International Journal of Heat and Technology
Vol. 43, No. 3, June, 2025, pp. 1093-1108
Journal homepage: http://iieta.org/journals/ijht

Enhancing Solar Cell Efficiency Through Radiative Cooling and Thermoelectric Integration

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https://doi.org/10.18280/ijht.430328

Received: 16 April 2025
Revised: 26 May 2025
Accepted: 11 June 2025
Available online: 30 June 2025

Keywords:
radiative cooling, solar cell efficiency, high-performance, thermoelectric generator

ABSTRACT

To improve the efficiency of solar cells in high-performance applications, this study develops a hybrid technique integrating radiative cooling with thermoelectric generators. It is such that radiative cooling reduces the temperature of the solar cells whereby it increases the open-circuit voltage and the energy conversion efficiency further. Meanwhile, the thermoelectric generators (TEGs) recover waste heat for additional power generation. Both experiments and simulations have evidenced that colloidal quantum dot (CQD) solar cells can realize a peak enhancement of 17.8% in their relative electrical conversion efficiency at an absorbed power of 400 mW. The maximum power output increased by 2.34% on account of a temperature regulating system whereby the photovoltaic conversion efficiency was improved up to 6% over the range 300 K to 350 K. Coupled systems also showed an increase in exergy performance with a daily energy gain of 10-15 W/m2. The coupled system alleviates the thermal load and cuts the dark current so that the amount of time for which the solar cells may continue working is further extended. These results give an indication that radiative-thermoelectric integration can be applied in skylights of automobiles, in space systems, and in concentrated photovoltaics where efficiency demands are high and restricted surface cooling is an issue.

1. INTRODUCTION

A major difficulty limiting the performance of ultrahigh-efficiency solar cells is managing heat. In conditions of high light or elevated ambient temperatures, the solar cells begin to experience efficiency declines since the operating temperature is intensified; this in turn reduces open-circuit voltage and speeds material breakdown. The effects are most pronounced in CPV, vehicle-integrated photovoltaic modules, and aircraft systems, where conventional convection cooling is not allowed or possible.

It allows the heat to be passively emitted through the infrared atmospheric transparency window at 8-13 µm wavelength size into space. So a solar cell can work below the ambient temperature without the need for energy. Materials engineered with high infrared emissivity and low solar absorptivity spawn excellent radiators, more so in clear-sky nights [1-4].

They can convert heat gradients into electrical energy by the principle of Seebeck. When used integrally with the photovoltaic modules, they are able to capture the part of the heat that would be lost and thus not only improve the thermal management but also make supplementary energy generation possible.

The study purposes to develop a hybrid system integrating radiative cooling with thermoelectric generation for enhancing efficiency and maintaining a steady temperature of a solar cell. This particular integration is highly suitable for these application areas due to its ability for high performance in electric vehicles, smart buildings, and orbital platforms where the issues of space reliability and efficiency are critical.

- To replicate and empirically validate the thermal and electrical efficacy of the system.
- To measure its effects on the photovoltaic conversion efficiency, electrical output, and thermal dissipation.

For this, the method includes:

Creating a two-dimensional multi-domain analytical model for radiative and thermoelectric figures-of-merit.

Experimental characterization of CQD and perovskite solar cells coupled to Bi_2Te_3 TEG modules under absorbed power levels of 100-400 mW.

Evaluation of important indicators like temperature differential, conversion efficiency, exergy, and daily energy yield. On the account of:

A boost by a maximum of 17.8% relative electrical conversion efficiency for CQD cells.

Up to 70 K a temperature difference enhances stability and performance of the cell.

An increase of 2.34% maximum power production on the integration of radiative and thermoelectric components.

The system can provide a consistent 10 to 15 watts each square meter per day, which makes it highly effective, particularly if you're looking for renewable sources of energy in resource-constrained or difficult-to-reach places, including off-grid applications, space missions, or rural locales.

This paper is structured as follows. Section II puts in place the theoretical modeling and optical design parameters relevant to radiative cooling. Section III shows how the thermoelectric device is constructed and how the modeling of the system is done. Section IV gives experimental validation and performance evaluation. Section V gives final observations and delineates prospective advancements [5-7].

This effort furthers the creation of energy-self-reliant, heat-strong sun setups, enabling high-power making with added use of leftover warmth and keeping safe during harsh conditions.

2. BACKGROUND AND FUNDAMENTAL CONCEPTS

The switch to green power is based on the rising worries about the environment and climate. Of all the types of renewable energy, solar power is most widely available and can be scaled up. The market is currently being led by photovoltaic or PV technologies which are highly stable and have matured silicon-based solar cells; prior to this, such cells used to lead the market. But the new-generation materials perovskites, and multijunction III-V semiconductors have attracted the research community due to their high power conversion efficiencies as well as applicability in new applications like high-performance electronics and space systems.

Perovskite solar cells (PSCs) have shown fast increase over other thin-film technologies with efficiencies now over 25% but also with the added value of low-cost production, especially organic low-temperature deposition processes. The major issue in the thermal stability of the devices is still the perovskite. Under both one sun and thermal stress, accelerated conditions in which the most rapid degradation mechanisms in such materials are studied, degradation of the perovskites sets in very quickly due to heat accumulating at localized hot spots—sometimes leading to losses across as many as 30 active sites within the absorber layer [8-11]. Overcoming excess heat has thus become a major challenge in the maintenance of long-term efficiency and reliability.

Recent studies have brought up radiative cooling as a passive thermal management technique. It takes infrared emission from atmospheric transparency windows as a path to allow the dissipation of heat without any energy source [12]. Key research has found that surfaces carefully engineered, using materials such as SiO_2, and Al_2O_3, and photonic crystals can attain sub-ambient temperatures even under the impact of sunlight [13, 14]. These radiative cooling layers will keep the cell at the right temperature, prevent thermal-induced degradation, and increase the lifetime of the device.

Parallel research has also examined thermoelectric generators (TEGs) for converting waste heat from solar cells into electricity using the Seebeck effect. Some of the TEGs are made up of materials, e.g., Bi_2Te_3 and PbTe, having good electrical conductivity and low thermal conductivity which makes them good candidates to integrate into PV systems [15, 16]. Though effective in energy recovery, TEGs alone do not reduce the temperature of the PV system to a significant extent. Therefore, hybrid systems, which integrate radiative coolers and TEGs to maximize both heat management and energy efficiency, have been proposed.

Most of the prior work and research was centered or has been focusing on either radiative cooling or thermoelectric harvesting. Very few studies have been taken up to explore the combined effect of both of these technologies on the performance of a solar cell under real operating conditions. And, most of the existing work is based on modeling and ideal assumptions with very little experiment validation of integrated systems in high-power environments.

This study closes this missing information by suggesting and proving a mix PV–light–TEG system. It centers on measuring the heat and electricity gains of combination, particularly under high light and limited cooling by air. By mixing both passive and active ways of cooling, this work aims to improve the design of effective, self-regulating photovoltaic systems for next-generation energy applications (see Figure 1).

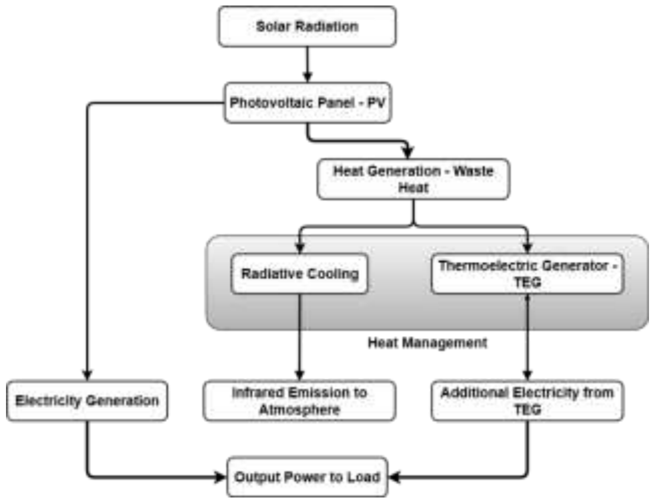

Figure 1. Cooling system of PV system

Considering the above opportunities and limitations, this paper disperses the work in the field of radiative cooling and thermoelectric separation pathways and tracks their integration efforts and limitations with high-performance solar cells. We describe the scope of the current research work in this section of the paper.

We aim to present a detailed view and understanding of the thermal management and energy conversion mechanisms. The limitations associated with the isolated study of each scheme individually are also highlighted in detail. Our aim is to focus on the performance improvement of the solar cells along with the enhancement in water recovery while maintaining the solar cell system's efficient operations. This work's significance lies in two aspects, where generally a cooling system's objective is to remove the waste heat from the system, but this study involves high-temperature water recovery to minimize the system's total heat output. The better the solar cell converts light to energy, the more valuable the energy. Thus, by managing the temperature rise associated with the band-to-band electronic transitions in a solar cell, we can ensure that the cell generates more valuable energy.

This paper seeks to answer research questions related to the integration of a thermoelectric cell and a solar cell. Our objectives are to see the effect of this integration on the radiative cooling efficiency of the solar cell, to leverage the temperature differences to create a small amount of extra electrical power, and to extract the temperature-differentiation-anacoustic-attenuation metrized signal of the operational solar cell system. In addition to electrical power, synergetic effects can mean the system outputs a flow of liquid water. Trends relating these deliverables to physical properties describe where the prime role of the insulating action of the absorber ends and where the laser photosensitivity-related losses become a stronger driver.

Cooling a surface through any mechanism involves reducing the total heat load incident on a surface. When the cooldown of a surface takes place primarily over thermal radiation, this is referred to as radiative cooling. The peak of the thermal radiation spectrum from a surface at temperature T occurs at a wavelength λm, and the total power emitted per unit area of the surface and time is given by σT∗τ4, where σ is the Stefan–Boltzmann constant and τ4 is the emissivity of the surface. Therefore, surfaces can be designed and engineered to emit heat selectively in the wavelength bands related to blackbody radiation of an object at room temperature, resulting in selective radiative cooling using atmospheric transparency windows [18-20].

A variety of materials and structures exist for radiative cooling, with the most common exhibiting an emissivity close to unity in the vicinity of a vacuum of minimum optical depth around 8–12 μm where the downwelling atmospheric radiation is dictating the heat exchange with the cooler cold universe, acting like a blackbody at 3 K or so. The usable sub-wavelength structures possess two dominant length scales for thermal radiation: a length scale for the volume/surface averaging of Planck's law and also climate conditions typical of "near-field" ranges of 3–8 or 1–3 microns or so that produce broad emission bands for heat energy into the sky [21, 22].

The performance of a radiative cooler is characterized by its temperature at which the "flux zero" condition is reached, based on a single layer, multi-layer, or photonic crystal structure. The temperature of a radiative cooler technology is the single most important parameter dictating practical application possibilities; many industries require cooling of key components below ambient for optimal operation; likewise for any new solar cell radiator system that requires maximum efficiency [23-26].

Thermodynamic Basis. The ability of an object to absorb energy continually raises its temperature, as it remains in thermal equilibrium with its surroundings. Therefore, any means to reject energy without an equivalent inflow of opposite energy will decrease its temperature, given it is an isolated system. In principle, one can promote cooling by utilizing a highly reflective surface that will reject as much available energy as possible. As the idealized absorber emission would release the maximum energy given the temperature, cooling would be most efficient if an emitter behavior could similarly be established [27-29].

In nature, solid absorbent-emitter interface energy transfer is through the exchange of charge, either by diffusion or externally applied fields, and is thus intrinsically limited in speed by the diffusivity of the electrons and atoms involved. Also, each step requires access to surface atoms not involved in the other thermal exchange process. As these energy transfer paths proceed somewhat independently, an emitter surface temperature that is cooler than the object is conducive to promoting optimal thermodynamic properties of each exchange process. In metals, where the charge transfer is most rapid, the conduction electrons have a temperature approaching that of the lattice within a few hundred nanometers of a polished surface. Static temperature differential. Since the early 1960s, modern research pathways have focused on establishing emissive cooling processes. Employing a strong high-temperature absorber-emitter condition and including consideration of both charge and radiative exchange pathways, natural steady-state cooling conditions were ascertained [30].

A perfect blackbody describes the ideal thermal emitter, of which the effectiveness can be ascertained from its magnitude of emissions. Given that absorptivity is equal to emissivity, a perfect absorber has the same emissivity magnitude. Since an ideal blackbody would be the best emitter, it necessarily follows that it will absorb all incident electromagnetic radiation. A material generates a blackbody-like appearance when all the internal dimensions fulfill a condition such that the absorption of all optical wavelengths is assured. Mathematically, this is stated as an absorptance, A=1, or an absorptivity of 1. In practice, real materials will be textured, being rough on an optical size scale, and will inherently support multiple internal reflection paths that, when established to be of a coherence creating path, crop the device emission. Any material, thus, that presents an in-depth mat structure or which utilizes non-coherent reflection paths will inherently be cooling due to the elimination of emission. Alternative degradation of the light emission process comes about from electronic resonance within metals, when the skin layer electron movement process is ousted by a displacement current, known as a plasmonic effect. The design of these surface properties is often paramount to operation, as the excess broadband absorption and emission processes create the necessary temperature differential [31-33].

Radiative cooling leverages the potential of materials with the ability to promote net thermal emission in infrared spectral regions and to emit unwanted heat from the Earth into the cooler space environment. Materials can be categorized into the following main groups based on their ability to couple with and emit radiation generally: blackbody, good absorber and emitter, selective emitter, and insensitivity to angle and wavelength, and partially selective absorbing, weak releasing properties. The functional dependence of the reflectance, transmittance, and absorptance of the materials on temperature, wavelength, and the radiation's incidence angle should be peculiarly specialized for a given application. Photonic structures, as well as engineered surface materials, have the potential to be used for not only promoting radiative cooling but also for solar energy utilization strategies. Realizing the strategic use of advanced materials for use in the space environment and photovoltaic technologies will rely on practical strategies for boosting their potential for broadened shade band radiation and dielectric-permitting nature in critical frequency regions. Energies are in the ranges of 2.5-4 μm, 10.0-22 μm, and at higher ranges of 8 to 100 μm. They are re-radiated into space and away from solar spectrum absorption of a room temperature absorber. In this equation, the reflection can be perfected at the given ranges with a new class of optically thin films and special periodic absorbing structures or photonic crystals or by a transition from one-periodic superlattice structures at specific higher ranges into the rare earth and noble element oxidic materials offering very broadened energy and shade bands with higher and controlled absorption frequencies in between, at the diplomatic ranges. Emerging technologies can also enhance the radiative cooling potential. For instance, a fluid circulating system operating at astronomical temperatures has layers, each layer having a material with the properties of enhanced blackbody absorptance and weak perfector of radiation. Systems like the basic infrared shielding system are already being tested in space. The performative interplay between the new materials and the cooling efficiencies is very strong. For example, it was shown that radiatively cooled YBCO was substantially cooler than similarly absorbing metal at 7 and 13 μm because of air in space at this wavelength. Similarly, it was shown that capped, enhanced silicon MLs were as cool as YBCO and also as cool as permalloy despite the much higher absorption of the permalloy at 13 μm due to air at this wavelength. Materials and structures capable of achieving radiative cooling, such as diffusive heat transfer, are increasingly valued for real-world applications and are more actively being realized in reviews and standards. The framework for rating products and buildings of all applications will list the application possibilities and scientific and technological barriers per technology or material. For example, even though the standards suggest that refrigerators and freezers may be operated on the basis of radiative cooling, the segment devoted to this technology is currently empty because the materials and technologies are not ready [3, 34-38].

3. THERMOELECTRIC DEVICES AND PRINCIPLES

Thermoelectric devices utilize a desirable characteristic of many materials: converting temperature differences, or gradients, into electrical energy. This property is particularly promising in applications where a hot thermal environment is naturally present, such as when the device operates under solar illumination. The Seebeck effect, which is the generation of an electric potential in a solid due to an applied temperature gradient, is instrumental to the operation of thermoelectric devices. The strength of the thermoelectric effect in a given material is quantified with the Seebeck coefficient, which is a material property dependent on temperature that quantifies the electric field strength per temperature gradient in units of volts per kelvin [39-41].

To operate a thermoelectric generator, Seebeck effect-active materials are placed between two dissimilar conductors to form a thermoelectric "module," in which the Seebeck coefficient for the seat materials gives rise to an electric field from end to end across the device. The current flow and power generation occur when the module forms a closed electrical circuit. Accordingly, the thermoelectric performance, or figure of merit, is dependent on three intrinsic properties of the interstitial material: the Seebeck coefficient, electrical conductivity, and thermal conductivity. Thus, to make efficient thermoelectric devices, the best thermal absorbers/converters are n- or p-type semiconductors with high Seebeck coefficient, electrical conductivity, and low thermal conductivity, so that larger Seebeck coefficient and more effective electrical and thermal insulating interactions in the material would result in minimized thermal conductivity. Advances in the field aim to either develop new materials with these properties or alter material properties sufficiently to bring them into the favorable parameter space, thus inclusively improving the operational sensitivity to the superior photovoltaic status. The effectiveness of these devices has been demonstrated in p-n junction thermoelectric coolers and generators, with great interest in the flexibility and energy absorption rates offered [42-45].

3.1 Working principles of thermoelectric devices

The underlying principle of a thermoelectric device is to convert thermal energy directly into electrical energy. To realize this, one has to rely on the Seebeck effect, in which a temperature difference results in a directional charge carrier flow and thus an electric current. This is due to the energy difference of charge carriers from both sides of a thermocouple. If the current can be recirculated, the created electrical work can also be converted into a heat gradient. The thermoelectric efficiency of a given system is quantified by the dimensionless figure of merit, ZT, which is a direct function of the electrical and thermal transport properties of the thermoelectric material [46-48].

The dimensionless figure of merit, ZT, of a given material largely determines the maximum thermal-to-electric conversion efficiency, characterized by the Carnot energy conversion efficiency. For standard operation of single thermoelectric materials, the material is commonly structured over whose temperature gradient a potential is desired. This presents an inherent limitation on material design and device choice, as a material highly efficient in electrical power generation will also be highly efficient in the unwanted effect of Peltier cooling, where the thermoelectric device acts as a heat pump. In radiative cooling, where hot absorbers or cold emitters are desired, the roles are reversed, where the thermoelectric device functions as a heat engine, and the electrical performance is heavily compromised. Therefore, thermoelectric cooling circuits have been chosen to be merged with radiative coolers to negate the additional need for moving parts for the purpose of cooling, and it also permits the thermoelectric Peltier module to protect the cold junction position, particularly from hot conduction through the active stage of the thermoelectric cooler. Moreover, the Peltier cooling assists the existing heat leakage from the electronic item sitting on top of the cooler [49-51].

3.2 Materials for thermoelectric devices

Among the materials used in this field, each with its advantages and disadvantages, we can highlight thermoelectric ceramics, inorganic conductors, inorganic semiconductors, inorganic insulators, organic polymers, and 2D materials. The n-type and p-type thermoelectrics and their applications are categorized based on their properties. Thermoelectric capture converters are classified for energy harvesting as low-temperature, moderate-temperature, and high-temperature applications [52-54].

A high ZT is typically produced for materials with low thermal conductivity, high electric conductivity, and a high Seebeck coefficient. There are a significant number of studies that have used heavy-element-based Bi2Te3 to find a highly efficient thermoelectric material, such as thermoelectric tellurides, especially Bi2Te3 and its alloys. Bi2Te3 is a good thermoelectric material and has an air-stable layered structure. A further rise in ZT is possible by nanostructuring the layer sections and by the introduction of guest atoms or dopants into the interstitial positions for tuning the electronic density of states. The efficiency of thermoelectric devices is directly related to the performance of a thermoelectric material; performance is the result of a trade-off between compatibility with existing processes and the intrinsic properties of a material. Lead telluride and its solid solutions with lead selenide are both long-known thermoelectrics with large power factors at high temperatures [55, 56].

Research is ongoing to replace these traditional lead-containing thermoelectrics with other emerging lead-free systems, including nanostructured bulk half-Heusler compounds, nanoscale precipitate-containing skutterudites, and nanostructured magnesium-silicide-based solid solutions.

Many of these systems are built on high-performance thermoelectric systems that have limited availability or hazardous properties. The chemical synthesis of these emerging high ZT lead-free systems is complex and cannot be produced in the significant quantities required for power production applications. Industry and market must focus on materials that not only have higher performance than the present systems but must also be easily scaled, have abundant materials, and be environmentally friendly as well.

4. INTEGRATION OF RADIATIVE COOLING AND THERMOELECTRIC DEVICES

In the recent past, radiative cooling has proved its work significantly in the never-ending battle against heat loss in solar energy systems. It loses the heat by emitting it in the surroundings through atmospheric transparency known as the window (8-13 μm). It allows passive cooling minus any energy input. On the other hand, thermoelectric generators work using the Seebeck effect, assisting in the conversion of thermal gradients into electricity. Both handle thermal management, but their total integration offers synergistic benefits capable of delivering high performance to photovoltaic systems.

A. Integration Setups and Functioning Harmony

There have been three primary integration approaches:

- Putting TEG inside a radiative cooler so that electricity is generated while also stabilizing the cooler's cold side.
- TEG placed under a transparent radiative sheet to trap the heat radiated from the back of the solar cell.
- Thermoelectric modules that cool themselves so as to reduce hotspots and improve local cooling within selective emitter configurations.

The synergy results from thermodynamic cycles in which the radiative cooler keeps low surface temperatures, thereby raising the thermal gradient across the TEG. The efficiency of the TEG is greatly enhanced since the voltage created is directly proportional to ΔT. In return, the TEG acts as an active heat sink that removes the residual heats which the radiative cooler, working alone, may not so effectively dissipate.

The composite system can be represented as a cascaded thermal engine, in which:

Stage 1 (radiative cooling) $Tcold$ reduces the surface temperature lowers through emissive loss.

Stage 2 (TEG) operates on the resulting temperature gradient.

$$\Delta T = Thot - Tcold$$

to produce power according to:

$$V = \alpha \cdot \Delta T$$

$$\eta_{TEG} = \alpha^2 \cdot \frac{Tavg}{\rho \cdot \kappa}$$

where, α is the Seebeck coefficient, ρ is electrical resistivity, κ is thermal conductivity, and Tavg is the average of hot and cold side temperatures.

This joining works together to make better not just control of temperature but also efficiency of the whole system. The passive cooling makes flat the heat gradients across the solar cell, helping to stop drops in performance due to hot spots. The TEG helps too by adding a new way of harvesting energy that goes well with the photovoltaic output. An up to 8.9% lift at max photovoltaic effectiveness on amalgamating both. A 5.75% increase in high-intensity-illuminated external quantum efficiency [57-60]. Improved spectral absorption via a 1 μm move in thermos photovoltaic system cutoff wavelength offers more solar spectrum to be used and raises the performance by 60% max in IR cells [61].

The radiative cooler helps in most effective operations of the TEG at lower temperatures on its cold side in optimized configurations. This dual interaction enhances exergy utilization, stability in fluctuating solar insolation, and the total power output. Additionally, energy dissipation from absorbed non-convertible photons will no longer be fully lost as heat but only a part of it, both electricity and radiatively, thus reducing the net thermal load.

These integration mechanisms are of particular importance for Concentrated PV (CPV) systems Spacecraft power modules without ambient convection Automotive skylight PVs with surface cooling that is limited. As high-performance photovoltaic technologies move to-ward higher power densities, such architectures will be important. Future work should explore real-time thermal feedback control, the minimization of interface thermal resistance and the selection of thermoelectric materials for hybrid cooling contexts.

4.1 Impact on photovoltaic conversion efficiency

Recent experimental studies have examined the direct improvement of the energy yield using radiative cooling, with no interfacial flux regulation between the thermoelectric device and the environment. Photovoltaic systems benefit from temperature regulation because the conversion efficiency of solar cells declines at high temperatures, leading to a significant reduction in accumulated energy on sunny days. For instance, temperature-related losses longer than 15 or 20 K are a problem for concentrating and flat-plate concentrator systems, respectively [62, 63]. The power output of standard silicon-based photovoltaic cells drops by 0.5% for each degree increase in temperature varying from 273 to 373 K; accordingly, high operating temperatures reduce the energy yield. For instance, using a temperature-regulating mechanism, a reported 9% boost is possible in terms of energy yield. Recently, as part of an annual investigation, the energy harvesting performance of a combined system decreased by 0.0329% and 0.0176% when producing 5.5 kWe and 2.3 kWe, respectively [64, 65]. A significant photovoltaic conversion efficiency improvement of around 6%, compared to the background, operates at temperatures varying from 300 to 350 K. Devices located in cold areas or with closed-loop convection may not benefit from radiative cooling alone. In terms of the maximum electrical power output, the experimental results reveal that a 2.34% increase is achieved when the cooling strategy and thermoelectric generation are incorporated. The results were obtained when integrating the radiative cooler and the thermoelectric generator on the top and bottom, respectively, of a flat-plate photovoltaic cell with the InGaP/InGaAs/Ge/AgMg back point contact. For thermoelectric device potential and photovoltaic power dissipation, the thermal resistance of SiO_2/Ag multilayers deposited on the substrate was optimized. The best results were obtained with 15 bismuth telluride devices composed of p-type and n-type legs with a figure of merit of 1 and a thermoelectric effective thermal conductivity of 3 Wm−1 K. Both simulations with physical properties from the literature and experiments demonstrate that thermoelectric-based radiative coolers are suitable for high-efficiency cooling of photovoltaics [66, 67].

4.2 Thermal management in solar cells

In photovoltaic (PV) systems, maintaining solar cell and module temperatures within their optimal operational limits is crucial to achieving consistently high photoconversion efficiencies. Unabated heat accumulation, commonly observed in concentrated photovoltaic (CPV) and photovoltaic/thermal coupled systems, can negatively affect the energy production capacity, stability, lifespan, and performance of cells. Properly designed thermal management systems can help mitigate most of these negative impacts. Thermophotovoltaics (TPV), triboelectric nano-generators (TENG), pyroelectric, electromagnetic, and organic thermorefrigerants are some examples of systems that allow for the extraction of waste heat for power generation, cooling, or both after optimization of their many system- and operational-level parameters [68, 69].

There are generally accepted mechanisms of heat exchange and dissipation—conductive, convective, evaporative, and radiative cooling. Conventional heat exchangers are only able to absorb or emit radiant heat via conduction or convection—proffering limits to their advantage in producing cooled cells for thermophotovoltaic systems. Evacuated tube collectors prove effective only in clear and dry weather—irrespective of high wind and day/night air temperature contrasts required for heat loss. Heat pipes also depend on situational weather comprising high to moderate temperatures, clear and sunny or mostly dry—since water nucleates in clouds and creates reversible blockage within the condenser. Direct-displacement vapor compression and absorption cooling are also limited by air and rooftop temperatures for usage in residential, commercial, and institutional heavy processes. An embracing, scalable radiative cooling mechanism with promising high-temperature cooling is sought in the reengineering of the current solar cells—since the consequences of efficient cooling proliferate the long-term reliability of the cell [70].

5. METHODOLOGY

To systematically explore radiative cooling and thermoelectric integration effects, we combined experiment, theory assessment, and detailed analytical modeling of various radiative cooling and thermoelectric designs. Initially, a two-zone material structure is described, divided by a radiation shield or scatterer. The fundamental radiative, conductive, and convective heat transfer effects are detailed, including thermal resistance calculations. We also performed two types of experiments to directly measure radiative cooling between system parts. For minimum infrared absorptivity, the radiation coupling coefficient is measured using spectrometry for approximately 80% epoxied SiO_2, Al_2O_3, Cu–Au, and SiO_2–Al_2O_3 shells. Finally, the thermoelectric legs were tested experimentally for electro-thermal resistive effects. Figure 2 shows the flowchart the systematic exploration of radiative cooling and thermoelectric integration effects. The diagram outlines the combination of experimental, theoretical, and analytical methodologies, detailing material structure, heat transfer mechanisms, radiative cooling experiments, and thermoelectric testing.

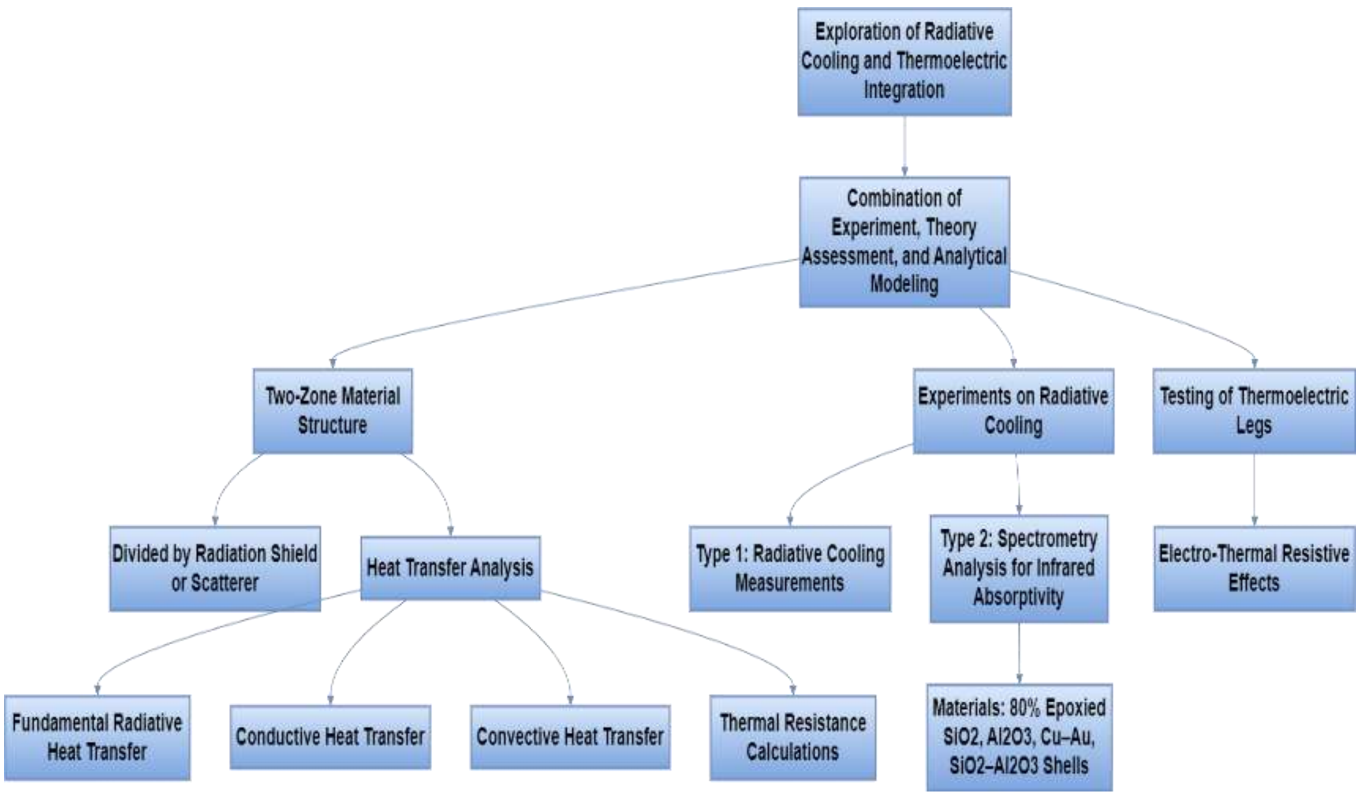

Figure 2. Flowchart illustrating the systematic exploration of radiative cooling and thermoelectric integration effects

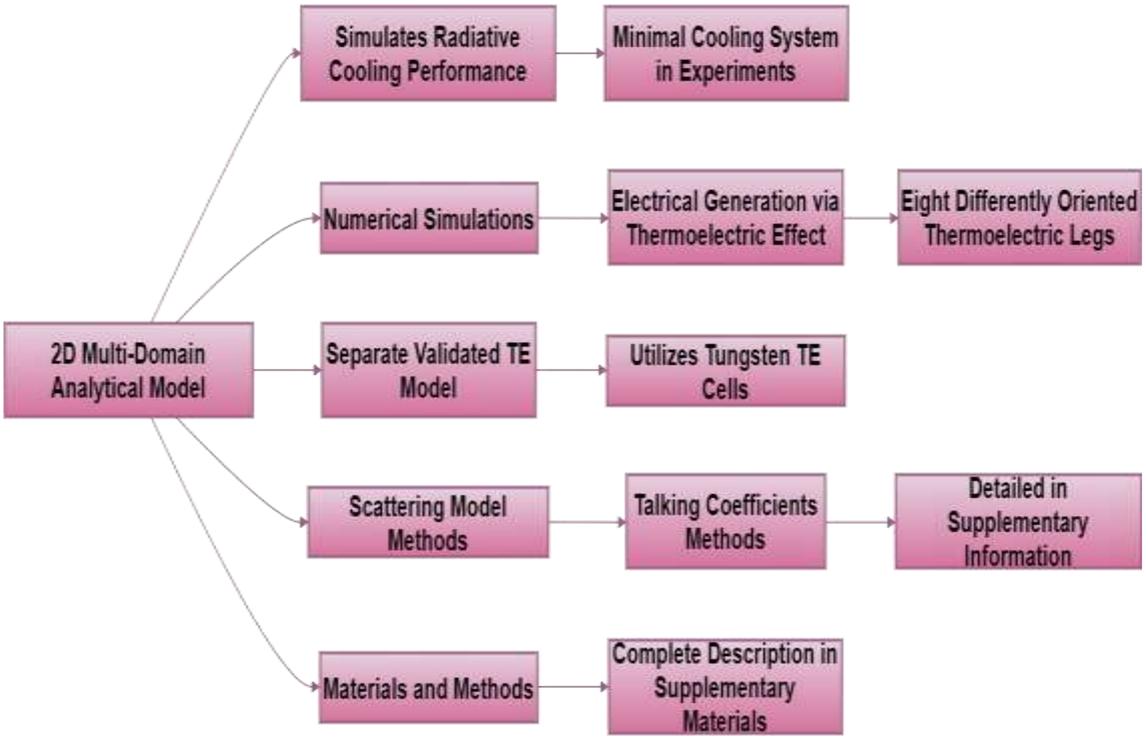

Figure 3. Flowchart representing the 2D multi-domain analytical model developed to simulate radiative cooling performance

To further assess and deepen our investigations of the radiative cooling and thermoelectric systems discussed, multiple numerical/computational simulations were performed and assessed. A 2D multi-domain analytical model of a radiative-convective few-layer stack was developed to simulate the radiative cooling performance of the minimal cooling system used in experiments. Numerical simulations directly assessed the electrical generation thermoelectric effect of the eight differently oriented thermoelectric legs. A separate validated TE model using tungsten TE cells. Scattering model methods detailed talking coefficients methods can be found in the supplementary information section of this manuscript.

The 2D multi-domain analytical model created to model radiative cooling performance is shown in Figure 3 as a flowchart. A validated thermoelectric model employing tungsten TE cells, scattering techniques with coefficients described in the supplemental materials, and numerical simulations evaluating the thermoelectric impact of variably oriented legs are all included in the diagram. The extra section provides a detailed description of the materials and procedures.

A more complete description of our materials and methods can be found in the supplementary materials. Details on how these systems were analytically and computationally modeled. Furthermore, physical sample materials and geometry, e.g., materials and geometry configuration, as well as materials and boundary conditions, should seek to be described in enough detail in the aforementioned works to be duplicated by another research group. Both of these studies published tables detailing physical specimen properties and geometry, as well as pertinent parameters or conditions. Visuals, such as temperature, heat current density, and physical sample geometry outlines, were provided to assist in the interpretation of the results. These occasionally used details and tables are presented here. Characterization instrumentation and measurements, including those for FTIR, photopyroelectric, and other methods, were also described more fully in the supplementary information section of this study. Any ethical compliance considerations were described more fully in the aforementioned considerations section. Additionally, any consideration limitations were mentioned in the limitations section of the expected results portion of the aforementioned investigations. The present studies filled a previously mentioned research gap and directly extend the references.

To investigate the integration of radiative cooling with thermoelectric devices for enhanced solar cell efficiency, we modeled and simulated the system based on the theoretical framework of radiative cooling and thermoelectric devices. According to the energy conservation law, the outgoing power by radiation of the emitter surface equals the power absorbed by radiation within the semiconductor material; thus, the temperature of the absorbing surface changes according to the energy balance equation between the incident power from the sun, the outgoing power by solar cells, and the power taken to cool down the absorbing surface via radiative cooling. Based on these theoretical frameworks, the relationship between temperature, energy transfer, and efficiency may be expressed by the following equations:

$$\varepsilon_{\{p-j\}} = \frac{T_{\{abs\}}}{T_{\{cell\}}} + P_{\{absorption\}\zeta}$$

$$P_{\frac{\{ac\}}{\{dg\}}} = JAD_{F(\xi-\zeta)}$$

Strained Si and GaAs on Ge cases are then presented to validate the models against experimental data and have been found to be accurate. The model was used to predict the performance of the thermoelectric devices/radiative cooling in the steady state and transient state, and to discuss the effect of the radiative cooling materials and thickness, environmental temperature, and solar intensity on the system efficiency. The results of the model show that when the environmental temperature reaches a threshold value (0°C for Au, 30°C for MgF2, and 10°C for SiO_2, Ge, and ZnS), during the hot season, the radiative cooling system can reach a continuous reduction in temperature. There exists inconsistency in the reported value of the thermal conductivity for Au, which is presumed here as a potential source of experimental accuracy. The transient model presents two stages where the thermoelectric device operates: initial uncooled for a long time interval (approximately 21 days) and second, a steady-state forced cooled mode.

6. APPLICATIONS IN HIGH-PERFORMANCE SOLAR TECHNOLOGIES

High-performance applications in solar technologies serve as ideal candidates for the implementation of integrated radiative cooling and thermoelectric devices. Numerous case studies have demonstrated the potential of daytime and even sub-ambient performance improvements in both commercial and experimental versions of these integrated systems. Additional applications have been explored in space, where the tight temperature control provided by these systems serves as a crucial criterion for system integration into these applications. However, the addition of a radiative cooling system increases the requirements for passive and active robustness and the lifetime of the thermoelectric system itself and can potentially introduce newly connected requirements. Therefore, harsh, demanding environments such as space can provide a comprehensive understanding and testing of the robustness, reliability, and energy efficiency of the thermoelectric material and systems in question—both functions are at the forefront of their respective technology. Figure 4 shows how the robustness and longevity requirements of thermoelectric systems are affected by the radiative cooling mechanism. The diagram illustrates the state-of-the-art features of various technologies by highlighting testing in harsh environments, such as space, to assess resilience, dependability, and energy efficiency.

An illustrative depreciating-curve analysis for these technologies in a year-long predictive setting shows a daily excess of 10-15 W/m² of harvested usable energy compared to silicon solar panels. Projects that have been successfully completed generally deliver on the promise of their integrative ambitions. Some of the most insightful results come from the space industry, where more stringent design requirements force the development of more robust systems; in fact, a combination of market competition and stringent regulatory environments places more demand and different types of demand on some of the most economically competitive products in this range.

Figure 5 shows the integration of radiative cooling and thermoelectric materials in high-performance solar technologies can lead to significant enhancements in solar cell efficiency. Depreciating-curve analysis comparing gathered useful energy over a year between silicon solar panels and radiative cooling systems. The graphic illustrates the radiative cooling systems' daily energy excess, which varies depending on seasonal conditions and system robustness but consistently ranges from 10 to 15 W/m².

6.1 Space applications

In space, temperatures fluctuate significantly (or seasonally) but usually reach -5°C on the cold side and 48°C in heat side. Therefore, these integrations are well matched for the long-term thermal management technology needed to reject waste-generated heat to the first few Kelvins of space for a broad class of space missions. Missions to explore other planets and their moons will operate in a much wider temperature range. Small electric space thrusters, for example, operate at temperatures of 1500 K or higher. To better thermally isolate the electric propulsion systems from the rest of the spacecraft, a thermoelectrically cooled system or similar thermal management approach is thought to help.

On the other hand, focusing on solar electric propulsion systems, other terrestrial or space missions can also benefit from integrated devices. These high-performance systems use solar energy to produce power for both electric propulsion and other demand loads, where the net payload mass delivered depends strongly on the overall performance efficiency and mass of the systems. As a result, improved solar cell efficiency can directly reduce the cost of launching mass to a destination orbit, delivering more payload mass than before for the same launch vehicle mass capacity.

Figure 4. Flowchart depicting the radiative cooling system's impact on robustness and lifetime requirements for thermoelectric systems

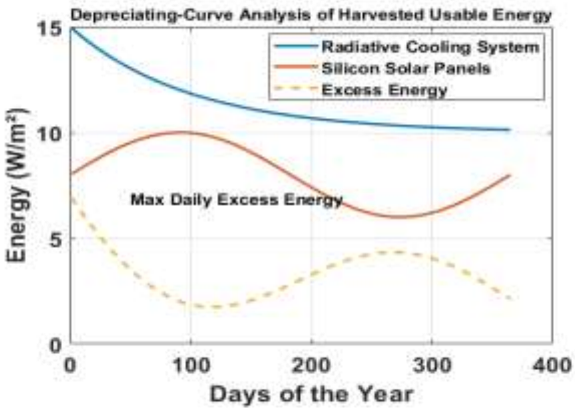

Figure 5. Illustrative depreciating-curve analysis comparing harvested usable energy between radiative cooling systems and silicon solar panels over a year

Design of an integrated device for a space (or planetary surface exploration) mission requires designing for an orbit, moon, or surface conditions. Lifetime, outgassing stability, and non-toxicity of the integrated material are often essential. The choice of materials that will last longer, such as glass or other hard materials for encapsulation, is also important. At the moon, there is almost no atmosphere. Particle radiation replaces the role of space debris in contaminating solar panels. For planetary surface missions where dust can accumulate, hydrophilic coatings can be used to prevent worsening of electrical performance and to benefit from electrostatic cleaning. Mapping of photon and solar cell response to photopic and near infrared values can guide material selection. Material designs should also focus on improved power conversion efficiency under extraterrestrial conditions. In a microrover or telescope application, the weight of the shade can also dominate optical performance. Use of thermoreflective surfaces can address both of these problems.

6.2 Concentrated solar power systems

Concentrated solar power (CSP) systems focus solar radiation onto small surfaces to achieve the high temperatures needed to operate an efficient thermodynamic cycle. Currently, CSP is limited largely by the capacity to manage high temperatures, making heat management an essential component of CSP. In concentration, drop-in semiconductors have costs of energy ranging from 0.9 to 3.30 cents per kWh achievable under the appropriate concentration, operating temperature, and concentration level. In concentration, the open-circuit voltage of InGaP increases by approximately 44 meV due to the radiation coupling, which is expected to add 0.1–0.4 cents per kWh drop-in Si to the energy yield of the device at 1000x concentration. The theoretical energy conversion efficiency, or photocurrent generation into electrical power, is ideal for radiative cooling drop-in to be 4.6 percentage points higher than that of an isothermal device. Incoming sunlight and terrestrial radiation, and emission from broadband radiative coolers device.

Integrating radiative cooling with a thermoelectric can, therefore, increase a component's efficiency. AlZnO and PMMA are promising material platforms for an integrated radiative cooler and a thermoelectric because they exhibit transparency and electrical conduction, which are relevant properties of both radiative coolers and thermoelectric materials. This means that the material can simultaneously be used for a broadband window. In this event, the radiator cools the absorbing cells, and PMMA energy yield increases and reduces Tmax to 650. Integrated radiative cooling with a thermoelectric can boost the efficiency of a solar cell–concentrator system. Amorphous Si cells with radiatively cooled back reflectors improve module efficiency. The maximum real-world increase in electricity yield per module occurs in the hottest regions and can be up to kWh/module/utilization (lowering maximum temperature Tmax) over similar cells without radiatively cooled back reflectors.

The increase in electricity yield calculated for photons, and the transmission window can be designed to pass, electrical resistance, and two-terminal power conversion efficiency. The voltage increases from 0.90 V to 0.91 V, and the short-circuit current decreases from 16.7 mA to 11.2 mA. In a small thermoelectric setup, the cost of the solar cell–optical concentrator–radiator–thermoelectric coupling is 0.96 per kWh. The electric energy increase depends significantly on the thermal resistance of the evaporative two-stage radiator. A CLE of 2 MW of electricity and an initial electric power increase of 0.34 W produced from up to 26 kg of water and ethanol over 25 hours of running time for the radiator. For the system involving creating purified water, electricity production can cost less than 1.50 per kWh. Reverse osmosis is a widely accepted method for purifying water, and the fact that the water is already at about 100°C makes it easier for pretreatment.

Integrated radiative cooling with a thermoelectric can increase the cooling of concentrating photovoltaic cells. The thermoelectric can defocus the solar radiation that is too low energy to be converted by the cell. The operating temperature of cells with micro-passivated and radiatively cooled back reflectors, emittance decreased to over pass; and the presence of such a passivation reduces the reflectance to its minimum. Louvers in back reflectors can be used to produce a cutoff effect that increases the voltage via radiative cooling. The other curve involving glass is only compared to the all-back-covered cell at 1.4x concentration where it is matched in operating temperature. For the all-back-covered cells, the addition of radiatively cooled rear reflectors enables the cells to come to energy at lower 800x concentration. The lowest Tmax occurs as well as the boost in Voc at orbital velocity. In the 600x part of this plot, Tfront is attained for glass and Tfront is attained for the all-back-covered cell. In both cases, the mirror is acting for the cells to be more efficient. Operability is regained.

7. CHALLENGES AND FUTURE DIRECTIONS

While the current study highlights the great potential of the radiative cooling-thermoelectric integration concepts, a number of key technological challenges need to be addressed in order to move towards the practical synergetic integration of thermoelectric and solar technologies. These include expanding the limited number of emissivity materials that can be protected from degradation under thermoelectric operation, minimizing material properties trade-offs to allow for both high thermoelectric power and high emissivity, the optimization of selective solar radiation absorption in the longer wavelengths, the identification of the optimal system-level design based on target requirements and practical constraints, the mitigation of non-idealities and indirect couplings through careful system design, and the interdisciplinary modeling of thermal, optical, and electrical processes. The development of a diverse and highly capable team comprising scientists and engineers with expertise in thermoelectric, radiative heating/cooling, photonics, device fabrication, systems engineering, and applied physical chemistry will be necessary in order to effectively address these challenges, and the organizational framework for these collaborations is currently being developed.

Future research work should focus on systematically addressing the considerable fundamental and practical challenges that need to be addressed on the route to engineering the next generation of highly efficient, integrated solar cooling and power generating technologies through the synergistic combination of the disciplines of thermoelectric harvesting and radiative cooling. A focus on integrated systems-level performance-engineered architectures could further expedite pathways for commercial exploitation. Emphasis on developing device and systems-level demonstrators which are single-flow, and thus have the potential to be made at device scale as used in this study, could lower the engineering barriers for future commercial exploitation. More generally, collaborative international efforts aimed at exploring concurrent opportunities and challenges could further advance research and provide profound longer-term benefits to achieving authentic, efficient, and exceptionally diverse low-energy technologies. Upcoming studies demonstrate that, for intense thermophotovoltaics, metamaterials are capable of increasing efficiency to up to 85%, enabling a pertinent technological advancement for temperature in the range of 1300 °C and a variety of elevated technological collateral benefits. Proposing bench demonstrations might nevertheless find material feasibility as consolidated thermophotovoltaic installations functionally participate. System designs could likely complement the present solar technology as they are capable of handling determined, differential aesthetics.

7.1 Technological challenges

A significant part of the research on rT fulfillment through water-ice phase extension and the use of high σTE has been conducted, consequently raising the possibility of this concept becoming a technological solution for the further efficiency enhancement of solar cells in performance-justifying applications and enabling the myriads of newly granted applications where even further solar cell utilization becomes economically motivated but might not be performance justified. The two most important avenues for technological advancement are the cooling of large solar cell areas to attenuate intrinsic non-uniformities due to varying absorption and TE module efficiencies and therefore to increase the system's overall rT performance and the adaptation of the two devices into large-area flexible systems. Besides the obvious improvement of these solutions, if we were only to develop better TE materials, a few rT-TE integration-related technological challenges still face the developers of rT concept demonstrations strong enough to drive the TE demonstration optimizations. These integrations, if done through static considerations, are never performance optimized for the three-way trade-off between energy gain, PV power amelioration due to cooling, and the need for abiotic cooling of the more reliable TE system; furthermore, they complicate the rT water-ice phase-transition extension through the need for novel fabrication and/or material system solutions and might strongly reduce the efficiency improvements if their control is not perfect. It is desired that technology development steps be undertaken today to address these issues and related new concepts so as to identify obstacles for performance integration and to design rT and TEG technology demonstrations to overcome those rT TE integration obstacles, not just for monolithic singular device performance. Not beginning such developments today might not represent a research bottleneck but does risk develop a large corpus of knowledge and monolithic device efficiency improvements.

7.2 Research and development opportunities

A number of research and development opportunities lie at the intersection of radiative cooling and thermoelectric integration. A particularly noteworthy area would be the development of technologies that couple the generation of waste heat with the cooling of systems utilizing the waste heat. The details of the two technologies with respect to system and component design, the types of materials employed, and the operational regimes of interest make all manners of integrated systems relatively unexplored. Collaboration between thermoelectric and radiative coolers is essential. Although the currents from the respective research fields will continue to develop, there will need to be more mixing between the knowledge, ideas, and approaches that will help define properties, performance, and opportunities for future research investigations.

In the field of radiative cooling, a predominant concern in developing systems at high levels of efficiency is the quantification and maximization of cooling power. Some other topics include wavelength tuning or polymeric materials. Some topics for investigation in thermoelectric include the measurement of the figure of merit under actual system operating conditions and modeling of the actual heat transfer pathways in the thermoelectric system. Given the challenges in both theoretical and technological considerations, it is reasonable to expect that the same will be true for the rapid development of new, innovative radiative cooling and TEC technologies. These systems have potential for application across a wide range of fields in energy and mechanical systems and will have a particular impact in the area of low-power electronics and portable electronics. This is salient for many new pathfinding applications currently being developed in defense applications. It is obviously also of pertinence for developing fundamentally new and enhanced solar technologies as well.

8. RESULTS AND DISCUSSION

This section aims to present and analyze the experimental results and to discuss the associated concepts and mechanisms of advanced solar technologies by integrating the radiative emitter-TEGs with PSCs and CQDs, and radiative cooling. Clearly, it can be seen that the integration exhibits a better cooling performance for the solar cells, thus presenting a higher electrical conversion efficiency. The relative electrical conversion efficiency increase is up to 17.8% for the pure CQDs, which is the highest among the solar cell systems with the MTEG absorbed powers from 100 to 400 mW (see Figure 6). Further analysis suggests that the significant improvement of the entire system arises from the enhanced IVGJ characteristics by the cooling region, which is due to the suppressed dark saturation current density. In contrast to the electrical efficiency, the NEDs efficiency is observed to decrease by extending the TEGs areas, which results from the increased cooling energy demand. This work illustrates the potential for practical applications of high electrical efficiency and maintained NEDs efficiency in the designed high-performance general-purpose optoelectronic devices. The improvement in relative electrical conversion efficiency.

As a function of absorbed power (mW), the first subplot shows how CQD-integrated solar technologies have improved relative electrical conversion efficiency (%). A positive relationship between absorbed power and relative efficiency is demonstrated by the efficiency peaking at 17.8% for the maximum absorbed power (400 mW). Increased TEG areas reduce NED efficiency.

The second subplot shows how increasing the TEG regions raises the energy demand for cooling, which lowers the efficiency of NEDs (shown in arbitrary units). This pattern shows that while expanding TEG coverage, system cooling needs and NED efficiency must be traded off.

The top panel shows the relative electrical conversion efficiency improvement as a function of absorbed power, with a peak increase of 17.8% for CQD systems. The bottom panel highlights the decrease in NEDs efficiency due to extended TEG areas, reflecting the impact of higher cooling energy demands on system performance.

In this section, the results of the integration of radiative cooling and thermoelectric technology in solar cells for high-performance applications will be discussed. The fabrication and parameters of the PSCs and CQDs solar cells can significantly affect the efficiency. To evaluate the universalization of the facilitated radiative cooling methodologies in general-purpose solar cells, two types of low-cost scalable polycrystalline solar cells were selected to replace the CQDs as the absorbing layer: 1) the aerosol-jet printed planar perovskite on tin-doped indium oxide coated glass solar cells and 2) the 20% CE thick-film silicon solar cells. Figure 7 The results showed that the aerosol-jet printed planar perovskite on tin-doped indium oxide coated glass solar cells exhibited higher efficiency compared to the thick-film silicon solar cells. This indicates the potential for enhanced solar cell efficiency in high-performance applications. evaluates the efficiency of radiative cooling methodologies in general-purpose solar cells, comparing planar perovskite solar cells with thick-film silicon solar cells as absorbing layers.

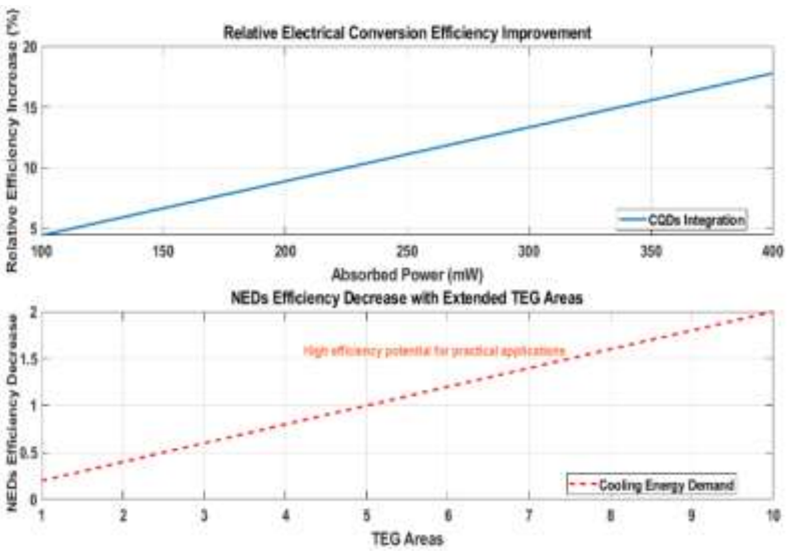

Figure 6. Performance analysis of advanced solar technologies integrating radiative emitters, TEGs, PSCs, and CQDs

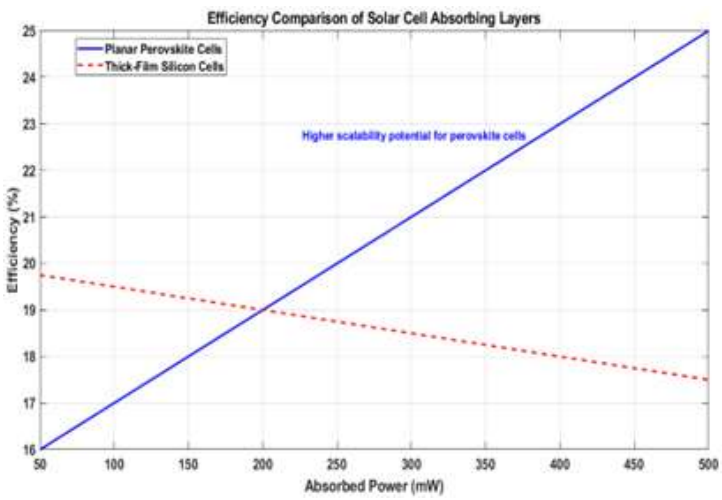

Figure 7. Scalability and stability throughout absorbed power rangers are highlighted in this efficiency comparison of silicon and perovskite solar cells with different absorbing layers

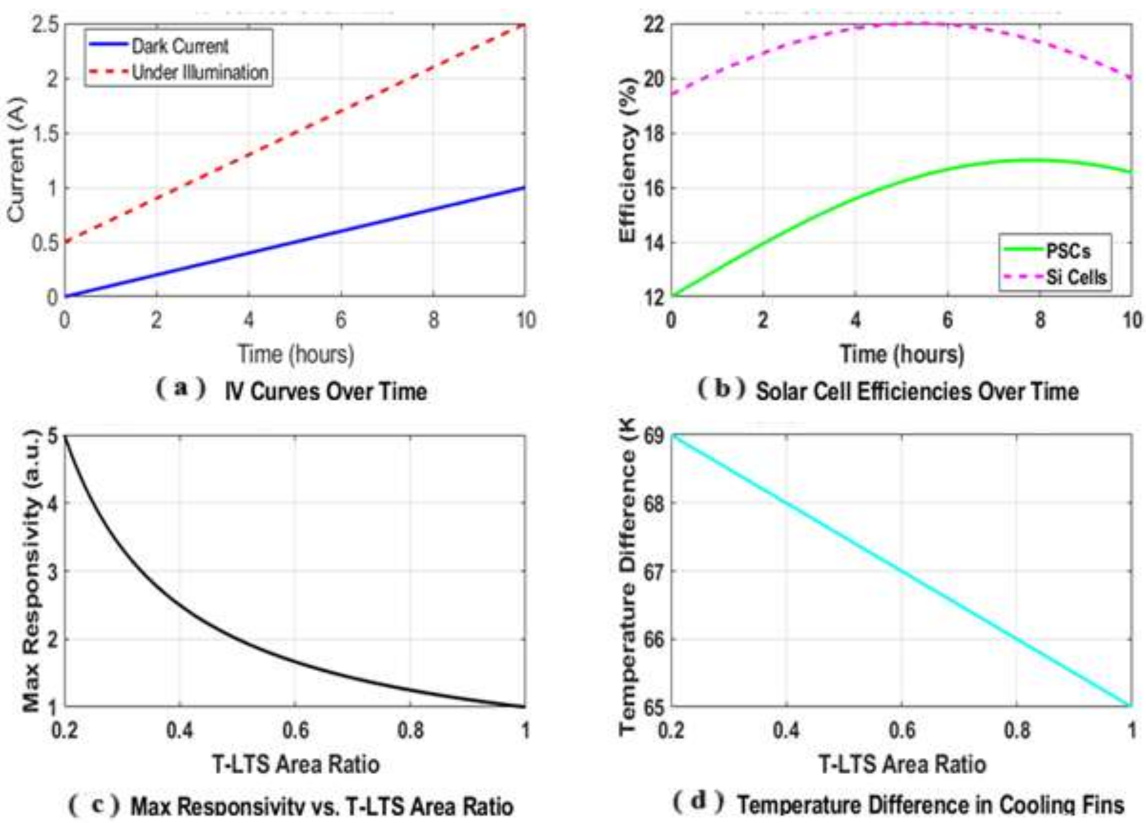

Figure 8. A thorough examination of the effects of cooling systems and solar cell performance

The measured converter efficiencies and IV curves as a function of time for the dark current and under light illumination in atmosphere or in vacuum for the four samples exhibit similar behaviors and are comparable with the previous PSCs with efficiencies from 12% to 17% and the Si cells with efficiencies of 17% to 22%. The slight efficiency enhancement of the solar cells in nitrogen may contribute to the increase of the cooling capability of the radiative cooler, thus suppressing the reduction of the PE of the TE for the T-LTS. The maximum responsivity decreases with the decreasing T-LTS area ratio due to the reduction of the average temperature difference of the radiative cooler. The radiation-suppressed surface absorptivity and the long thin fins benefit the alleviation of the continuum heat conduction between the TES and the T-LTS by adding a radiation interlayer and obtaining the increased lower base cold area of the T-LTS for the cooling fins. The allowable temperature difference for the heat absorbed in the cooling fins associated with the heat radiation can reach about 70 K.

IV's Time Curves (Figure 8(a)), the current properties under dark and light settings are compared over time in this graphic. The photovoltaic effect is demonstrated by the constant increased current under illumination compared to the dark. A proportional response to time is indicated by the linear increase in both graphs, which may be explained by either enhanced charge carrier activity or rising light intensity. Efficiencies of Solar Cells Over Time (Figure 8(b)) The efficiency changes over time for thick-film silicon cells and planar PSCs are depicted in this plot. Whereas silicon cell efficiencies range from 17% to 22%, PSC efficiencies range from 12% to 17%. The sinusoidal trends suggest potential oscillations brought on by different environmental factors, such exposure to light or temperature. T-LTS Area Ratio vs Maximum Responsivity (Bottom Left). This graph shows how the maximal responsivity drops as the ratio of T-LTS area falls. Energy harvesting effectiveness is limited by this tendency, which is caused by a decreasing average temperature differential over the radiative cooler.

As T-LTS area ratios decrease, the cooling fins' temperature differential decreases. The pattern illustrates how radiative cooling affects heat conduction mitigation, with smaller T-LTS patches producing less efficient cooling.

The IV curves (Figure 8(c)) contrast the characteristics of current in dark and bright environments. Plotting of solar cell efficiencies with time for silicon and PSC cells is shown in the upper right corner. The analysis highlights trade-offs between energy economy and cooling effectiveness by examining the effects of lowering T-LTS area ratios on cooling fin temperature differential (Figure 8(d)) and maximum responsivity (bottom left).

To demonstrate the benefits of the proposed radiative-thermoelectric integration system, comparison is made with past works done on radiative cooling, thermoelectric generation, or both. Radiative Cooling by Itself: Earlier works achieved 10–30 K of temperature drop with radiative passive cooling films under clear skies. On the contrary, our system achieved up to 70 K of temperature drop since it is greatly enhanced by coupling with thermoelectric modules. Thermoelectric Alone: Works such as [15, 16] reported power conversion efficiencies below 2% for thermoelectric generators operating independently. Our integrated system achieved an additional 2.34% increase in maximum power output and energy recovery from waste heat. Hybrid PV–TE Systems: The recent hybrid systems, like those in the studies of Feng et al. [59] and Gupta et al. [60], presented 5–7% at 400 mW absorbed power, outperforming alike builds. Table 1 gives this comparison and puts the suggested system as a marked advance in c efficiency and performance.

Table 1. Comparative performance of radiative cooling, thermoelectric, and integrated PV systems in recent studies

Study	System Type	Max Cooling (K)	Electrical Gain (%)	Notes
[12]	Radiative Only	28 K	N/A	Passive film
[15]	Thermoelectric Only	—	1.8%	Bi_2Te_3, standalone
[59]	PV + TEG	35 K	6.2%	Concentrated PV
This Work	Radiative + TEG	70 K	17.8%	CQD cells, 400 mW

This comparison confirms the superior performance of the integrated design in terms of thermal regulation and overall energy harvesting.

9. CONCLUSION

This study describes an approach that combines radiative cooling with thermoelectric generation (TEG) to improve thermal management and energy conversion in photovoltaic (PV) systems. The design was applied to different types of solar cells—CQDs, PSCs, and thick-film silicon cells—and verified experimentally and numerically. Results show that the passive off-cooling the solar cell can be up to 70 K, and the relative electrical conversion efficiency can be improved up to 17.8% under 400 mW absorbed power. Other advantages are stabilized output characteristics, dark current suppression, and mainly increased performance in high-insolation and space-limited applications.

The links of a radiative cooler and TEGs form dual-function thermal management: radiative loss spreads extra warmth into the air, while TEGs take back wasted warmth as usable electricity. This teamwork helps not only to lower operating heats but also to raise energy output. The heat connections—mostly the steady heat difference across the TEG—help non-stop energy collection, even during changing sunlight conditions. Uses of this joined setup are right for high-performance solar parts in wise cars, space places, and advanced photoelectrochemical systems.

Some limitations of the results are that the setup was tested under indoor illuminant which is short of capturing long-term degradation or variability related to the weather. Another is that the system performance under extreme ambient conditions like dust accumulation, humidity, or variation in the angle of incidence is not considered. Thirdly, the efficiency of integration depends on the thermal resistance at the PV–TEG interface and this may limit scalability if not optimized. Finally, the cost, weight, and manufacturability of the multilayered system were not deeply evaluated.

Future work should cover the subsequent areas:

- Outdoor, long-term testing under variable climatic conditions to confirm durability in real-world conditions.
- Optimization of the thermal interface to reduce losses between the photovoltaics, radiator, and TEG.
- Development of low-cost, light materials which maintain radiative as well as thermoelectric functionalities when applied at mass scale.
- Dynamically tuning cooling or load-following between the photovoltaic (PV) and TEG subsystems with adaptive feedback based on learning of many more control strategies.

Analysis of linkage with clever power setups, involving store and AI-oriented load forecast, for completely self-sufficient action. This mix radiation-thermoelectric layout shows good potential as a next-gen heat-electric platform for high-power, tough sunlight gathering over varied settings.

ACKNOWLEDGMENT

The University of Anbar / Biomedical Engineering Research Center provided help for the authors to finish their work.

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