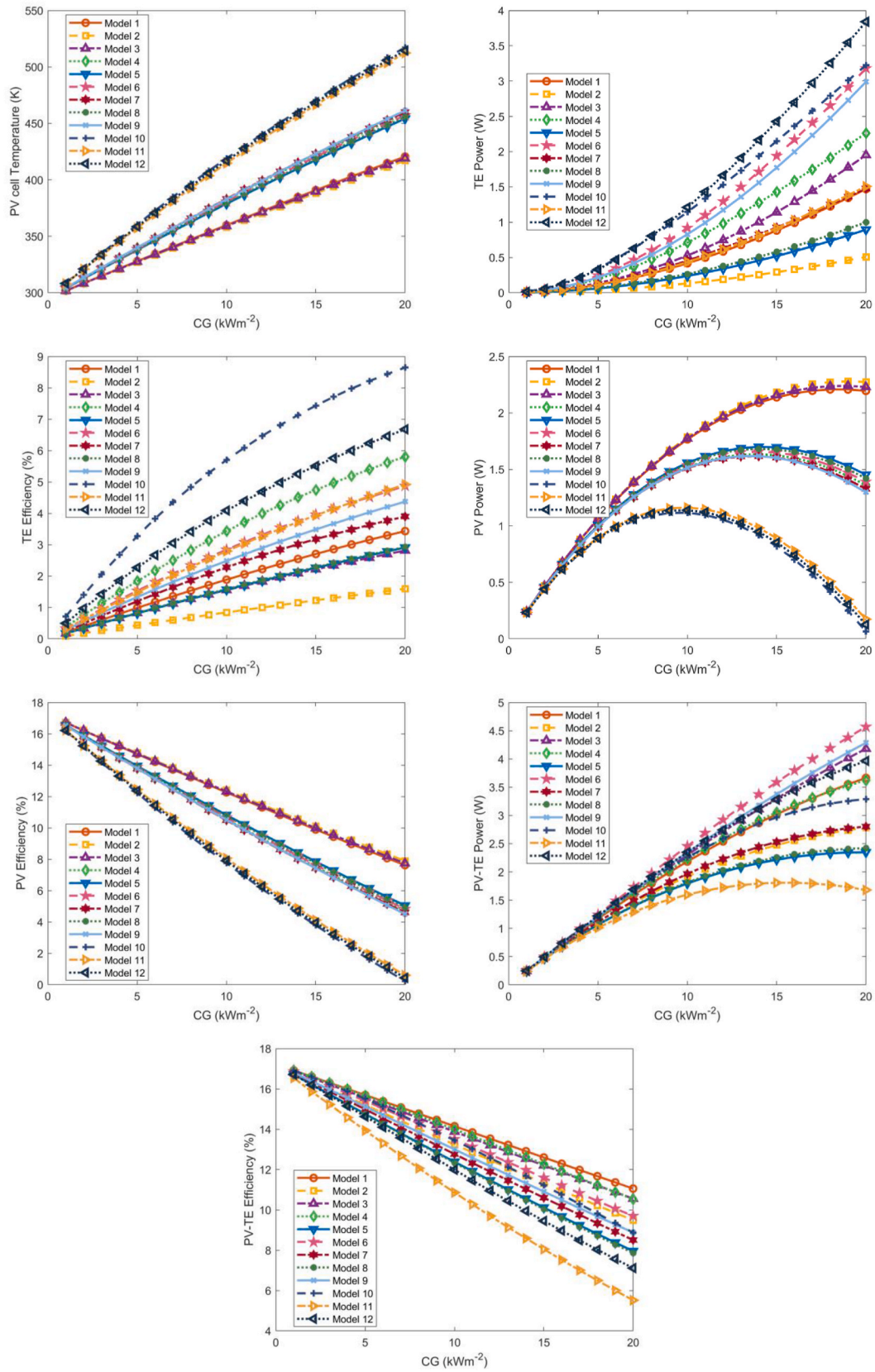


Fig. 7. Effect of solar heat flux on the performance of the twelve PV-TEs.

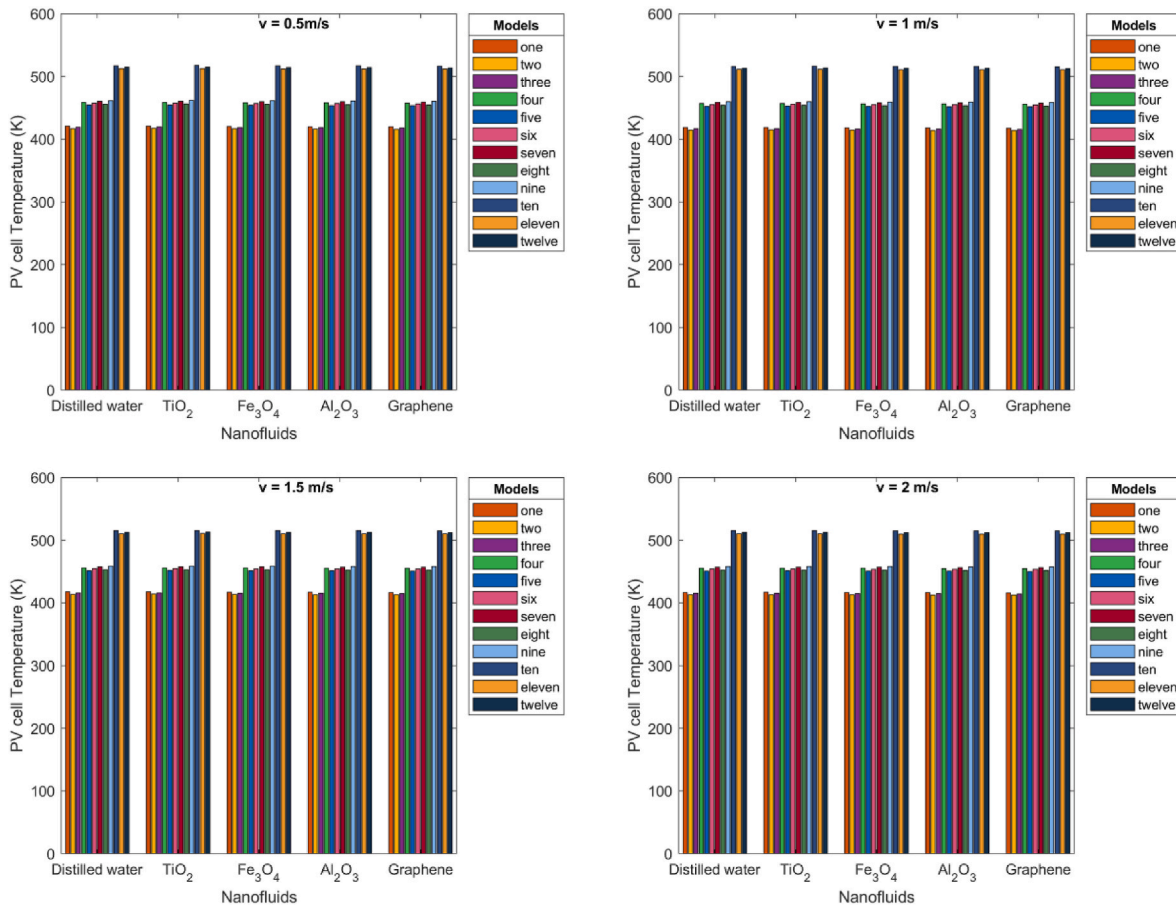


Fig. 8. Effects of different nanofluids on the PV cell temperature across the various PV-TE models.

temperature difference and enhancing electrical power output via the Seebeck effect. Model 12, a multi-stage segmented TEG with trapezoidal pellets, achieves the highest power output of 3.84 W at 20 kW/m². Conversely, model 2, a single-stage TEG with rectangular skutterudite pellets, exhibits the lowest power output. This aligns with previous findings favoring bismuth-telluride over skutterudite in PV-TE systems, emphasizing the impact of configurations, materials, and geometry on TE power generation.

In terms of TE efficiency, model 10 excels, consistent with research on multi-stage systems with variable area leg geometry TE pins. This efficiency boost is attributed to minimizing heat flow while maximizing power output through the cascading effect. Model 2 shows the lowest TE efficiency, emphasizing the influence of configurations and materials on PV-TE system performance.

3.1.3. PV power and efficiency

The plot depicting the behavior of PV power output and efficiencies across various models with increasing heat flux reveals several insights. Generally, as the heat flux increases, the PV power also rises, reaching a peak before declining with further increases in heat flux. Models 1–3 demonstrate the highest PV power output and efficiency. While these models exhibit similar power and efficiency at low heat flux levels, the differences become more pronounced at higher heat fluxes.

At the highest concentrated heat flux of 20 Suns, model 2 delivers the top power output and efficiency of 2.27 W and 16.72%, respectively. This observation suggests that single-stage systems using bismuth-telluride, skutterudite, and segmented materials yield the greatest system power outputs and efficiencies, due to their superior cooling effects. In this context, "20 Suns" signifies that the intensity of sunlight applied to the photovoltaic-thermoelectric system is 20 times higher than the

standard solar radiation under typical conditions. The unit "Suns" is commonly employed in solar energy research to quantify the degree of sunlight concentration, providing a measure of the solar flux density on the PV-TE system.

In contrast, the lowest PV power and efficiencies are observed in models 10–12, which correspond to the multi-stage systems using bismuth telluride, skutterudite, and segmented materials. It appears that these multi-stage or cascaded thermoelectric systems can lead to overheating and a subsequent decrease in crystalline Si-PV power and efficiencies. This can be attributed to the extra stages, which induce higher heat retention at the TEG hot junction, thereby raising the Si cell temperature and diminishing the PV power output and efficiency.

3.1.4. PV-TE power and efficiency

The culminating plot in this study illustrates the relationship between PV-TE power outputs and efficiencies with concentrated heat flux across various models. Understanding these intertwined systems' performance can be complex. At the top of the chart is Model 6, utilizing multi-stage/cascaded thermoelectric systems with uniform cross-section, rectangular-shaped elements from segmented thermoelectric elements. Model 6 achieves the highest power output, peaking at 4.57 Watts under 20 Suns. This model showcases the synergistic effects of material segmentation and cascading of thermoelectric systems, resulting in the most potent PV-TE power output in these conditions. This aligns with the research conducted by Ref. [79] on a single-leg cascaded thermoelectric generator, demonstrating enhanced performance.

On the other end of the performance spectrum is Model 11, representing the lowest point in system efficiency or power output. This system incorporates multi-stage/cascaded thermoelectric (TE) modules comprising skutterudite semiconductors with trapezoidal cross-sections.

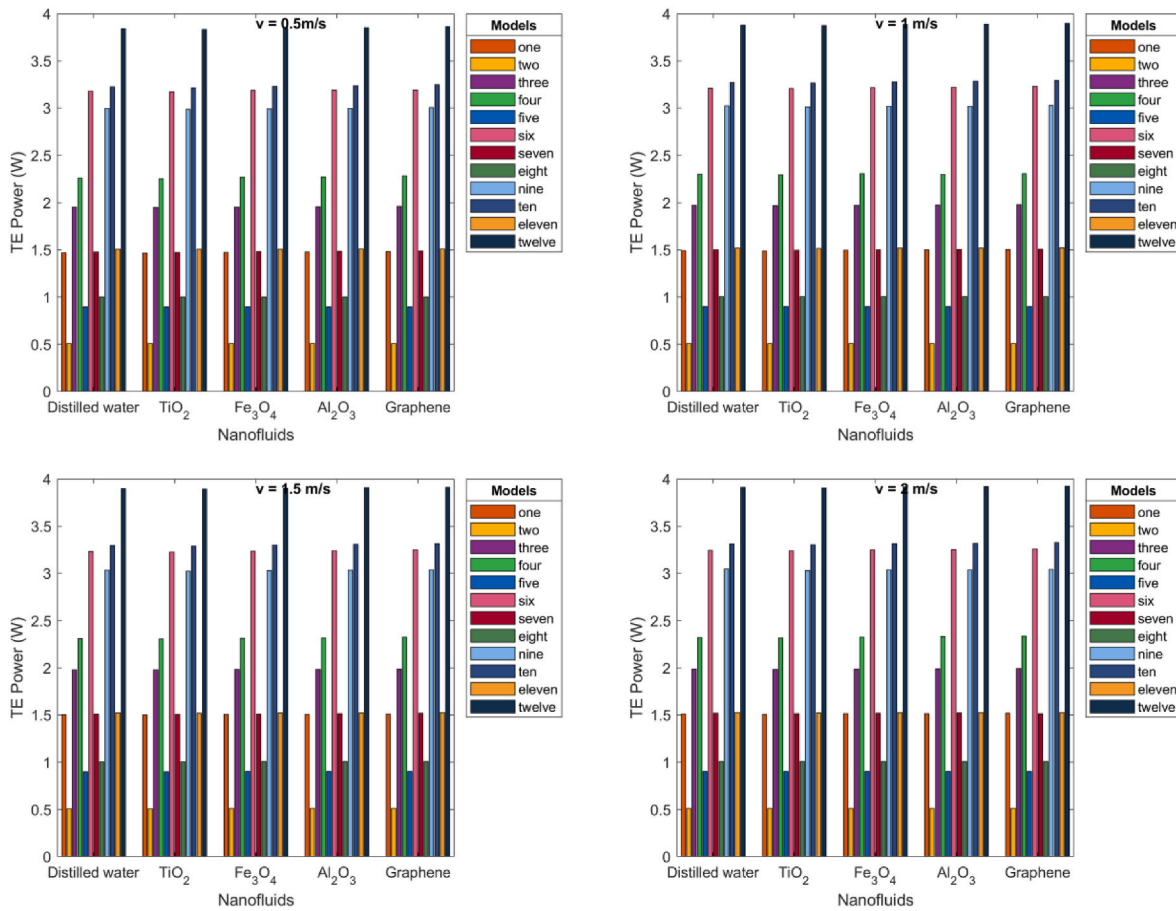


Fig. 9. Effects of different nanofluids on the TE power on the various PV-TE models.

Model 11 achieves a modest maximum power output of 1.81 Watts under optimal concentrated solar irradiance (16 Suns). The performance is influenced by factors like the thermal properties of skutterudite semiconductors, which can elevate cell temperature, impacting PV power and overall PV-TE power. The trapezoidal geometry of the model may introduce parasitic thermal losses in cascaded thermoelectric systems, reducing power outputs. For baseline comparison, Model 1 represents a conventional approach without multi-staging and material segmentation, producing 3.66 Watts of PV-TE power at 20 Suns. Compared to Model 1, the best-performing Model 6 exceeds its performance by 24.86% under identical conditions, emphasizing the potential of advanced thermoelectric configurations in concentrated solar PV-TE systems.

3.2. Effect of nanofluid cooling and fluid velocity

In this section, a delve is made into the investigation of the influence of various nanofluids – specifically distilled water as the base fluid [80], titanium oxide (TiO_2) [81], iron oxide (Fe_3O_4) [82], aluminum oxide (Al_2O_3) [83], and graphene [84] – on the performance parameters of Si-PV and TE systems. These nanofluids are scrutinized at a range of flow velocities (0.5 m/s to 2 m/s in increments of 0.5 m/s), with the intention of determining their impact on the Si-PV cell temperature, TE power generation, TE efficiency, PV power generation, PV efficiency, combined PV-TE power, and the overall PV-TE system efficiency. These analyses are conducted under a fixed concentrated solar irradiance of 20 kW/m^2 reflective of practical concentrated solar applications.

The study focuses on exploring the impact of different nanofluids on the thermal and electrical characteristics of hybrid PV-TE systems. By altering thermal conductivity and heat transfer rates, nanofluids play a

crucial role in influencing PV and TE performance parameters. This research contributes valuable insights to renewable energy knowledge, offering practical considerations for optimizing the efficiency and power output of PV-TE systems. The unique thermal properties of nanofluids present an innovative solution to address heat management challenges in hybrid PV-TE systems, emphasizing their potential for renewable energy generation.

3.2.1. PV cell temperature

Figure 8 shows the impact of various nanofluids at different velocities on the average temperature of PV cells across twelve models. Despite apparent similarities, nuanced shifts in temperatures are observed, especially in model 2, which presents the lowest average cell temperature when cooled with graphene nanofluids at a flow velocity of 2 m/s. Factors such as the choice of thermoelectric materials, nanofluid properties, and flow velocity contribute to these variations. Notably, an increase in flow velocity from 0.5 m/s to 2 m/s in model 2 results in a substantial 3.73 K reduction in PV cell temperature, a critical factor given the temperature coefficient of the Silicon PV cell. Conversely, model 10, utilizing TiO_2 nanofluids at 0.5 m/s, records the highest PV cell temperature due to the inefficiency of cascaded thermoelectric systems in removing waste heat. This finding is largely due to the use of multi-stage or cascaded thermoelectric systems in this model, which, as previous studies have demonstrated [36] exhibit less efficiency in removing waste heat from the backplates of PV systems. In summary, the analysis emphasizes the complex interplay of nanofluid choice, flow velocity, thermoelectric materials, and system design, providing crucial insights for optimizing hybrid PV-TE systems in renewable energy applications.

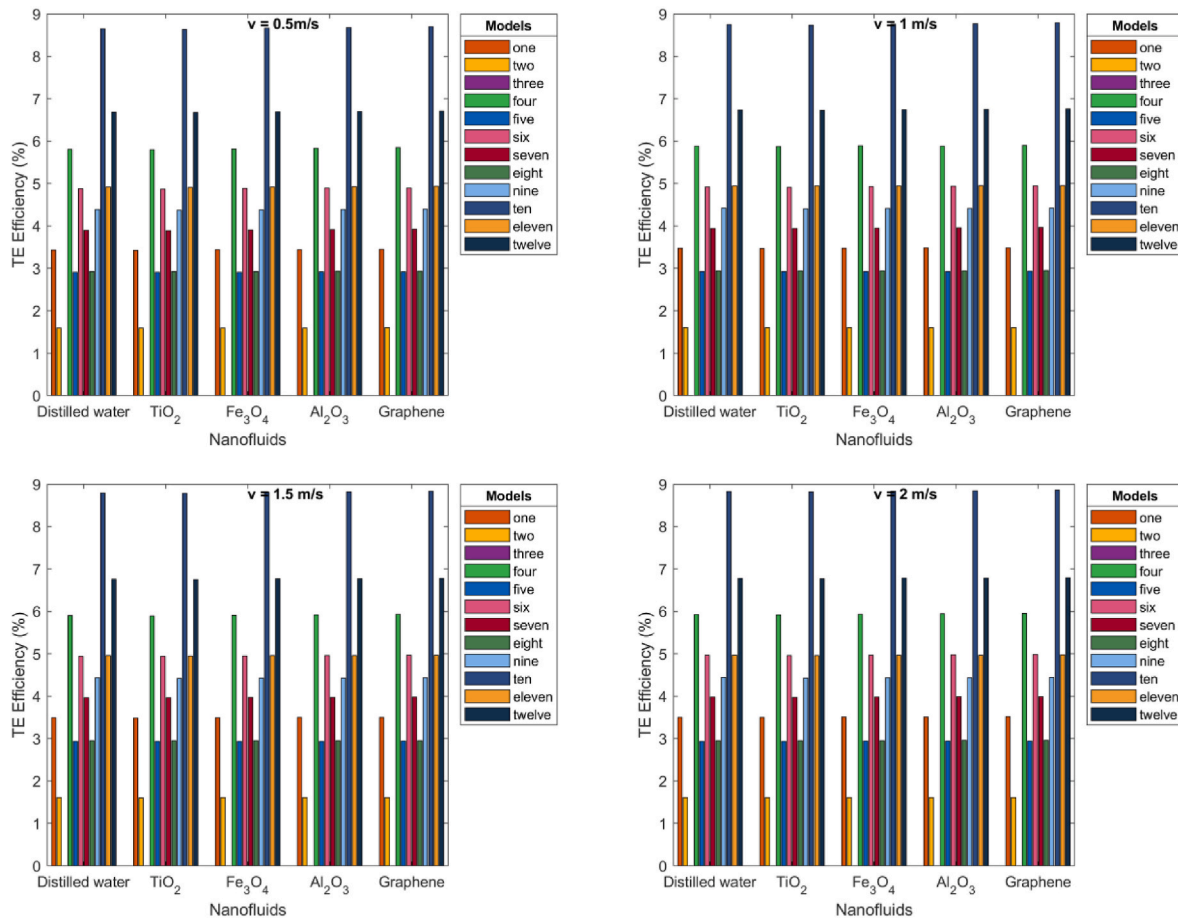


Fig. 10. Effects of different nanofluids on the TE efficiency across the various PV-TE models.

3.2.2. TE power and efficiency

Fig. 9 illustrates the impact of different nanofluids at varying flow velocities on the thermoelectric (TE) power output generation rate for twelve distinct photovoltaic-thermoelectric (PV-TE) models. The TE power output is intricately influenced by model configuration, nanofluid selection, and flow velocity, showcasing noticeable effects upon closer examination. Model 12 distinguishes itself by attaining the peak TE power output of 3.92 W, employing graphene nanofluid cooling at a flow velocity of 2 m/s, a scenario reminiscent of a study conducted by Ref. [85]. In that particular investigation, 0.5% graphene nanofluid was employed to generate power in a CPVT-TE system. This peak output marks a 1.5 % enhancement compared to a flow velocity of 0.5 m/s, suggesting potential performance gains with even higher velocities. In contrast, model 2, cooled with TiO_2 nanofluid at 0.5 m/s, exhibits the lowest power production of 0.51 W. A compelling comparison between model 2 and the top-performing model 12 reveals a remarkable 7.7-fold increase in power output, emphasizing the substantial impact of model configuration and nanofluid choice on TE power generation in PV-TE systems.

Fig. 10 demonstrates that the trends in thermoelectric (TE) efficiency align with power output observations, with model 12 exhibiting superior performance. When utilizing graphene nanofluid cooling at 2 m/s, this model achieves the highest TE efficiency at 5.43%. A slight efficiency decreases to 5.36% occurs at a reduced flow velocity of 0.5 m/s, emphasizing the impact of flow velocity on TE efficiency. In stark contrast, model 2, cooled with TiO_2 nanofluids at 0.5 m/s, presents the least efficiency at 1.32%. By leveraging the advantages of graphene nanofluids at 2 m/s, model 12 enhances TE efficiency to a value 4.11 times higher than that of model 2. This comprehensive analysis unveils intricate relationships between TE power output and efficiency,

nanofluid characteristics, flow velocity, and PV-TE system configuration. The insights gained provide a robust foundation for designing more efficient and adaptable renewable energy systems, emphasizing the critical role of each component and its operating conditions in holistic PV-TE hybrid system performance.

3.2.3. PV power and efficiency

Fig. 11 illustrates the PV power output variations across diverse PV-TE models based on nanofluid type and respective flow velocities. Notably, model 2 achieves the highest PV power output at 2.38 W when using graphene nanofluid cooling at 2 m/s. This optimization aligns with the previously recorded lowest PV cell average temperature of 412.05 K for model 2, showcasing the skutterudite material's efficient thermal management and waste heat reduction, resulting in superior PV power generation. Modulating the flow velocity to 0.5 m/s marginally decreases model 2's PV power to 2.3 W, emphasizing the pivotal role of flow velocity in PV power generation. In contrast, model 10, cooled with TiO_2 nanofluid at 0.5 m/s, generates the minimum PV power output of 0.061 W, attributed to the high cell temperature of 517.47 K. Juxtaposing these extremes underscores how optimal cooling techniques with model 2 can amplify PV power output to levels 39 times higher than model 10.

Similarly, Fig. 12 reveals comparable trends in PV efficiencies among the different models. The zenith of PV efficiency, 8.27%, is claimed by model 2, employing graphene nanofluid cooling at 2 m/s. In addition, the influence of fluid velocity on PV efficiency is evident, with the efficiency of model 2 subtly declining as the fluid velocity diminishes. Specifically, when the graphene nanofluid flow velocity is set to 0.5 m/s, model 2 manifests a PV efficiency of 7.99%, indicating a 0.28% drop due to the reduced fluid velocity. Finally, the nadir of PV efficiency, 0.21%,

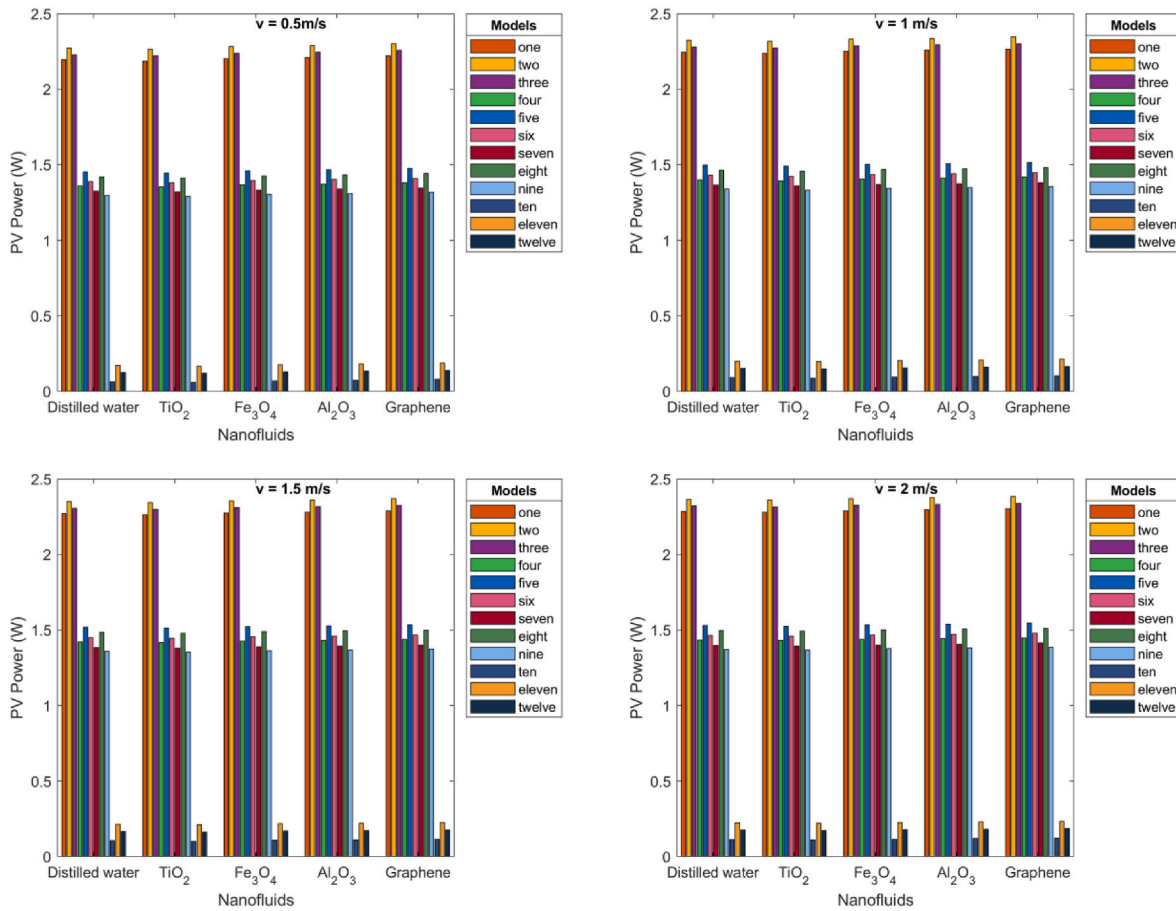


Fig. 11. Effects of different nanofluids on the PV power across the various PV-TE models.

is attributed to model 10, utilizing TiO_2 nanofluid cooling at 0.5 m/s. Relatively, these findings underscore that the PV efficiency of model 2 is a staggering 39.4 times higher than that of model 10.

To conclude, this in-depth analysis effectively elucidates the profound impact of cooling techniques, nanofluid types, and flow velocities on the overall power output and efficiency of PV cells in hybrid systems. It offers invaluable insights for future endeavors in optimizing these hybrid renewable energy systems.

3.2.4. PV-TE power

Fig. 13 provides insights into the intricate dynamics of various nanofluids and their flow velocities, impacting hybrid photovoltaic-thermoelectric (PV-TE) power output across twelve models. Model 6 stands out, achieving a peak power output of 4.74 W with graphene nanofluid at 2 m/s. This model's multi-stage thermoelectric generator, featuring rectangular cross-sectioned bismuth-telluride elements, exemplifies superior combined power output due to effective interplay between photovoltaic and thermoelectric systems. Similar investigation shows. Model 6's performance aligns with previous discourse, emphasizing the advantages of segmented rectangular thermoelements and multi-staging for enhanced PV-TE power generation. Notably, trapezoidal designs impair power output due to thermal losses.

Models 6, 9, 3, and 12 surpass the baseline (Model 1) in PV-TE power output, attributed to multi-staging, non-uniform cross-sections, and material segmentation. Despite their superiority, variations in TE element cross-sections diminish PV-TE power output due to increased Si-cell heating. Model 6's remarkable 24.08% enhancement over Model 1 underscores the impact of nanofluid velocity, producing 4.74 W at 2 m/s and 4.6 W at 0.5 m/s. This highlights the crucial relationship between fluid velocity and power output, emphasizing the need for precise

cooling manipulation in optimizing hybrid PV-TE system performance.

In summation, this exhaustive exploration elucidates the profound influence of nanofluid type, flow velocity, and PV-TE system architecture on the overall power output. This newfound comprehension sets the stage for strategic design and development of renewable energy systems that are not only more efficient, but also versatile, ushering in a new era of renewable energy research and innovation.

3.2.5. PV-TE efficiency

Explaining how different nanofluids and their corresponding velocities impact the efficiency of PV-TE, Fig. 14 unveils a captivating panorama of dynamic interrelationships in renewable energy optimization. The baseline model, Model 1, achieves the maximum PV-TE efficiency of 11.52% when operating with graphene nanofluids at a flow velocity of 2 m/s. This stellar performance results from superior heat extraction facilitated by rectangular-shaped TE elements, reducing cell temperature and amplifying system efficiency. Notably, efficiency is sensitive to nanofluid velocity, with a decrease to 11.17% at 1 m/s, indicating a 0.35% efficiency loss due to reduced flow velocity.

In a paradoxical twist, models (3, 6, 9, and 12) boasting the highest PV-TE power outputs exhibit lower efficiencies than the baseline. Specifically, under graphene nanofluid at 2 m/s, these models yield efficiencies of 10.66%, 9.8%, 8.97%, and 7.19%, respectively. Model 3 stands out with the highest efficiency, attributed to its single-stage design preventing overheating of the PV module backplate, conserving efficiency. This observation extends to models 9 and 12, where multi-staging leads to efficiency depreciation despite boosting power outputs. Multi-staging inadvertently increases thermal parasitic losses at the PV backplate, impairing cell efficiencies. A parallel reduction in efficiency is noted with material segmentation. Thus, despite enhancing

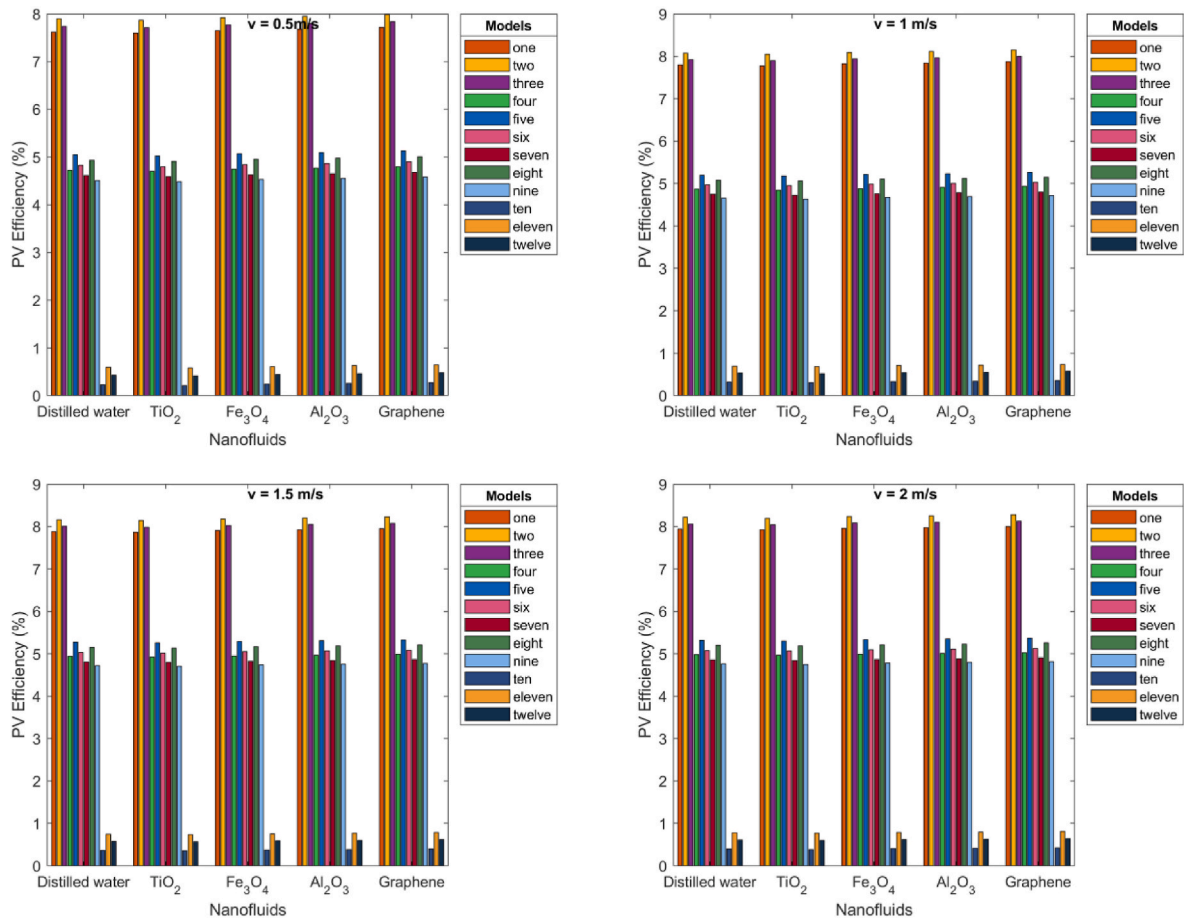


Fig. 12. Effects of different nanofluids on the PV efficiency across the various PV-TE models.

power outputs, these strategies pose trade-offs by diminishing PV-TE efficiency.

3.2.6. Steady tradeoffs between PV-TE power and efficiency

The task at hand thus morphs into an intricate balancing act between PV-TE power output and efficiency as illustrated in the three-dimensional distribution of PV-TE power and efficiency across the selected models in Fig. 15. An examination of model 6, which, as previously elucidated, offers the highest power output, reveals a subsequent efficiency reduction of 16.24% in contrast to the baseline, model 1. In contrast, the selection of model 3 results in a more moderate efficiency reduction of 7.35%, compared to model 6. Therefore, the user is left to weigh the merits of selecting model 6 for the highest possible PV-TE power output, albeit with an efficiency reduction of 16.24% compared to model 1. Alternatively, for those prioritizing efficiency conservation, model 3 may be a more desirable choice, even though it entails an 8.6% reduction in PV-TE power compared to model 6.

In essence, the selection process emerges as an intricate dance of multi-objective optimization and calculated trade-offs. The discerning user must gauge the balance between PV-TE power and efficiency while benchmarking the top-performing systems against the baseline model 1. This rigorous analysis provides not only an exhaustive understanding of the underlying dynamics but also furnishes a roadmap to the conscientious selection of the most suitable system tailored to individual needs and priorities.

3.3. Transient annual performance analysis

Here, we explore the annual transient evolution of key performance parameters for photovoltaic (PV), thermoelectric generator (TEG), and

combined PV-TE systems. In contrast to existing research that often focuses on steady-state analysis or limited single-day assessments, this study adopts a more comprehensive approach. Utilizing environmental weather data collected at 15-min intervals throughout an entire year, the study employs statistical tools to condense the dataset into an effective weather profile representing conditions over a 12-h period. The TEG's cold junction is cooled with graphene nanofluids flowing at 2 m/s. This dynamic and realistic analysis provides a nuanced understanding of annual transient performance, offering valuable insights into the real-world conditions and contributing uniquely to the existing knowledge in the field.

3.3.1. Transient performance parameters evolution

Fig. 16 encapsulates a year-long investigation into critical parameters - Si-PV cell temperature, TE power and efficiency, PV power, and PV-TE power and efficiency - accounting for South-Eastern Nigeria's 2022 weather conditions. A parabolic distribution is evident, featuring a concave downward trend for PV cell temperature (T_{PV}), TE power (P_{TE}) and efficiency (η_{TE}), PV power (P_{PV}), and PV-TE power (P_{PV-TE}), and a concave upward behavior for PV (η_{PV}) and PV-TE efficiencies (η_{PV-TE}). This implies the lowest Si-cell efficiency during peak solar illumination, consistent with prior research.

Optimal performance consistently occurs around 12:35 p.m., allowing fair model comparisons. Superior models maintain performance, summarized in Table 5, while variations in parameters show distinct trends. PV and PV-TE efficiencies peak at the minimum objective target, aligning with the concave upward distribution. Conversely, for PV cell temperature, TE power and efficiency, PV and PV-TE power, maximum objective target values align with optimal values, conforming to the concave downward distribution.

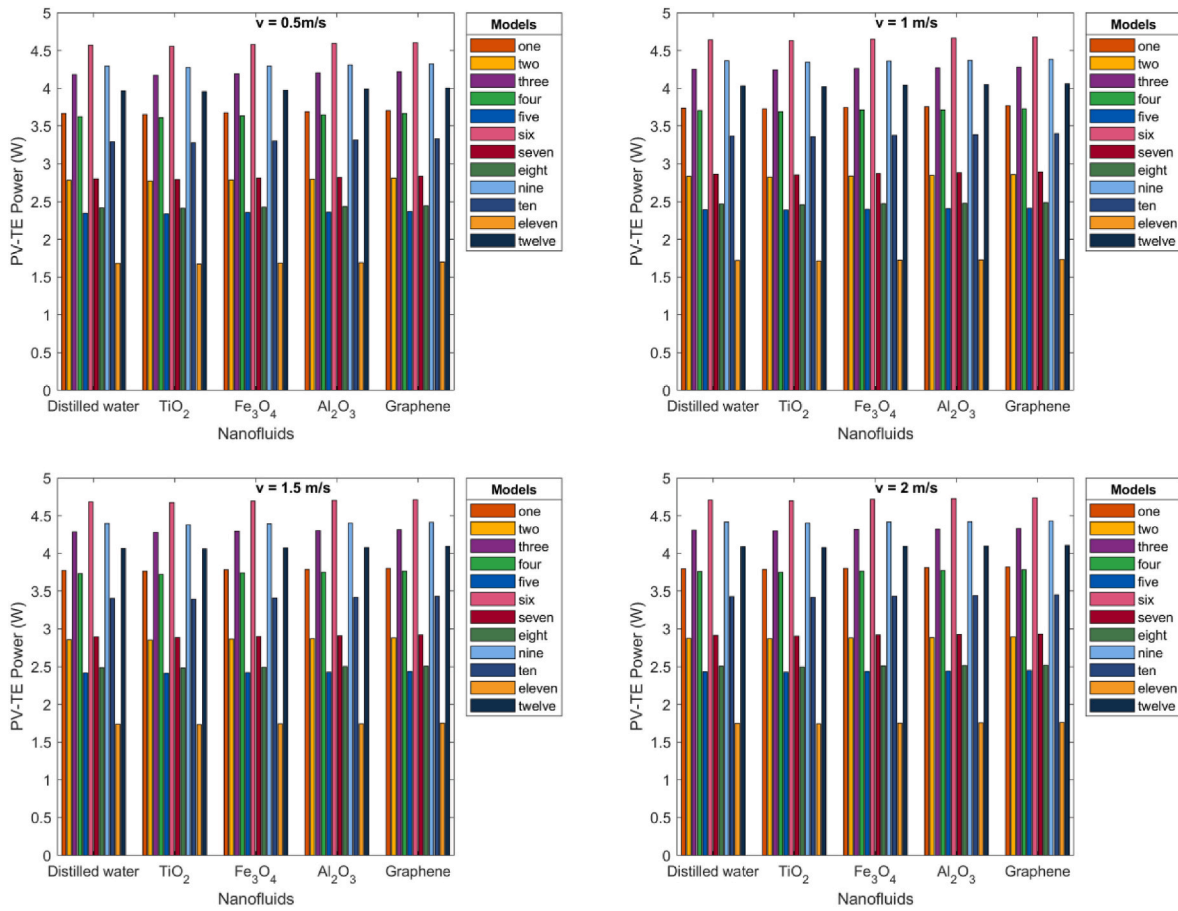


Fig. 13. Effects of different nanofluids on the PV-TE power across the various PV-TE models.

Table 5 provides a comparative overview of the best, worst, and base models in terms of various performance parameters. Models 1–3, utilizing single-stage constant cross-section systems with different semiconductor types (BiTe, SKT, or segmented), exhibit similar Si-PV cell temperature, power output, and efficiency distributions. In contrast, their multi-stage counterparts (Models 10–12) perform worse, indicating the detrimental impact of multi-staging on PV-TE system parameters.

Model 12 excels in TE power, while Model 10 showcases optimal TE efficiency. The discrepancy between their efficiencies is attributed to increased thermal parasitic losses in non-uniform, multi-staged TE couples, degrading TE efficiency. Model 2, with uniform cross-section skutterudite semiconductors in single-stage TEGs, consistently ranks as the worst performer.

For PV-TE power output, Model 6 stands out, generating a peak output of 3.03 W, a 12.2% increase from the base model (Model 1). Surprisingly, the base model achieves the highest efficiency (13.1%). Model 11, employing multi-stage non-uniform cross-section skutterudite thermoelements, consistently performs poorly in both PV-TE power and efficiency, highlighting the unfavorable nature of such a configuration for PV-TE systems.

3.3.2. Transient trade-offs evaluation and optimal model selection

This section aims to determine the most effective Photovoltaic-Thermoelectric (PV-TE) model by balancing power output and efficiency. Model 6 emerges as the peak performer in power generation, yielding an expected PV-TE efficiency of 12.33%. Comparing this efficiency to the highest-performing Model 1 (13.1%), a relative decrease of 5.95% is observed. Conversely, if Model 1 is chosen for its stellar efficiency, an expected PV-TE power output of 2.7 W is anticipated.

Contrasting this with Model 6's power output of 3.03 W reveals a relative degradation of 10.89% in power output. The analysis and Table 6 underscores the significant trade-offs between power output and efficiency, reaffirming Model 6 as the best-performing model despite a slight efficiency sacrifice. This insight is crucial for informed decision-making in the optimization of PV-TE systems.

3.4. Comparative Evaluation of thermal and electrical distributions

This segment provides a comprehensive analysis of the thermal and electrical variations within various Photovoltaic-Thermoelectric (PV-TE) configurations. The study quantitatively evaluates the cooling efficiency of diverse thermoelectric (TE) models for a silicon photovoltaic (Si-PV) cell under standardized conditions, including a constant concentrated solar heat flux of 20 Suns and a graphene nanofluid flow at 2 m/s. Utilizing ANSYS simulation software and predefined boundary conditions, the analysis delves into three-dimensional energy conservation equations, offering insights into temperature variations across all integrated PV-TE system components. The electrical distribution, primarily driven by the Seebeck effect in the TEG, is meticulously examined. Overall, this rigorous comparative analysis enhances understanding of PV-TE model behavior under standardized operating conditions.

3.4.1. Temperature distribution across PV-TE configurations

Fig. 17 visually represents temperature variations across different PV-TE configurations under defined boundary conditions. Multi-stage or cascaded system arrangements, particularly model 10 with non-uniform cross-sections in the TEG module, exhibit the highest temperatures. Model 12, utilizing segmented thermoelectric pins, shows lower peak

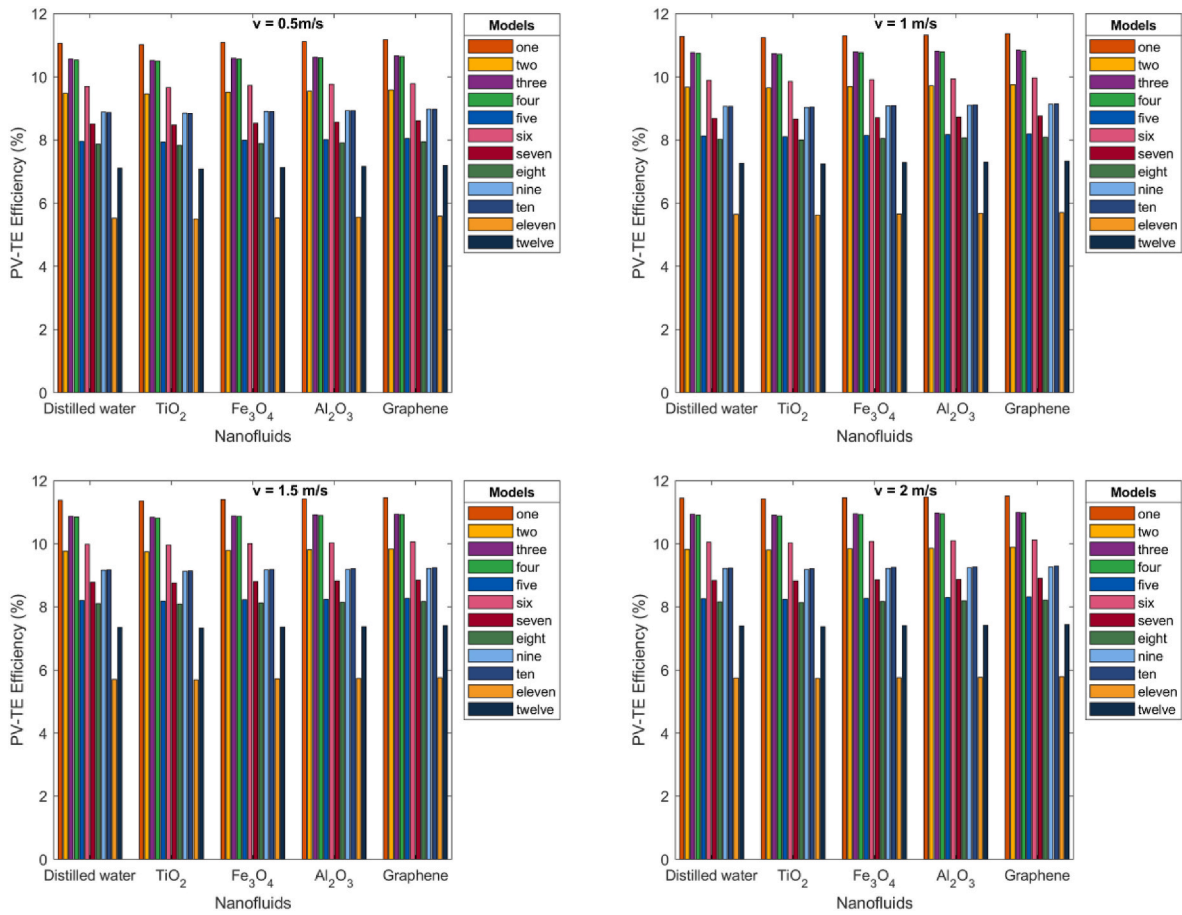


Fig. 14. Effects of different nanofluids on the PV-TE efficiency across the various PV-TE models.

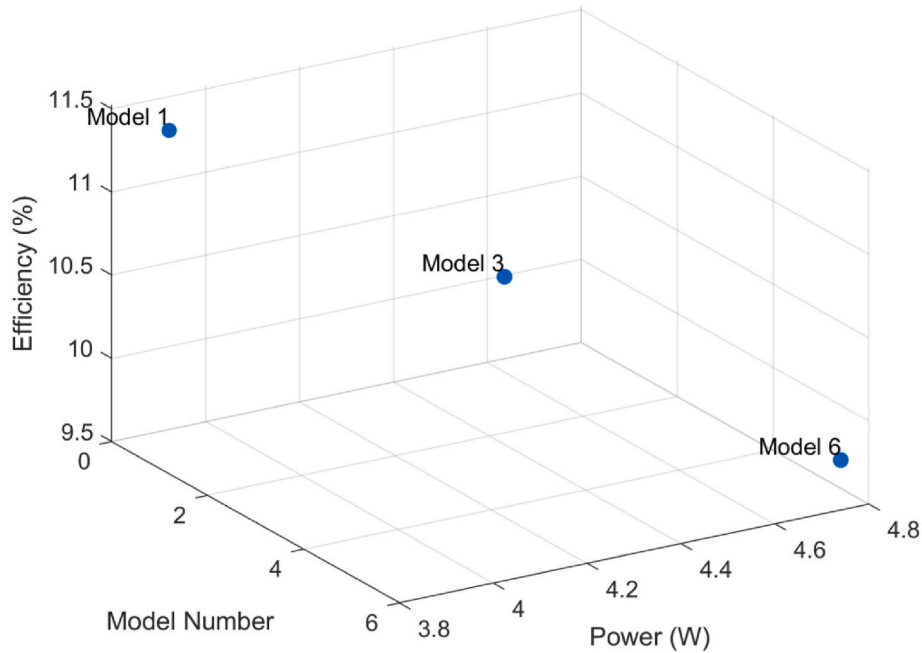


Fig. 15. Three-dimensional representation of power and efficiency trade-offs among selected PV-TE models.

temperatures than model 10, highlighting the cooling benefits of material segmentation.

Model 11, incorporating skutterudite semiconductors, achieves a

lower peak temperature than model 10, emphasizing the cooling effects of skutterudite usage. However, it's crucial to note that these improvements in temperature do not guarantee automatic enhancements in PV-

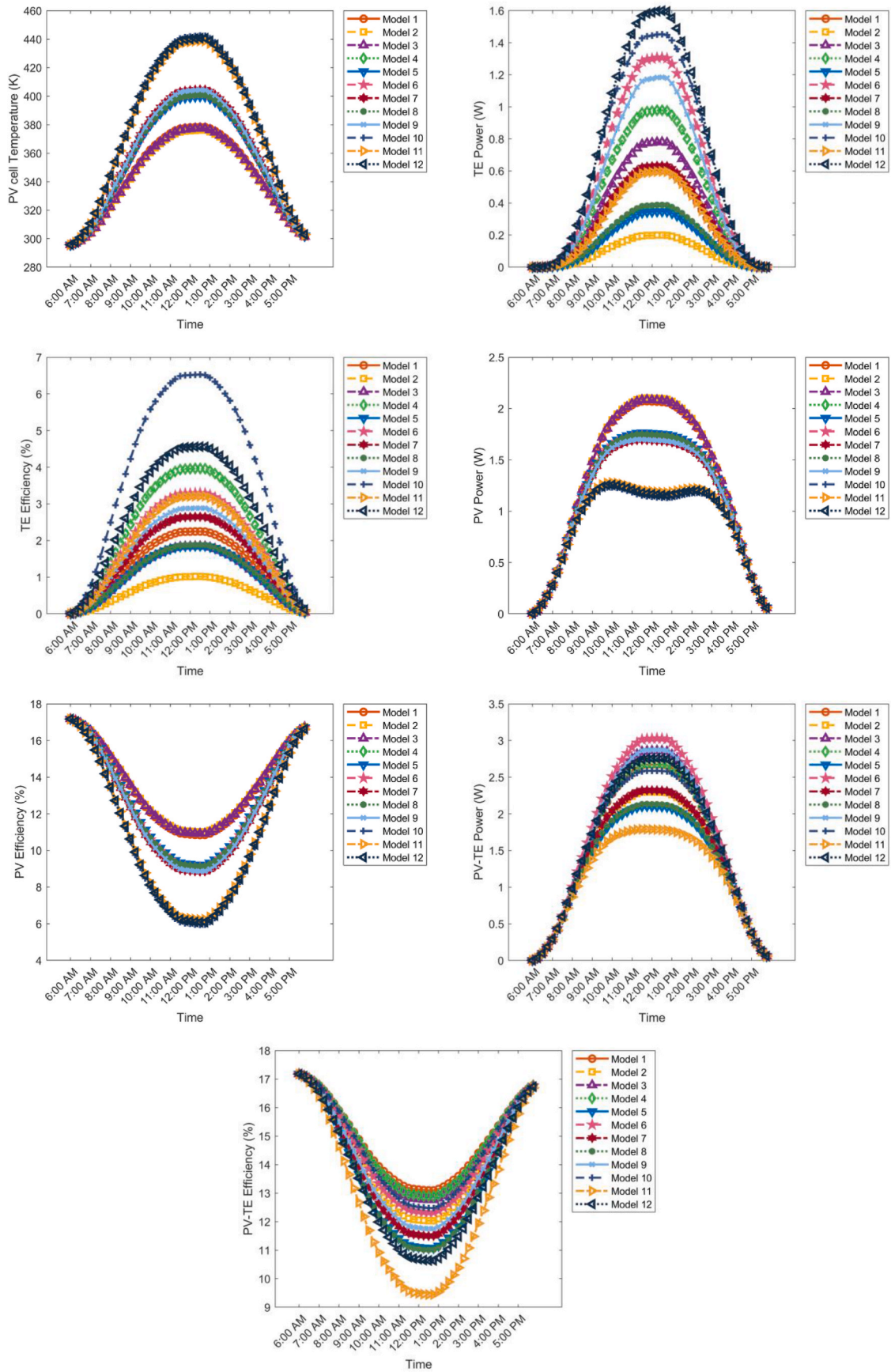


Fig. 16. Transient annual trend of key parameters for PV-TE models under South-Eastern Nigerian climatic conditions in 2022.

Table 5

Comparative evaluation of key parameters across the best, worst, and base PV-TE models.

S/ N	Parameter	Optimum Model	Optimum Value	Worst Model	Worst Value	Base Model 1 Value
1.	T_{PV}	Model 1-3	≈ 377.4 K	Model 10-12	≈ 440.6 K	Same as Model 1-3
2.	P_{TE}	Model 12	1.6 W	Model 2	0.2 W	0.61 W
3.	η_{TE}	Model 10	6.52%	Model 2	1.02%	2.25%
4.	P_{PV}	Model 1-3	≈ 2.1 W	Model 10-12	≈ 1.3 W	Same as Model 1-3
5.	η_{PV}	Model 1-3	$\approx 10.9\%$	Model 10-12	$\approx 6.1\%$	Same as Model 1-3
6.	P_{PV-TE}	Model 6	3.03 W	Model 11	1.79 W	2.7 W
7.	η_{PV-TE}	Model 1	13.1%	Model 11	9.4%	Same as Model 1

Table 6

Comparative Analysis of PV-TE power and efficiency for optimum models 1 and 6 under transient conditions.

Model	PV-TE Efficiency (%)	PV-TE Power Output (W)
Model 1	13.1	2.7
Model 6	12.33	3.03

TE power output and efficiencies. Factors like thermal parasitic losses associated with material segmentation and skutterudite usage play a pivotal role in determining individual power outputs and efficiencies for PV and TE components. This detailed evaluation contributes significantly to understanding the complex interplay of various components and conditions governing PV-TE system performance.

3.4.2. Voltage distribution across PV-TE configurations

Fig. 18 illustrates the Seebeck voltage distribution across different semiconductors in the TEGs of varied PV-TE configurations. The trend showcases a spectrum of voltage values, with zero voltage in n-type semiconductors and the highest in p-type semiconductors, aligning with the electrical boundary conditions. Model 10, utilizing non-uniform cross-sections, records the highest electrical voltage at 3.16 V, emphasizing the impact of temperature on Seebeck voltage. Model 7, a single-stage system, closely follows with an impressive voltage of 2.98 V. In contrast, model 5, employing skutterudite semiconductors with uniform cross-sections, shows the lowest electrical voltage. These results highlight the crucial role of TEG module integration, semiconductor choice, and design in shaping electrical voltage distributions, emphasizing the importance of careful selection and system design for optimal PV-TE performance.

3.5. Discussion of key findings

The present study delves into the intricate dynamics and performance characteristics of hybrid Photovoltaic-Thermoelectric systems through meticulous simulations and analyses. By scrutinizing key parameters such as heat flux dynamics, nanofluid cooling, transient weather conditions, and electrical distributions, the study offers valuable insights into optimizing the design, operation, and efficiency of PV-TE systems. Here, we discuss the main findings and implications of this comprehensive investigation:

i Impact of Heat Flux Dynamics:

The analysis of heat flux dynamics reveals nuanced relationships between concentrated solar irradiance and system performance. Models employing multi-stage systems with segmented geometries exhibit higher temperatures, emphasizing the importance of design configurations in heat retention and energy conversion. Conversely, single-stage systems demonstrate superior cooling effects, leading to lower temperatures and enhanced power outputs.

ii Influence of Nanofluid Cooling and Fluid Velocity:

The investigation into nanofluid cooling and fluid velocity elucidates their significant impact on system performance parameters. Variations in nanofluid types and flow velocities demonstrate distinct effects on Si-PV cell temperature, TE power generation, PV power output, and overall system efficiency. These findings validate the critical role of cooling techniques in mitigating thermal losses and optimizing energy conversion in PV-TE systems.

iii. Transient Weather Conditions:

The analysis of annual transient performance under real-world weather conditions provides valuable insights into system behavior over extended periods. The parabolic distribution of key parameters highlights peak performance during specific times of the day, offering practical considerations for system optimization and operational strategies. This comprehensive approach moves beyond steady-state analyses, providing a holistic understanding of PV-TE system dynamics.

iv. Comparative Evaluation of PV-TE Configurations:

Comparative evaluations of different PV-TE configurations show the trade-offs between power output and efficiency. Models employing multi-stage systems exhibit higher power outputs but may sacrifice efficiency due to increased thermal losses. Conversely, single-stage systems demonstrate better efficiency but may have lower power outputs. This trade-off necessitates careful consideration in system design and selection to achieve optimal performance tailored to specific objectives.

v Electrical Distributions and Semiconductor Selection:

The examination of electrical distributions across various semiconductor materials highlights the importance of semiconductor choice and TEG module integration in shaping voltage distributions. Variations in semiconductor types and configurations result in distinct voltage profiles, emphasizing the need for meticulous system design to optimize electrical performance and energy conversion efficiency.

In conclusion, the results advance our understanding of PV-TE hybrid systems by elucidating the complex interplay of design parameters, operational conditions, and material characteristics. The findings provide a valuable foundation for future research and development efforts aimed at enhancing the efficiency, reliability, and adaptability of renewable energy systems in diverse environmental conditions. By integrating insights from heat flux dynamics, nanofluid cooling, transient weather analysis, and electrical distributions, this study contributes to the ongoing quest for sustainable energy solutions in the face of evolving environmental challenges.

4. Limitation and future work

i. Single Nanofluid Type Consideration:

The investigation focused on the influence of specific nanofluid types on system performance. Future studies could explore a broader range of nanofluid compositions and properties to assess their comparative advantages and limitations under different operating conditions. Additionally, examining the long-term stability and compatibility of

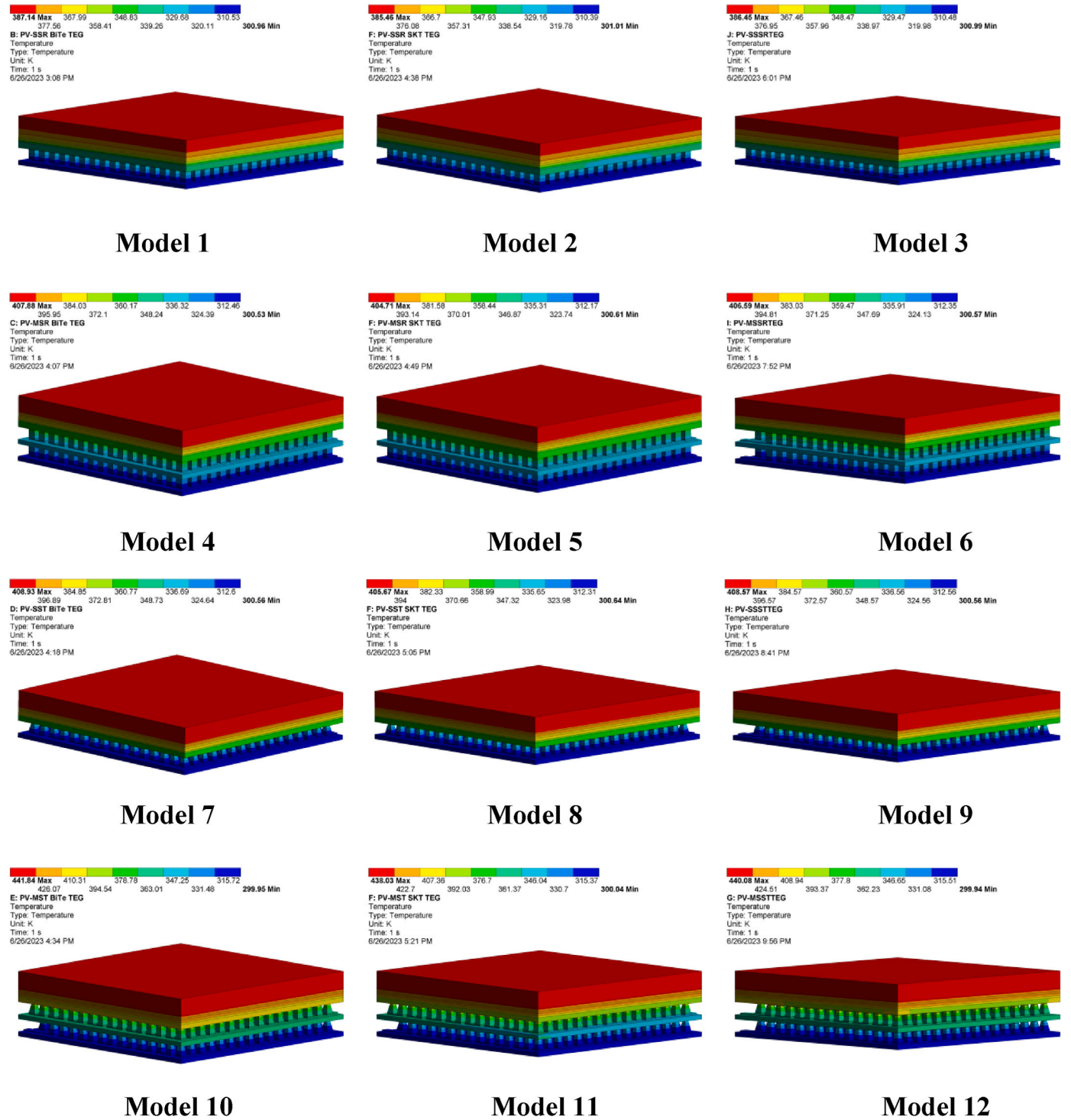


Fig. 17. Comparison of thermal distributions for the various PV-TEs.

nanofluids with system components could offer valuable insights for practical implementation.

ii. Integration of Energy Storage Systems:

The study did not consider the integration of energy storage systems, which could enhance the reliability and stability of PV-TE hybrid systems by mitigating intermittency and matching supply with demand. Investigating the synergies between PV-TE systems and energy storage technologies could unlock new opportunities for grid integration and

off-grid applications.

While this study provides valuable insights into the performance characteristics and optimization strategies of PV-TE hybrid systems, addressing these limitations and pursuing future research directions could further advance our understanding and facilitate the practical deployment of renewable energy technologies for sustainable development.

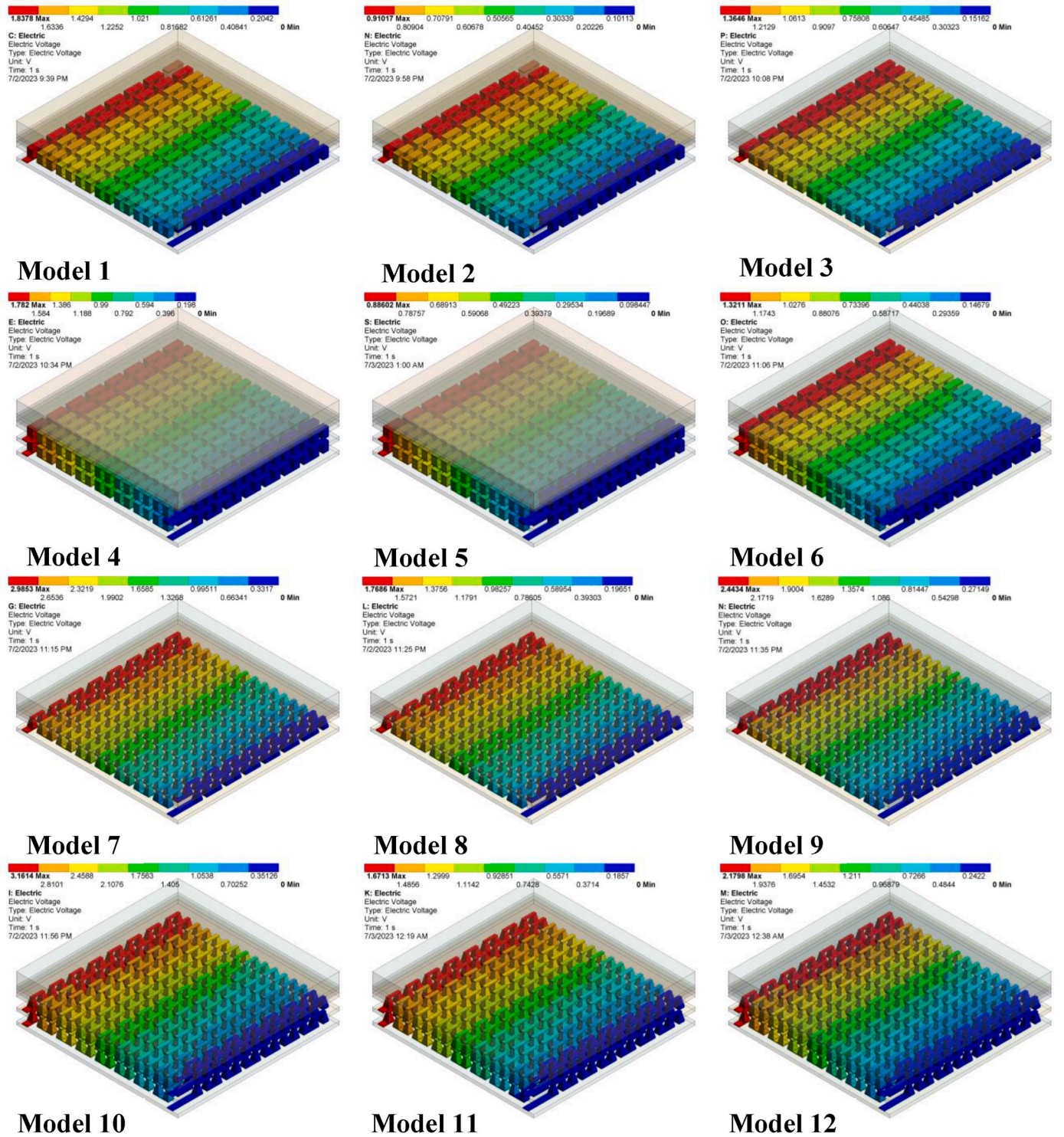


Fig. 18. Comparison of electrical voltage distributions for various PV-TEs.

5. Conclusions and future research

This comprehensive study of Photovoltaic-Thermoelectric (PV-TE) systems unveils crucial insights into their multifaceted dynamics and potential. Evaluating twelve unique PV-TE configurations has brought key factors impacting both steady-state and transient performance to light.

- Model 6, despite a slight 5.95% efficiency drop compared to the base PV-TE, Model 1, proved superior in terms of power output, delivering 3.03 W, a 12% improvement over the base model. This result unequivocally places Model 6 as the prime choice for electrical power generation under both steady and transient conditions, and over annual transient performance.
- Substantial temperature variations across the models are observed, with the highest temperatures typically associated with multi-stage or cascaded system arrangements. However, innovative strategies

such as the segmentation of thermoelectric materials in Model 12, and the replacement of conventional semiconductors with skutterudite semiconductors in Model 11, successfully moderated these high temperatures.

- This study also underscored the significant influence of nanofluids on system performance. Notably, graphene nanofluid emerged as the most effective cooling medium, particularly at an optimal flow velocity of 2 m/s, significantly enhancing the cooling efficiency of these systems.
- In terms of Seebeck voltage, a wide range of values is observed across the thermoelectric generators of different PV-TE configurations. Although higher temperatures generally corresponded to higher Seebeck voltages, the findings confirmed that the selection of semiconductors and the design of the TEG module markedly influence these voltage distributions, and subsequently, the overall system performance.

To summarize, the research findings underscore the following:

- ✓ Model 6 excels in balancing power output and efficiency, not just under steady-state conditions but also over annual transient performance, making it the optimal configuration.
- ✓ The segmentation of thermoelectric materials and the use of skutterudite semiconductors can effectively manage temperature variations in PV-TE systems.
- ✓ The flow velocity of 2 m/s for graphene nanofluid significantly enhances the cooling efficiency of the system.
- ✓ The choice of semiconductors and the design of the TEG module substantially affect the Seebeck voltage distributions, which in turn influence the overall system performance.

In conclusion, these valuable insights highlight the importance of meticulous system design and prudent selection of components, given their far-reaching implications on the performance of PV-TE systems. The results of the research form a solid foundation for future exploration, yet underline the need for further studies to refine and expand upon these findings. Paving the way for future investigations in this promising area, the potential of PV-TE systems in the global pursuit of sustainable energy solutions becomes increasingly evident.

CRediT authorship contribution statement

Hisham Alghamdi: Writing – review & editing, Resources, Formal analysis, Conceptualization. **Chika Maduabuchi:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Kingsley Okoli:** Writing – review & editing, Software, Investigation. **Abdullah Albaker:** Visualization, Resources, Methodology, Formal analysis. **Ibrahim Alatawi:** Validation, Resources, Investigation. **Mohammed Alghassab:** Visualization, Resources, Project administration, Investigation, Formal analysis. **Hind Albalawi:** Visualization, Resources, Methodology, Funding acquisition, Formal analysis. **Mohammad Alkhedher:** Supervision, Resources, Project administration, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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References

- [1] Butti K, Perlin J. *A golden thread: 2500 years of solar architecture and technology*. Palo Alto : New York: Cheshire Books ; Van Nostrand Reinhold; 1980.
- [2] How Does Solar Work?," Energy.gov. Accessed: July. 4, 2023. [Online]. Available: <https://www.energy.gov/eere/solar/how-does-solar-work>.
- [3] Chapin DM, Fuller CS, Pearson GL. A new silicon p-n junction photocell for converting solar radiation into electrical power. *J Appl Phys* May 2004;25(5): 676–7. <https://doi.org/10.1063/1.1721711>.
- [4] Best research-cell efficiency chart [Online]. Available: <https://www.nrel.gov/pv/cell-efficiency.html>. [Accessed 4 July 2023].
- [5] Skoplaki E, Palyvos JA. On the temperature dependence of photovoltaic module electrical performance: a review of efficiency/power correlations. *Sol Energy* May 2009;83(5):614–24. <https://doi.org/10.1016/j.solener.2008.10.008>.
- [6] Zhang J, Xuan Y. An integrated design of the photovoltaic-thermoelectric hybrid system. *Sol Energy* Jan. 2019;177:293–8. <https://doi.org/10.1016/j.solener.2018.11.012>.
- [7] Alghamdi H, et al. A prediction model for the performance of solar photovoltaic-thermoelectric systems utilizing various semiconductors via optimal surrogate machine learning methods. *Eng Sci Technol Int J Apr*. 2023;40:101363. <https://doi.org/10.1016/j.jestech.2023.101363>.
- [8] Shittu S, Li G, Tang X, Zhao X, Ma X, Badiel A. Analysis of thermoelectric geometry in a concentrated photovoltaic- thermoelectric under varying weather conditions. *Energy* 2020;202:1–13. <https://doi.org/10.1016/j.energy.2020.117742>.
- [9] Yin E, Li Q. Achieving extensive lossless coupling of photovoltaic and thermoelectric devices through parallel connection. *Renew Energy* Jun. 2022;193: 565–75. <https://doi.org/10.1016/j.renene.2022.05.054>.
- [10] Liu C, Cui YJ, Wang KF, Wang BL. Bending strength evaluation and power generation performance optimization of a curved photovoltaic-thermoelectric hybrid device. *Compos Struct* Oct. 2023;321:117297. <https://doi.org/10.1016/j.compstruct.2023.117297>.
- [11] Wang N, Ni L-L, Wang A, Shan H-S, Jia H-Z, Zuo L. High-efficiency photovoltaic-thermoelectric hybrid energy harvesting system based on functionally multiplexed intelligent thermal management. *Energy Convers Manag* Nov. 2022;272:116377. <https://doi.org/10.1016/j.enconman.2022.116377>.
- [12] Azimi P, Shahsavari A, Azimi N. Improving the performance of photovoltaic modules using ultrasonic- thermoelectric generators. *Appl Therm Eng* Feb. 2023; 220:119704. <https://doi.org/10.1016/j.applthermaleng.2022.119704>.
- [13] Xie H, Wang J, Xi T, Liu Y, Ai F. Dependence of the thermal conductivity of nanoparticle-fluid mixture on the base fluid. *J Mater Sci Lett* Oct. 2002;21(19): 1469–71. <https://doi.org/10.1023/A:1020060324472>.
- [14] Mahian O, et al. Recent advances in modeling and simulation of nanofluid flows- Part I: fundamentals and theory. *Phys Rep* Feb. 2019;790:1–48. <https://doi.org/10.1016/j.physrep.2018.11.004>.
- [15] Maheshwary PB, Handa CC, Nemade KR. A comprehensive study of effect of concentration, particle size and particle shape on thermal conductivity of titania/ water based nanofluid. *Appl Therm Eng* Jun. 2017;119:79–88. <https://doi.org/10.1016/j.applthermaleng.2017.03.054>.
- [16] Loon YW, Sidik NAC. A comprehensive review of recent progress of nanofluid in engineering application: microchannel heat sink (MCHS). *J Adv Res Appl Sci Eng Technol* Oct. 2022;28(2):2. <https://doi.org/10.37934/araset.28.2.125>.
- [17] Sharaf M, Yousef MS, Huzayyin AS. Review of cooling techniques used to enhance the efficiency of photovoltaic power systems. *Environ Sci Pollut Res* Jan. 2022;29 (18):26131–59. <https://doi.org/10.1007/S11356-022-18719-9>. 2022 2918.
- [18] Shah TR, Ali HM. Applications of hybrid nanofluids in solar energy, practical limitations and challenges: a critical review. *Sol Energy* May 2019;183:173–203. <https://doi.org/10.1016/j.solener.2019.03.012>.
- [19] Rejeb O, et al. Comparative investigation of concentrated photovoltaic thermal-thermoelectric with nanofluid cooling. *Energy Convers Manag* May 2021;235: 113968. <https://doi.org/10.1016/j.enconman.2021.113968>.
- [20] Soltani S, Kasaeeian A, Lavajoo A, Loni R, Najafi G, Mahian O. Exergetic and environmental assessment of a photovoltaic thermal-thermoelectric system using nanofluids: indoor experimental tests. *Energy Convers Manag* Aug. 2020;218: 112907. <https://doi.org/10.1016/j.enconman.2020.112907>.
- [21] Khalili Z, Sheikholsami M. Analyzing the effect of confined jet impingement on efficiency of photovoltaic thermal solar unit equipped with thermoelectric generator in existence of hybrid nanofluid. *J Clean Prod* 2023;406(Jun):137063. <https://doi.org/10.1016/j.jclepro.2023.137063>.
- [22] Abesh Ahmadlou L, et al. Experimental investigation of PV/T and thermoelectric systems using CNT/water nanofluids. *Appl Therm Eng* Jun. 2023;227:120350. <https://doi.org/10.1016/j.applthermaleng.2023.120350>.
- [23] Praveenkumar S, Agyekum EB, Kumar A, Velkin VI. Thermo-enviro-economic analysis of solar photovoltaic/thermal system incorporated with u-shaped grid copper pipe, thermal electric generators and nanofluids: an experimental

- investigation. *J Energy Storage Apr.* 2023;60:106611. <https://doi.org/10.1016/j.est.2023.106611>.
- [24] Lee M-Y, Seo J, Lee H, Garud KS. Power generation, efficiency and thermal stress of thermoelectric module with leg geometry, material, segmentation and two-stage arrangement. *Symmetry May* 2020;12(5):786. <https://doi.org/10.3390/sym12050786>.
- [25] Aljaghtham M, Celik E. Numerical analysis of energy conversion efficiency and thermal reliability of novel, unileg segmented thermoelectric generation systems. *Int J Energy Res* 2021;45(6):8810–23. <https://doi.org/10.1002/er.6416>.
- [26] Maduabuchi C, Alobaid M. Geometry and stage number optimization of a concentrating solar multistage segmented thermoelectric generator by exploiting different optimization schemes. *Int J Energy Res* 2022;(July):1–20. <https://doi.org/10.1002/er.8595>.
- [27] Siddique ARM, Venkateshwar K, Mahmud S, Van Heyst B. Performance analysis of bismuth-antimony-telluride-selenium alloy-based trapezoidal-shaped thermoelectric pallet for a cooling application. *Energy Convers Manag* 2020;222 (March):113245. <https://doi.org/10.1016/j.enconman.2020.113245>.
- [28] Maduabuchi C, Lamba R, Ozoegwu C, Njoku HO, Eke M, Ejiogu EC. Chapter 14.3 - parametric optimization of a segmented thermoelectric generator in a concentrated photovoltaic system under fluctuating weather conditions. In: Padmanaban S, Khan B, Mahela OP, Alhelou HH, Rajkumar S, editors. *Active electrical distribution network*. Academic Press; 2022. p. 415–30. <https://doi.org/10.1016/B978-0-323-85169-5.00020-4>.
- [29] Maduabuchi C, Eneh C, Alrobaian AA, Alkhdher M. Deep neural networks for quick and precise geometry optimization of segmented thermoelectric generators. *Energy Jan.* 2023;263(PC):125889. <https://doi.org/10.1016/j.energy.2022.125889>.
- [30] Guo X, et al. A new hybrid system composed of high-temperature proton exchange fuel cell and two-stage thermoelectric generator with Thomson effect: energy and exergy analyses. *Energy* 2020;195:117000. <https://doi.org/10.1016/j.energy.2020.117000>.
- [31] Ge Y, He K, Xiao L, Yuan W, Huang S-M. Geometric optimization for the thermoelectric generator with variable cross-section legs by coupling finite element method and optimization algorithm. *Renew Energy Jan.* 2022;183:294–303. <https://doi.org/10.1016/j.renene.2021.11.016>.
- [32] He Y, Tao YB, Zhao CY, Yu XK. Structure parameter analysis and optimization of photovoltaic-phase change material-thermoelectric coupling system under space conditions. *Renew Energy Nov.* 2022;200:320–33. <https://doi.org/10.1016/j.renene.2022.09.129>.
- [33] Cui YJ, Wang BL, Li JE, Wang KF. Performance evaluation and lifetime prediction of a segmented photovoltaic-thermoelectric hybrid system. *Energy Convers Manag May* 2020;211(January):112744. <https://doi.org/10.1016/j.enconman.2020.112744>.
- [34] Maduabuchi C, Alanazi M, Alzahmi A. Accurate prophecy of photovoltaic-segmented thermoelectric generator's performance using a neural network that feeds on finite element-generated data. *Sustain Energy Grids Netw Dec.* 2022;32: 100905. <https://doi.org/10.1016/j.segan.2022.100905>.
- [35] Zhao Q, Zhang H, Hu Z, Hou S. Achieving a broad-spectrum photovoltaic system by hybridizing a two-stage thermoelectric generator. *Energy Convers Manag May* 2020;211:112778. <https://doi.org/10.1016/j.enconman.2020.112778>.
- [36] Maduabuchi C, Lamba R, Njoku H, Eke M, Mgbemene C. Effects of leg geometry and multistaging of thermoelectric modules on the performance of a photovoltaic-thermoelectric system using different photovoltaic cells. *Int J Energy Res Oct.* 2021;45(12):17888–902. <https://doi.org/10.1002/er.6925>.
- [37] Mgbemene CA, Njoku HO, Agbo COA. Investigation of parametric performance of the hybrid 3D CPC/TEM system due to thermoelectric irreversibilities. *Front Energy Res Oct.* 2018;6(October):1–11. <https://doi.org/10.3389/fenrg.2018.00101>.
- [38] Maduabuchi C, Lamba R. Chapter 7. Photovoltaic-thermoelectric power generation: effects of photovoltaic cell type, thermoelectric leg geometry, and multistaging on system performance. In: *Sustainable energy storage for furthering renewable energy*. Begell House; 2022 [Online]. Available: https://www.begellhouse.com/ebook_platform/monograph/chapter/7c4e2997275ac4cd-165.html. [Accessed 26 June 2023].
- [39] Alghamdi H, et al. Transient numerical simulations in innovative thermoelectric power: a comprehensive study on material segmentation and cross-section design for multi-faceted excellence. *Case Stud Therm Eng Oct.* 2023;103684. <https://doi.org/10.1016/j.csste.2023.103684>.
- [40] Alghamdi H, et al. Pioneering sustainable power: harnessing material innovations in double stage segmented thermoelectric generators for optimal 4E performance. *Appl Energy Dec.* 2023;352:121885. <https://doi.org/10.1016/j.apenergy.2023.121885>.
- [41] Zhou J, Zhang Z, Liu H, Yi Q. Temperature distribution and back sheet role of polycrystalline silicon photovoltaic modules. *Appl Therm Eng Jan.* 2017;111(1): 1296–303. <https://doi.org/10.1016/j.applthermaleng.2016.10.095>.
- [42] Nyarko FKA, Takyi G, Amalu EH, Adaramola MS. Generating temperature cycle profile from in-situ climatic condition for accurate prediction of thermo-mechanical degradation of c-Si photovoltaic module. *Eng Sci Technol Int J Apr.* 2019;22(2):502–14. <https://doi.org/10.1016/j.jestech.2018.12.007>.
- [43] Schroedter-Homscheidt M, et al. The Copernicus atmosphere monitoring service (CAMS) radiation service in a nutshell. Abu Dhabi, United Arab Emirates: hal-01386187. In: 22nd SolarPACES conference 2016; 2016. p. 1–4 [Online]. Available: <https://hal-mines-paristech.archives-ouvertes.fr/hal-01386187>.
- [44] Randles CA, et al. The MERRA-2 aerosol reanalysis, 1980 onward. Part I: system description and data assimilation evaluation. *J Clim Sep.* 2017;30(17):6823–50. <https://doi.org/10.1175/JCLI-D-16-0609.1>.
- [45] Syam Sundar L, Singh MK, Sousa ACM. Investigation of thermal conductivity and viscosity of Fe3O4 nanofluid for heat transfer applications. *Int Commun Heat Mass Tran May* 2013;44:7–14. <https://doi.org/10.1016/j.icheatmasstransfer.2013.02.014>.
- [46] Abdelkareem MA, et al. Prospects of thermoelectric generators with nanofluid. *Therm Sci Eng Prog Mar.* 2022;29:101207. <https://doi.org/10.1016/j.tsep.2022.101207>.
- [47] Ahammed N, Asirvatham LG, Wongwises S. Thermoelectric cooling of electronic devices with nanofluid in a multiport minichannel heat exchanger. *Exp Therm Fluid Sci Jun.* 2016;74:81–90. <https://doi.org/10.1016/j.expthermflsci.2015.11.023>.
- [48] Sieder EN, Tate GE. Heat transfer and pressure drop of liquids in tubes. *Ind Eng Chem Dec.* 1936;28(12):1429–35. <https://doi.org/10.1021/ie50324a027>.
- [49] Ramos-Castañeda CF, Olivares-Robles MA, Méndez-Méndez JV. Analysis of the performance of a solar thermoelectric generator for variable leg geometry with nanofluid cooling. *Processes* 2021;9(8). <https://doi.org/10.3390/pr9081352>.
- [50] Zhou J, Yi Q, Wang Y, Ye Z. Temperature distribution of photovoltaic module based on finite element simulation. *Sol Energy Jan.* 2015;111:97–103. <https://doi.org/10.1016/j.solener.2014.10.040>.
- [51] Maduabuchi C. Improving the performance of a solar thermoelectric generator using nano-enhanced variable area pins. *Appl Therm Eng Apr.* 2022;206(May 2021):118086. <https://doi.org/10.1016/j.applthermaleng.2022.118086>.
- [52] Maduabuchi C, Eneh C. Performance improvement of a concentrated photovoltaic-thermoelectric system by exploiting geometry configuration. *Int J Ambient Energy Aug.* 2022;(0):1–13. <https://doi.org/10.1080/01430750.2022.2101520>.
- [53] Maduabuchi C, Lamba R, Ozoegwu C, Njoku HO, Eke M, Ejiogu EC. Parametric optimization of a segmented thermoelectric generator in a concentrated photovoltaic system under fluctuating weather conditions. In: *Active electrical distribution network*. Elsevier; 2022. p. 415–30. <https://doi.org/10.1016/B978-0-323-85169-5.00020-4>.
- [54] Maduabuchi C, Ejenakevwe K, Ndukwe A, Mgbemene C. High performance solar thermoelectric generator using asymmetrical variable leg geometries. *E3S Web Conf Feb.* 2021;239(January):00005. <https://doi.org/10.1051/e3sconf/202123900005>.
- [55] Maduabuchi C, Eke M. Solar electricity generation using a photovoltaic-thermoelectric system operating in Nigeria climate. *IOP Conf Ser Earth Environ Sci Apr.* 2021;730(1):012029. <https://doi.org/10.1088/1755-1315/730/1/012029>.
- [56] AlNimr MA, AlAmmari WA, Alkhalidi A. A novel hybrid photovoltaics/thermoelectric cooler distillation system. *Int J Energy Res Feb.* 2019;43(2): 791–805. <https://doi.org/10.1002/er.4309>.
- [57] Evans DL. Simplified method for predicting photovoltaic array output. *Sol Energy* 1981;27(6):555–60. [https://doi.org/10.1016/0038-092X\(81\)90051-7](https://doi.org/10.1016/0038-092X(81)90051-7).
- [58] Maduabuchi CC, Mgbemene CA. Numerical study of a phase change material integrated solar thermoelectric generator. *J Electron Mater Oct.* 2020;49(10): 5917–36. <https://doi.org/10.1007/s11664-020-08331-3>.
- [59] Maduabuchi C, Njoku H, Eke M, Mgbemene C, Lamba R, Ibrahim JS. Overall performance optimisation of tapered leg geometry based solar thermoelectric generators under isoflux conditions. *J Power Sources Jul.* 2021;500(July):229989. <https://doi.org/10.1016/j.jpowsour.2021.229989>.
- [60] Maduabuchi C, Lamba R, Ozoegwu C, Njoku HO, Eke M, Ejiogu EC. Electro-thermal and mechanical optimization of a concentrated solar thermoelectric generator. In: T. D.SK, V.-B.-H. A., editors. *Mitigating climate change*. Springer proceedings in energy. Cham: Springer; 2022. p. 65–81. https://doi.org/10.1007/978-3-030-92148-4_3.
- [61] Alghamdi H, et al. Smart optimization of semiconductors in photovoltaic-thermoelectric systems using recurrent neural networks. *Int J Energy Res* 2023; 2023:e6927245. <https://doi.org/10.1155/2023/6927245>.
- [62] Maduabuchi CC, Eke MN, Mgbemene CA. Solar power generation using a two-stage X-leg thermoelectric generator with high-temperature materials. *Int J Energy Res Jul.* 2021;45(9):13163–81. <https://doi.org/10.1002/er.6644>.
- [63] Maduabuchi C, Fagehi H, Alatawi I, Alkhdher M. Predicting the optimal performance of a concentrated solar segmented variable leg thermoelectric generator using neural networks. *Energies* 2022;15(16):6024. <https://doi.org/10.3390/en15166024>.
- [64] Shittu S, Li G, Tang X, Zhao X, Ma X, Badii A. Analysis of thermoelectric geometry in a concentrated photovoltaic-thermoelectric under varying weather conditions. *Energy Jul.* 2020;202:117742. <https://doi.org/10.1016/j.energy.2020.117742>.
- [65] Motiei P, Yaghoubi M, GoshtashbiRad E, Vadiiee A. Two-dimensional unsteady state performance analysis of a hybrid photovoltaic-thermoelectric generator. *Renew Energy Apr.* 2018;119:551–65. <https://doi.org/10.1016/j.renene.2017.11.092>.
- [66] Alghamdi H, et al. Beyond traditional boundaries: exergo-economic and thermo-mechanical optimization of segmented thermoelectric generators with varied cross-sections. *J Power Sources Oct.* 2023;581:233500. <https://doi.org/10.1016/j.jpowsour.2023.233500>.
- [67] Kraemer D, et al. High-performance flat-panel solar thermoelectric generators with high thermal concentration. *Nat Mater* 2011;10(7):532–8. <https://doi.org/10.1038/nmat3013>.
- [68] Alghamdi H, et al. From sunlight to power: enhancing 4E performance with two-stage segmented thermoelectric generators in concentrated solar applications. *J Clean Prod Oct.* 2023;139314. <https://doi.org/10.1016/j.jclepro.2023.139314>.
- [69] Motiei P, Yaghoubi M, GoshtashbiRad E, Vadiiee A. Two-dimensional unsteady state performance analysis of a hybrid photovoltaic-thermoelectric generator. *Renew Energy* 2018;119:511–65. <https://doi.org/10.1016/j.renene.2017.11.092>.
- [70] Lee H. *Thermoelectrics*. first ed. West Sussex, UK: John Wiley & Sons Ltd; 2017.

- [71] Kossyvakis DN, Vossou CG, Provatidis CG, Hristoforou EV. Computational analysis and performance optimization of a solar thermoelectric generator. *Renew Energy* 2015;81:150–61. <https://doi.org/10.1016/j.renene.2015.03.026>.
- [72] Li G, Shittu S, Ma X, Zhao X. Comparative analysis of thermoelectric elements optimum geometry between photovoltaic-thermoelectric and solar thermoelectric. *Energy Mar.* 2019;171:599–610. <https://doi.org/10.1016/j.energy.2019.01.057>.
- [73] Shrotriya V, Li G, Yao Y, Moriarty T, Emery K, Yang Y. Accurate measurement and characterization of organic solar cells. *Adv Funct Mater Oct.* 2006;16(15):2016–23. <https://doi.org/10.1002/adfm.200600489>.
- [74] Tan NYJ, Zhang X, Neo DWK, Huang R, Liu K, Senthil Kumar A. A review of recent advances in fabrication of optical Fresnel lenses. *J Manuf Process Nov.* 2021;71: 113–33. <https://doi.org/10.1016/j.jmapro.2021.09.021>.
- [75] Jiang C, et al. A review of the compound parabolic concentrator (CPC) with a tubular absorber. *Energies Jan.* 2020;13(3):3. <https://doi.org/10.3390/en13030695>.
- [76] Pan S-Y, Snyder SW, Packman AI, Lin YJ, Chiang P-C. Cooling water use in thermoelectric power generation and its associated challenges for addressing water-energy nexus. *Water-Energy Nexus Jun.* 2018;1(1):26–41. <https://doi.org/10.1016/j.wen.2018.04.002>.
- [77] Jiang H, et al. A novel thermoelectric distiller integrated with water cooling circulation for alcohol distillation. *Appl Therm Eng Jan.* 2023;219:119392. <https://doi.org/10.1016/j.applthermaleng.2022.119392>.
- [78] Bondar KE, Shulaev NS, Ivanov SP. Hydrodynamic tests of small-sized circulating water cooling devices. *Chem Petrol Eng Jan.* 2021;56(9):794–8. <https://doi.org/10.1007/s10556-021-00844-w>.
- [79] Aljaghtham M, Celik E. Design of cascade thermoelectric generation systems with improved thermal reliability. *Energy Mar.* 2022;243:123032. <https://doi.org/10.1016/j.energy.2021.123032>.
- [80] Bin-Abdun NA, et al. The comparison between the performance of water and CuO/water nanofluid in improving the heat transfer of small spaces. *IOP Conf Ser Mater Sci Eng Nov.* 2018;429:012073. <https://doi.org/10.1088/1757-899X/429/1/012073>.
- [81] Saleh R, Putra N, Wibowo RE, Septiadi WN, Prakoso SP. Titanium dioxide nanofluids for heat transfer applications. *Exp Therm Fluid Sci Jan.* 2014;52:19–29. <https://doi.org/10.1016/j.expthermflusci.2013.08.018>.
- [82] Chen F, Ilyas N, Liu X, Li Z, Yan S, Fu H. Size effect of Fe₃O₄ nanoparticles on magnetism and dispersion stability of magnetic nanofluid. *Front Energy Res* 2021; 9. Accessed: Jul. 13, 2023. [Online]. Available: <https://www.frontiersin.org/articles/10.3389/fenrg.2021.780008>.
- [83] Sridhara V, Satapathy LN. Al₂O₃-based nanofluids: a review. *Nanoscale Res Lett Jul.* 2011;6(1):456. <https://doi.org/10.1186/1556-276X-6-456>.
- [84] Barai DP, Bhanvase BA, Sonawane SH. A review on graphene derivatives-based nanofluids: investigation on properties and heat transfer characteristics. *Ind Eng Chem Res Jun.* 2020;59(22):10231–77. <https://doi.org/10.1021/acs.iecr.0c00865>.
- [85] Rejeb O, et al. Comparative investigation of concentrated photovoltaic thermal-thermoelectric with nanofluid cooling. *Energy Convers Manag May* 2021;235: 113968. <https://doi.org/10.1016/j.enconman.2021.113968>.