Optimizing combined photovoltaic and thermoelectric hybrid harvesting of energy systems for various climate regions

Deepak Rajput[1], Raghvendra Singh[2], Samir Mishra[3],
Faculty of Engineering & Technology, Rama University Uttar Pradesh Kanpur 209217 India
Email Id: deepak87nk@gmail.com

Abstract:

With the growing concern for the environment, the significance of Zero-Energy Buildings (ZEB) is steadily rising as energy conservation becomes a crucial aspect.Consequently, extensive research is being carried out on high-efficiency renewable energy systems that can be implemented in metropolitan areas. Efforts to enhance the efficiency of Building Integrated Photovoltaics (BIPV) have been suggested and examined in response to the demand for clean energy. Examples of methods involve applying phase switch material (PCM), employing heat fins, selecting specific wavelengths, reducing PV surface temperature, using a thermoelectric generator (TEG), and implementing convection cooling by harnessing waste heat from the PV. Previous research mostly evaluated the performance of each strategy through experiments or simulations. Nevertheless, the evaluation of the design for optimal performance has yet to be carried out. Hence, this study examines the design of a Building Integrated Photovoltaic (BIPV) system combined with a Phase Change Material (PCM) and a Thermoelectric Generator (TEG), referred to as BIPV-TEG-PCM. In this study, we conducted computational fluid dynamics (CFD)-based simulations to investigate three variables: the temperature of phase change of the PCM, the heat fin spacing in the PCM container, and the TEG arrangement. Furthermore, the best design of the BIPV-TEG-PCM system was obtained using multiple objectives to optimize. The analysis yielded the following conclusions for the recommended structure: the correct melting point of the Phase Change Material (PCM) is 40 °C, the heat fin interval is 12.4 mm, and the setup of the Thermoelectric Generator (TEG) is 187 millimeter.

Keywords: Thermoelectric Generator (TEG), Phase Change Material (PCM), Zero-Energy Buildings, BIPV-TEG-PCM

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1.0 Introduction

The urbanization has resulted in a higher population density in metropolitan areas, necessitating the construction of additional structures [1]. Furthermore, there is a growing prevalence of electronic gadgets being employed within buildings, including internet of things (IoT) sensors, electric automobiles, and air conditioning (HVAC) systems, among others. Consequently, much research is being performed to implement renewable energy sources in urban areas in order to achieve a substantial reduction in electric energy use while being environmentally sustainable. Photovoltaic, or PV, panels are the most commonly employed system. However, the fact remains that it is difficult to provide a significant quantity of renewable energy due to the restricted area and resources available in cities. Consequently, numerous studies have been undertaken to enhance the efficiency of the photovoltaic (PV) panel.

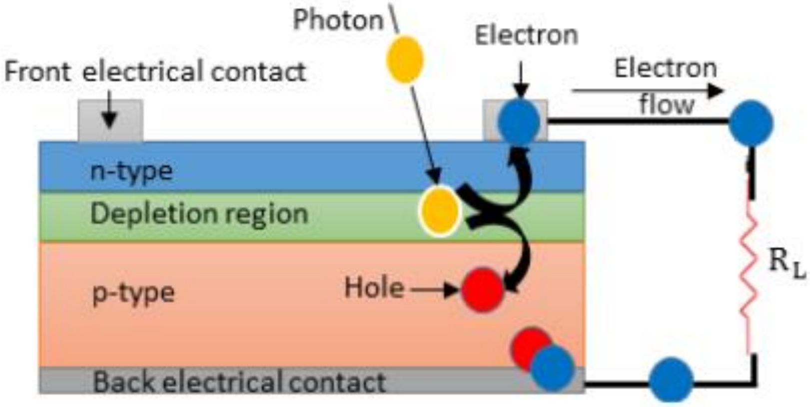


Figure:1.0 Basic Schematic Diagram of Photovoltaic

However, in contrast to traditional photovoltaic systems, building-integrated photovoltaics (BIPVs) are permanently attached to the wall or roof of the structure. Consequently, Building Integrated Photovoltaics (BIPVs) have a restricted duration and angle for receiving sunlight, which leads to a decrease in the efficiency of PV panels due to inadequate heat dissipation. The efficiency of a photovoltaic (PV) panel is directly influenced by its temperature. As the temperature of the PV cell rises, the efficiency of power output reduces by 0.4 to 0.65% per degree Celsius [2]. Furthermore, it should be noted that if the temperature of the panel surface hits 65 ℃, the efficiency of power generation might decrease significantly to approximately 2.6% [3]. Consequently, in order to address this issue, multiple approaches have been examined to mitigate the increase in temperature of the PV cell. The cooling technology of PV panels can be categorized into three types based on the heat transmission method: convection, conduction, and radiation. Typically, it has been suggested that a panel cooling system use both convection and conduction. Out of the several cooling strategies, liquid convection cooling demonstrated the greatest increase in efficiency at 22%. Phase change materials exhibited an improvement of up to 21.2%, air convection cooling by 20%, and radiation cooling by up to 2.6%. These improvements in efficiency were observed in the PV panel [4].

Consequently, several techniques have been proposed to improve the efficiency of Building Integrated Photovoltaics (BIPVs) by facilitating heat dissipation through convection. Koyunbaba et al. created a Building Integrated Photovoltaic Thermal (BIPVT) system that utilises an air-cooled design and incorporates Trombe wall technology. Based on the analysis of the trials and computational fluid dynamics (CFD) simulations, it was found that the median electrical effectiveness for this system may reach 4.52%, while the average thermal efficiency can reach 27.2%. Kaiser et al. performed a study on a Building Integrated Photovoltaic (BIPV) module system in the presence of forced convection circumstances. This study did an empirical analysis to examine the influence of the air gap size and the forced convection ventilation system. When the duct velocity was set at 6 m/s, the power generation showed a 19% increase compared to the situation with natural ventilation [5]. In addition, particular studies have focused on the application of water-cooling in BIPVT systems. Kim et al. performed a comprehensive examination of the energy efficiency of a water-cooled Building Integrated Photovoltaic Thermal (BIPVT) system that was put on a roof. According to the experimental findings, the BIPVT demonstrated improved average thermal and electrical efficiencies of 30% and 17% respectively [6].

However, there are disadvantages linked to this method, as it requires the utilisation of additional power sources like pumps and valves, and the system becomes complex when using a fluid. Moreover, most of the solar heat generated by the photovoltaic (PV) system is emitted into the surrounding environment of the city, thus intensifying the urban heat island effect.

The maintenance and installation of BIPV (structure Integrated Photovoltaics) are more complex than ordinary PV panels because they are positioned on the exterior of a structure. Therefore, the use of fluid is difficult since it has a tendency to cause problems, such as leakage. Therefore, a research investigation was conducted on the Building Integrated Photovoltaic (BIPV) system utilising a phase change material (PCM) and a thermoelectric generator (TEG) in order to improve efficiency using a passive method. Previous research has shown that using Phase Change Material (PCM) is a very efficient method for passively cooling Photovoltaic (PV) panels [7–11]. Hasan et al. performed a thorough examination of the PV-PCM system in a warm climate utilising both empirical and computational techniques. Studies have demonstrated that the utilisation of Phase Change Materials (PCMs) can effectively lower the temperature of Photovoltaic (PV) panels by 13℃ during periods of maximum demand. In addition, the panels that utilised phase change materials (PCMs) demonstrated a 5.9% improvement in energy efficiency compared to panels that did not incorporate PCMs. This enhancement was regularly observed annually [12]. Sharma et al. analyse the properties of the paraffin wax utilised in the Building-Integrated Concentrated Photovoltaic (BICPV) system. A lap-scale experiment was conducted to examine the cooling effect of PCM under different levels of xenon light irradiation (500, 750, and 1200 W/m2). The experimental results demonstrate that the electrical efficiency experienced incremental improvements of 1.15%, 4.2%, and 6.8% respectively. In addition, the PV panel's surface temperature reduced by 3.8 ℃ [13]. Stropnik and Stritih utilised TRNSYS software to analyse the degree to which the efficacy of photovoltaic (PV) panels improved with the implementation of a phase change material (PCM). The experimental findings indicate that the incorporation of phase change material (PCM) with photovoltaic (PV) panels significantly decreases the temperature of the PV panel by 35.6 ℃ in comparison to PV panels lacking PCM. Furthermore, this integration results in an annual growth in electricity generation of 7.3% [14]. Furthermore, the study revealed that the PV-TEG hybrid system has the capacity to increase efficiency by 1-16% in comparison to the traditional PV panel system. Makki proposed a hybrid system that integrates a heat pipe with a photovoltaic-thermoelectric generator (PV-TEG). The proposal was evaluated using both numerical models and physical tests. This study illustrates the possibility of attaining a further 5% enhancement in the overall efficiency of the system by the utilisation of a TEG [15]. In addition, Cotfas et al. performed an investigation on the three distinct types of TEG material utilised in the PV-TEG hybrid system. The simulation results indicate that the PV-TEG hybrid system has the potential to provide around 7% more electrical power and enhance the overall system efficiency by 18.93% compared to a standard PV panel [16]. Prior research has indicated that the PV-TEG hybrid system requires a cooling source, such as air or water, to be present on the cold side of the TEG. However, most convection systems require additional power sources to enable the movement of fluids. The PV-TEG-PCM system was subjected to a numerical and experimental investigation by Darkwa et al. Based on the results, the PV-TEG-PCM system exhibited a more than 9.5% boost in electric power generation compared to both the standalone PV system and the PV-TEG hybrid system [3]. Ko and Jeong suggest employing the BIPV-TEG-PCM system and assess its power generation efficiency. The proposed system has the capacity to generate an annual output of 3.05 kilowatt-hours (kWh) using the thermoelectric generator (TEG). Furthermore, there have been documented improvements in the efficiency of power generation during various seasons, with respective increases of 0.91%, -1.32%, 2.25%, and 3.16% from spring to winter [17]. Previous study has concentrated on doing a feasibility analysis and assessing the energy efficiency of a system that combines photovoltaic (PV), thermoelectric generator (TEG), and phase change material (PCM). However, additional research is necessary to identify the most effective design for obtaining maximum efficiency. Therefore, a quantitative analysis was conducted to identify the optimal design for producing the proposed BIPV-TEG-PCM. This system use microencapsulated phase change material (mPCM) to catch and harness solar/thermal energy that would otherwise be lost from the building envelope.

2.0 Operation of system

A computer simulation was run to simulate the surface temperature associated with Building-Integrated Photovoltaic-Thermoelectric Generator-Phase Transition Materials (BIPV-TEG-PCM) panels in the present investigation. The modeling process utilized infinite volume the discretization inside of the computational fluid dynamics (CFD) The structure employing ANSYS Fluent R1. The mathematical equations controlling the system and their corresponding boundaries were solved inside a computing area with a predetermined grid. The investigation aimed to evaluate the melting temperature of the phase change material (PCM), the spacing of heat fins, and the configuration of the thermoelectric generator (TEG) in order to maximize the variation in temperature in the the TEG whilst minimizing the surface heating of the panels. An investigation of heat transport was conducted using a three-dimensional geometry in ANSYS Fluent.

The time step was set to 1 second, and the overall duration of the simulation was 2 hours, equivalent to 7200 seconds. The simulation was started using the standard test condition (STC) of the PV panel, with an initial temperature of 25°C. Figure 2 depicts the boundary conditions used in the CFD analysis. Except for the glass surface, all other external surfaces were assumed to be adiabatic, whereas the glass surface was exposed to solar radiation of 1000 W/m^2, as shown in Figure 2. Therefore, it was assumed that the movement of the phase change material (PCM) was smooth and orderly, without any turbulent flow caused by convection. Tables 1 and 2 provide a comprehensive overview of the physical characteristics of the BIPV-TEG-PCM. The PiAnO program was utilized to examine the computational experimental data in order to enhance the system.

The objective was to determine the most efficient arrangement in which the photovoltaic (PV) panel would produce the highest amount of electricity per day, while simultaneously ensuring that the temperature of the thermoelectric element remained at its maximum level at both ends. A predictive model was created to estimate the daily power generation from the PV panel and the ambient temperature at both ends of the piezoelectric component. The predicting model, in conjunction with a weighting mechanism, was subsequently employed to ascertain the most advantageous design parameters for the BIPV-TEG-PCM combination.

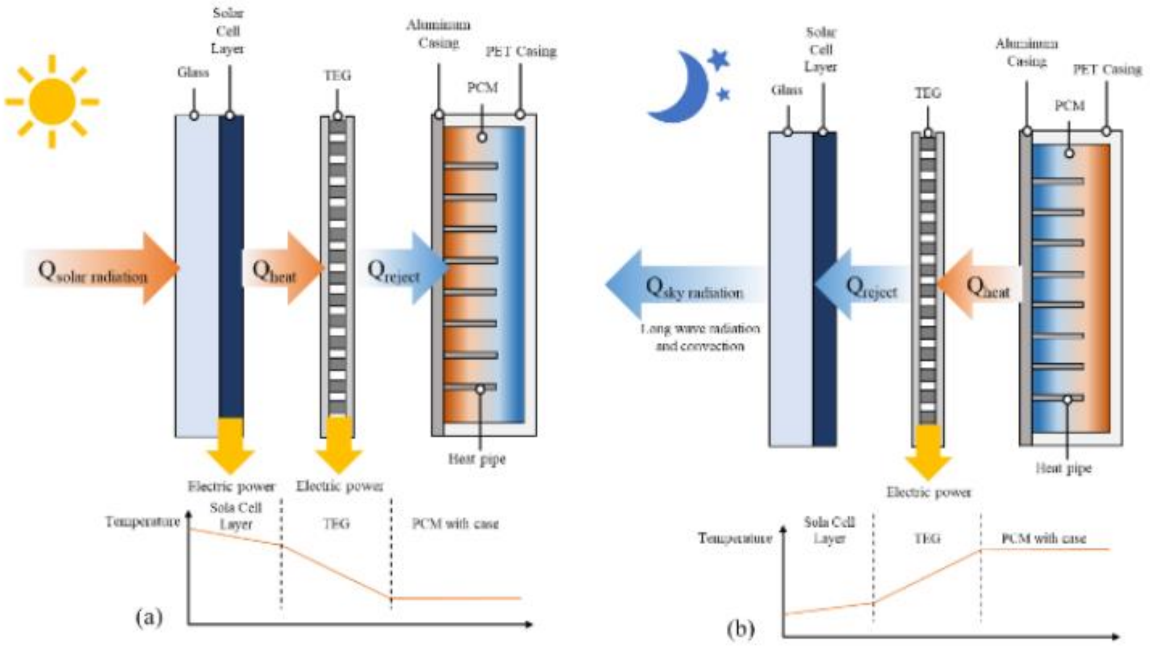


Figure: 2 (a) Daylight BIPV-TEG-PCM working (b) Nighttime BIPV-TEG-PCM working.

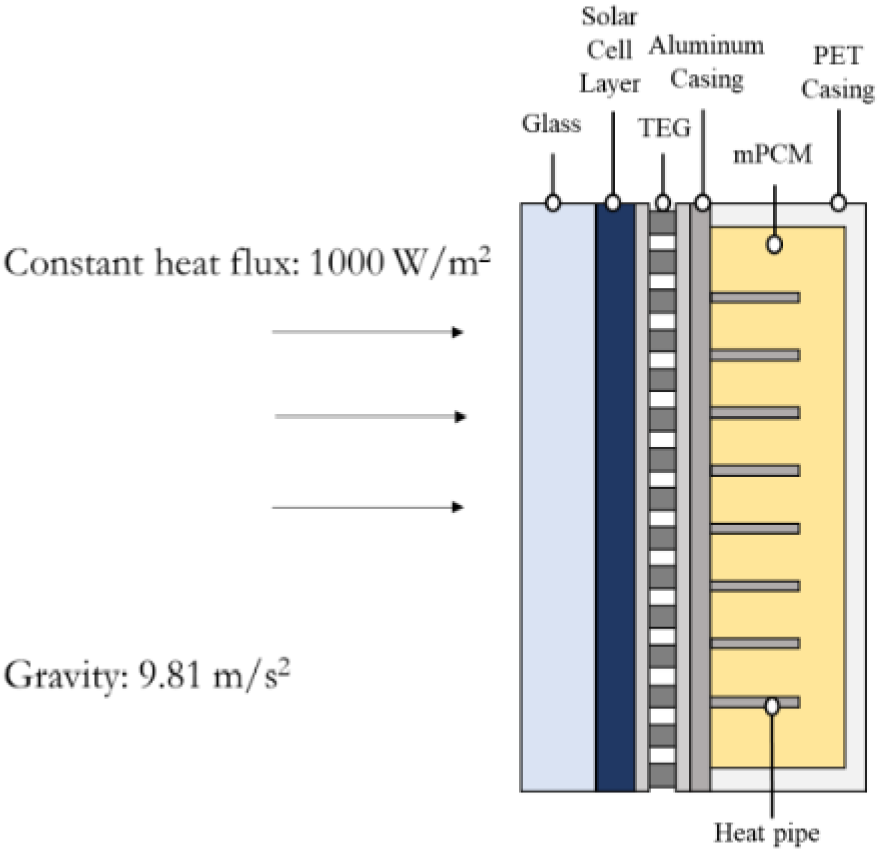


Figure 3: boundary circumstances and geometry for CFD

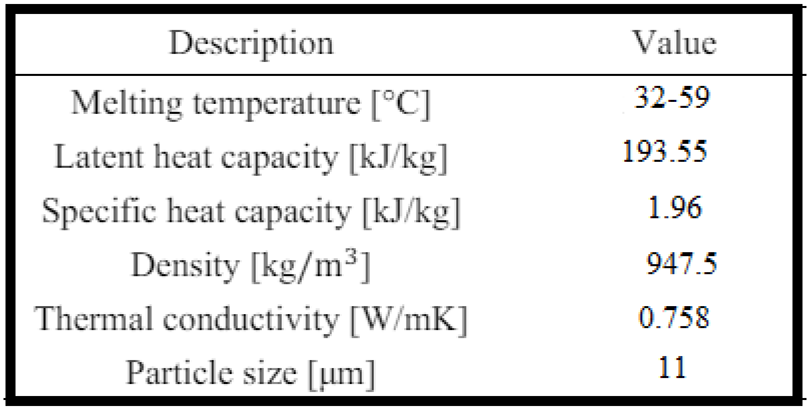
3.0 Simulation Description

The study involved the simulation of high temperatures on a solar energy system known as BIPV-TEG-PCM. The simulation was conducted via finite volume discretization, a computational fluid dynamics (CFD) based method. The simulation utilised the ANSYS Fluent R1 software. The resolution of the governing equations and their corresponding boundary conditions depends on a computing domain that has a specified grid. This study investigated the correlation between the melting temperature of phase change material (PCM), the spacing of heat fins, and the design of the thermoelectric generator (TEG) to enhance the temperature difference in the TEG while minimising the surface temperatures of the panels.

The investigation of heat conduction was carried out with ANSYS Fluent, employing a three-dimensional configuration. The time interval was set to 1 second, and the total duration of the simulation was 2 hours and 7200 seconds. The simulation analysis was carried out using the standard test condition (STC) of the PV panel as the baseline, with an initial temperature of 25℃. Therefore, Figure 2 illustrates the boundary conditions for computational fluid dynamics (CFD). All exterior surfaces, save for the glass surface, were in an adiabatic state. The glass surface got direct sunshine with an intensity of 1000 W/m2, as shown in Figure 2. Therefore, roughness does not appear in mPCM while considering convection. Therefore, it is assumed that the mPCM displays the attributes of laminar flow. The physical features of the BIPVT-EG-PCM are displayed in Tables 1 and 2.

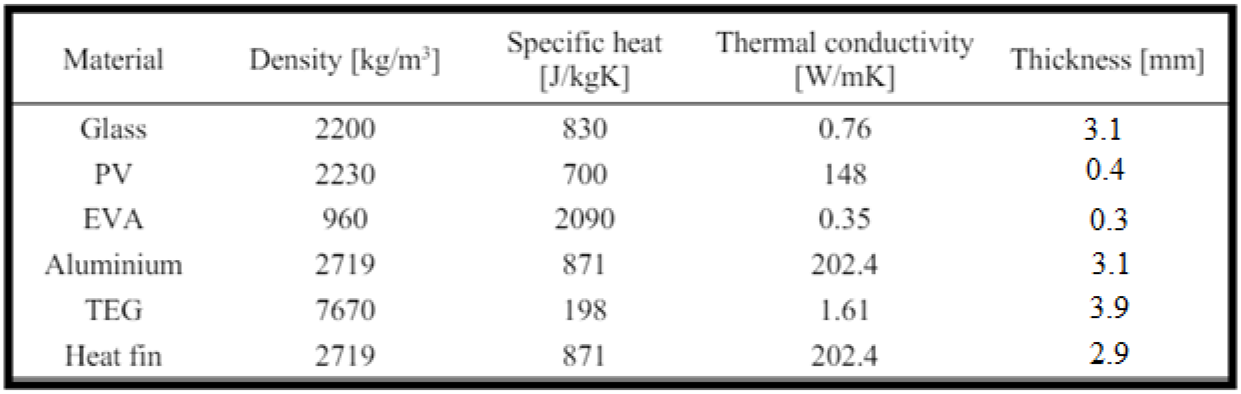
In this study, the computational experiment data for the optimisation was analysed using the PiAnO programme. The goal was to identify the optimal location for the photovoltaic (PV) panel to provide maximum daily power output, while also ensuring that the thermoelectric element maintains its highest temperature at both ends. Hence, the goal function was formulated and employed to predict the daily power output of the PV panel and the ambient temperature at both ends of the piezoelectric element. The optimal design point of the Building Integrated Photovoltaic-Thermoelectric Generator-Phase Change Material was found through the utilisation of a prediction model and a weighing approach.

Table 1 displays the characteristics of the mPCM used in the CFD calculation.



Description	Value
Melting temperature [°C]	32-59
Latent heat capacity [kJ/kg]	193.55
Specific heat capacity [kJ/kg]	1.96
Density [kg/m^3]	947.5
Thermal conductivity [W/mK]	0.758
Particle size [μm]	11

Table 2: Characteristics relating to the BIPV-TEG-PCM utilized in CFD simulations.



Material	Density [kg/m³]	Specific heat [J/kgK]	Thermal conductivity [W/mK]	Thickness [mm]
Glass	2200	830	0.76	3.1
PV	2230	700	148	0.4
EVA	960	2090	0.35	0.3
Aluminium	2719	871	202.4	3.1
TEG	7670	198	1.61	3.9
Heat fin	2719	871	202.4	2.9

4.0 Results and Discursion

The Optimum Latin Hypercube Designing (OLHD) were utilised to perform a computerised experiment for the meta model. This meta model is a reinforcement model of the LHD approach, which is a statistical tool commonly referred to as piano. It is utilised for the development of the metaphysical model. The selected variables for the parametric analysis included the periodicity of the thermoelectric component, the temperatures of the phase change materials, and the frequency of the fin temperature. Each element was divided into 15 distinct categories, resulting in a total of 15 occurrences. The aim variable was selected as the daily power generation of the solar panel and the outside temperature differential of a thermocouple element.

The computational experiment data for the optimisation was analysed using the PiAnO programme in this study. The purpose was to identify the optimal point where the outside temperature of both ends of the piezoelectric element could be maintained at the highest level, while maximising the daily power production of the PV panel. Consequently, a predictive algorithm was created to ascertain the daily electrical energy production of the photovoltaic (PV) panel and the temperature at both extremities of the thermoelectric generator (TEG). Subsequently, this algorithm was employed as the objective function. Presently, a meta-model has been developed utilising a Radial Basis Function (RBF) interpolation model, which is well-suited for computational investigations.

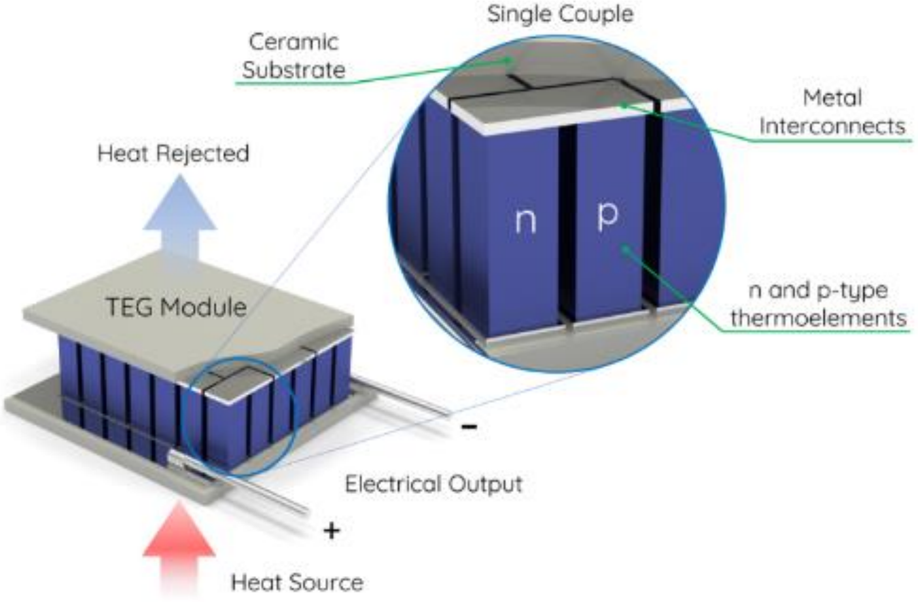


Figure:4. Schematic Diagram of thermoelectric generator

The optimal design point of Building Integrated Photovoltaic-Thermal Energy Generation with Phase Change Material (BIPV-TEGPCM) was identified through the utilisation of a prediction model and the application of a weighting technique.

5.0 Conclusion

The current study employed computational techniques to assess the influence of heat fin spacing, TEG arrangement, and phase change temperature on the BIPV-TEG-PCM system through transient CFD simulations. The integration of phase change material (PCM) has been found to enhance the efficiency of photovoltaic (PV) panels, while also generating additional power through the Seebeck effect of the thermoelectric generator (TEG). The simulations were conducted under standard test conditions (STC). The findings demonstrated that a lower phase transition temperature effectively delayed the rise in temperature of the PV panel. Alternatively, employing a phase change material (PCM) with a higher melting point, in conjunction with optimal spacing between heat fins, led to the sustained maintenance of uniform temperatures for an extended duration.

Thus, selecting the suitable melting temperature phase change material (PCM) and ensuring the correct heat fin spacing can enhance the efficiency of photovoltaic (PV) panels. The optimisation results indicated that the PV cell and TEG achieved the highest performance under standard test conditions (STC) when the phase change material (PCM) had a melting temperature of 40°C, the radiant heat fins were spaced 12.4 mm apart, and the TEG was positioned 187 mm distant.

The BIPV-TEG-PCM system demonstrated high efficiency in generating power and may function continuously without requiring additional equipment. It achieved this by enhancing efficiency and using waste heat sources, leading to the development of structures that are energy-neutral. To adequately address the diverse environmental factors present in the real world, it is essential to conduct regional optimisation simulations that incorporate multiple environmental aspects. In addition, ongoing research endeavours are concentrated on constructing models and assessing their efficacy through field trials.

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