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Advanced PV/T Systems

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Abstract*: A significant amount of research and development work on the photovoltaic/thermal (PVT) technology has been done since the 1970s. Many innovative systems and products have been put forward and their quality evaluated by academics and professionals. A range of theoretical models has been introduced and their appropriateness validated by experimental data. Important design parameters are identified. Collaborations have been underway amongst institutions or countries, helping to sort out the suitable products and systems with the best marketing potential. This article gives a review of the trend of development of the technology, in particular the advancements in recent years and the future work required..*

Keywords: Hybrid solar system, Photovoltaic/thermal collector, Energy conversion, Exergy analysis, Technology review

I. INTRODUCTION

A photovoltaic/thermal hybrid solar system (or PVT system for simplicity) is a combination of photovoltaic (PV) and solar thermal components/systems which produce both electricity and heat from one integrated component or system. In other words, PV is used as (part of) the thermal absorber. Those PV and solar thermal panels operating side by side are therefore not exactly within this ‘‘combi-panel” terminology. There are alternative approaches in PVT integration. Among many others, there can be selections among air, water or evaporative collectors, monocrystalline/ polycrystalline/amorphous silicon (c-Si/pc-Si/ a-Si) or thin-film solar cells, flat-plate or concentrator types, glazed or unglazed panels, natural or forced fluid flow, standalone or building-integrated features, etc. Accordingly, available installations are ranging from PVT air and/or water pre-heating system to hot water supply through PV integrated heat pump, and to actively-cooled PV concentrator through the use of economical reflectors. Design decisions have to be made on the collector type, the thermal to electrical yield ratio, as well as the solar fraction for optimizing the overall benefits. These all have determining effects on the system operating mode, working temperature and efficiency. Fig. 1 shows the main features of a flat-plate PVT collector. Fig. 2 shows the longitudinal cross-sections of some common air-type PVT collector configurations whereas the cross-sectional views of some examples of the water. A significant amount of research and development work on the PVT technology has been conducted in the last 35 years with a gradual increase in the level of activities. There appears a wider scope of international participations after the turn of the century. Nevertheless, real project applications are still limited at this stage. This article gives a review of the trend of development of the technology, starting from the early groundwork and placing more emphasis on the developments after year 2000. A projection of the future work is also given. PCM and nanomaterials at low and high loading to overcome the increased PV module temperature and temperature uniformity to improve the PV/T system’s cooling and thermal regulation. Some of the primary metrics used to evaluate the performance of PV/T systems include average PV module temperature, coolant outlet temperature or temperature gain across the working fluid, thermal and electrical power output, and overall, thermal and electrical efficiency. Moreover, the impact of different parameters on PV/T system performance is thoroughly investigated, including flow rate and inlet temperature of the working fluid, intensity of solar irradiation, PCM type, PCM thickness, and its mass, flow channel configurations, size, and different loading (low-high) of nanomaterials. At the end of this study, the future scope of this study has also been presented, highlighting the unsolved worked prospects of using nanomaterials in PV/T systems, and their actual use has been analyzed, as well as the numerous conclusion notes of this work. Therefore, the present review article compiles and summarises all relevant information on the usage of nanomaterials in PV/T systems in order to serve as a useful reference for the researchers. It is noted that there is a lack of a comprehensive and detailed review study exploring nanomaterials' role in PV/T system performance and its influence on the thermo-physical properties of PCM. It is revealed that the use of nanomaterial in PCM and coolant has sparked much interest because of their positive effects on PV module cooling and thermal regulation, as well as increased both energetic and exergetic efficiencies. The research articles available of eminence journals in the area of PV/T systems integrated with PCM/NEPCM and using air, ethylene glycol, water, and NF cooling techniques are identified in the following step. For the literature published in recent years, various search tools such as Google Scholar, Web of Science, and Science Direct are employed. There are a total of 163 works of literature cited in this article.

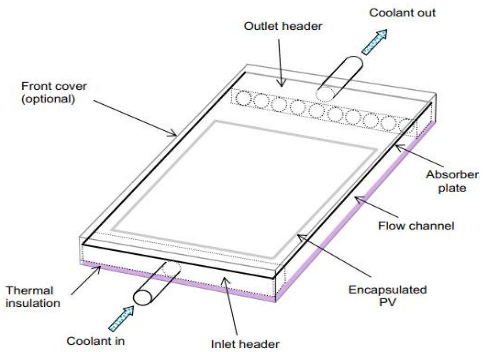

Fig. 1. Main features of a flat-plate PVT collector.

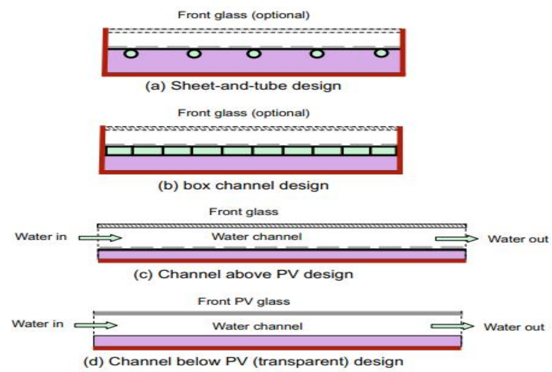

Fig. 2. Cross-sections of some common PVT/w collector designs.

II. AIR-BASED PV/T SYSTEM

2.1. Air-based PV/T-PCM system

Lin et al. [1] assessed the performance of a ceiling ventilation-based system with PV/T-PCM. The proposed study compares the test system with a PCM natural ventilation system without PCM and a house without using PV/T and PCM. The innovative PV/T-PCM system significantly improves the indoor thermal comfort of the building without using air-conditioning systems in winter by using the low-grade energy of heat and enhanced indoor thermal comfort in summer sessions through nighttime radiative cooling. Sohel et al. [2] theoretically observed the effect of several parameters on the PV/T system cooled by air and combined with salt hydrate (Tm = 22 ^{O}C) as PCM. The study observed that increasing the airflow velocity across the channels boosts both electrical and thermal efficiency (ɳth). At the same time, the depth of the channel has a restricted consequence on the test system performance (till a certain depth). The electrical efficiency (ɳel) of the test system increases linearly, and ɳth increases up to reaching a plateau on increasing the solar irradiation. Nouira and Sammouda [3] examined numerically the effect of exterior operating conditions like wind speed, wind direction, and dust accumulation on the PV-PCM system. The TPVmodule decreases when wind speed increases due to heat losses caused by forced convection. It is also observed that electrical power decreases to 1.2, 2.8, and 3 W on the deposition of dust accumulation density of 3, 6, and 9 g/m^2 on the test system. Therefore, dust accumulation on the PV panel decreases electrical power. The orientation of the PV panel, incident angle, and wind direction in any direction and towards the south direction. ϒPV and ϒW are the angles made by the horizontal projection of normal on the PV module from the south direction. If panel oriented in south direction ϒPV = 0 and ϒ = ϒW. The study concluded that PV temperature increases by increasing the wind azimuth angle. It is because of the flow of wind towards the module surface. Therefore, heat losses by force convection increase. By which, drop in temperature of panel attained. Wong wuttanasatian et al. [4] examined the performance of a passively cooled PV module integrated with palm wax. The palm waxes attached on the rear of the PV module surface have the three test specimen boxes grooved, tubed, and finned. To measure the performance assessment of the three different boxes, reverse saturation current is measured. Out of finned, grooved, and tubed boxes containing palm wax attached to PV modules, the finned box was found to be having the best cooling performance by reducing the module temperature by 6.1 ◦C. It is also observed that the passive cooling of PV integrated with PCM is not always beneficial. It depends upon

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the sola irradiation. If solar irradiation is more than 500 W/m^2 then there is a need for PV cooling. Fiorentini et al. [5] analytically developed a model of Heating Ventilation and Air-conditioning (HVAC) system, i.e. PV/T system integrated with PCM using a heat pump and cooled by air. This system is proposed for building management during winter and summer sessions. The PV/T collector is utilized to heat/cool the surrounding air, and this heated/ cooled air can be used for household purposes. The energy stored in PCM can be utilized for domestic uses or to pre-heat the air in the air handling unit (AHU). The study also conducted an experimental analysis that validated the modelling results. Choubineh et al. [6] studied the effect of PCM on the PV/T system performance using air as a working fluid. The experiments are conducted in four cases with natural air convection, forced air convection using low, medium, and high velocity. The study stated a decrease in TPVmodule by 4.3, 3.7, 3.6, and 3.4 ^{O}C in natural air convection and forced air convection using the low, medium, and high-velocity modes, respectively, using a 6 mm thick PCM sheet. Sharma et al. [7] assessed the building-integrated concentrating photovoltaic (BICPV) performance integrating with PCM by conducting indoor experiments using a solar simulator. The experiments are performed at 500, 750, and 1200 W/m^2 solar irradiation, and it is observed that there is an enhancement in ɳel by 1.15%, 4.2%, and 67.8%, respectively at 500, 750, and 1200 W/m2 solar irradiation. It is also noticed that the average centre temperature of the proposed system drops by 3.8 ◦C when compared to the non-PCM-based system. Khanna et al. [8] studied the electrical enhancement period of PV integrated with PCM. The results observed that the electrical enhancement period increases on increasing the wind speed. The variation of ɳel and electricity generation concerning wind speed. The study observed that there is an enhancement in ɳel and electricity generation on rising the wind speed. The reason was because of an increase in heat flow from the PV module on increasing the wind speed. By which there is a drop-in panel average temperature. Therefore, there is an improvement in ɳel, and electricity generation takes place on increasing the wind speed. Ren et al. [9] investigated the air-cooled PV/T system integrated with PCM used as TES to address the issue of energy demand and supply misalignment. This mismatching of energy is complete by the drive of the rotary desiccant wheel. The viability of the setup is examined by using the three factors like Solar thermal contribution (STC), Supply air temperature unsatisfied (SATU), and Supply air humidity ratio unsatisfied (SAHRU). The study observed that there is an enhancement in STC from 82.6% to 100% on reducing the regenerative temperature from 70 to 60 ◦C. In comparison, the SAHRU factor falls from 24.2% to 6%, raising the regeneration temperature from 60 to 70 ◦C. Hence, this system effectively runs the desiccant wheel to fulfill the energy demand and supply used for residential purposes. Kibria et al. [10] developed a thermal model for building integrated with PV modules using the PCM. The study developed a one dimensional (1-D) transient energy balance model. The finite difference method (FDM) is used for the discretization of the energy balance equation. The study observed that the use of PCM is effective for limiting the rise in TPVmodule. As a result, thermal performance improves by up to 5%. Hasan et al. [11] conducted the experiments using different PCM with Tm = 25 ± 4 ◦C for thermal management of building combined with PV. The study recommends that thermal management with PCM is better as compared to other thermal management techniques like heat pipe cooling, Peltier cooling, hydraulic cooling, natural and forced air circulation methods. The results noticed that the thermal performance of a PCM mainly depends on its thermal mass and k. The maximum temperature reduction is achieved for calcium chloride hexahydrate. Kazanci et al. [12] investigated the cooling, heating, and ventilation of the Denmark house. The house is designed to have no heat loss to surrounds for those insulations are used, namely conventional and compressed mineral wools. The study results by an annual investigation observed that a combined PV/T system is more valuable than having distinct systems for thermal and electrical elements. Lin et al. [13] investigated the thermal performance and optimization of building integrated photovoltaic thermal (BIPV/T) collectors using the organic (RT18HC) and inorganic (SP21E and SP24E) commercial PCM of Rubitherm. The study observed that the house's coefficient of thermal performance enhancement (CTPE) for the RT18HC, SP21E, and SP24E was improved by 43.3%, 48.8%, and 46%, with the PV/T system having a mass flow rate (M) = 2000 kg/h and PCM thickness of 20 mm. If optimization is performed by using the Taguchi method, there was an additional improvement in CTPE of the house, and it was found to be 70% with an airflow rate of 3000 kg/h for SP21E PCM having a thickness of 30 mm. Renet al. [14] also examined the thermal performance of PV/T system coupled with PCM using the Taguchi method. The study is evaluated by stored energy for TES applications. The PCM brick thickness, PCM type, charging air flow rate of PCM, and the air gap between the PV cell of PV/T collector and glass cover are primarily considered as

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controlling factors. Out of these factors, the type of PCM and charging air flow rate of PCM are the most critical factors for storing the energy for TES applications.

2.2. Air-based PV/T system integrated with NEPCM

Ma et al. [15] investigated the key issues and problems associated with using NEPCM in buildings for its thermal management and efficient energy performance. For this, a case study on the ceiling ventilation system with PV/T collectors and RT24 PCM dispersed with Cu NPs was conducted. The outlook of the ceiling ventilation system with PV/T and NEPCM used in the study. The study observed that NEPCM has better solidification and melting rates than pure PCM. Therefore, 8.8% more heat is charged in, and 25% more heat is released from NEPCM than pure PCM under test days. Sharma et al. [16] examined the thermal management of BICPV with or without using the PCM and NEPCM. For the examination, six configurations are tested: un-finned plate, micro-finned plate, un-finned plate with PCM and NEPCM, and micro-finned plate with PCM and NEPCM. The TPVmodule of the un-finned and micro-finned plate with PCM or NEPCM is reduced by 9.6, 11.2, 10.7, and 12.5 ◦C, respectively, according to the study. As a result, the micro-finned plate with NEPCM showed a maximum reduction of TPVmodule of 12.5 ◦C (18.5%).

III. WATER-BASED PV/T SYSTEM

3.1. Water-based PV/T-PCM system

Maatallah et al. [17] experimentally examined the exergetic and economic assessment of PV/T-PCM system having serpentine type flow channel arrangement at the backside of the module and cooled by water analysis paraffin wax was used as PCM. The test specimen with aluminum absorber plate, Cu serpentine tube, and paraffin wax was filled in Al container shown in Fig.3. The experiment was conducted at various mass flow rates of 0.004–0.02 kg/s. The study observed that the ɳel and overall efficiency (η_{ov}) of the PV/ T integrated with PCM was 17.33% and 28.86% higher, respectively, as compared to the PV module. The payback period of the proposed system was 11.26% smaller than that of the PV module, and this system had a lifecycle efficiency of 27% than the conventional PV module. Al Imam et al. [18] examined the conversion of solar radiation into heat energy and energy storage into PCM in a PV/T collector. The PV/T collector is mounted with a compound parabolic concentrator (CPC) for enriched solar radiation. The experiments were carried out during clean and semi-cloudy winter days of Feb-Dec 2014 between 11 am and 4 pm. The study observed that the ɳth of PV/T solar collectors varies from 40% to 50% during the clean day, and it reached 40% during semi-cloudy days. In comparison, ɳov varies between 46% and 55% and 55–63% during the semi-cloudy and clean day. Malvi et al. [19] presented the model of energy balance and simulated the results for hybrid PV and solar thermal systems using the PCM. The study observed that hybrid PV and the solar thermal system is a pleasing technology because PV alters the ultra-violet and visible parts of the solar spectrum. While the solar thermal system used the infra-red part of the solar spectrum and waste energy from PV.

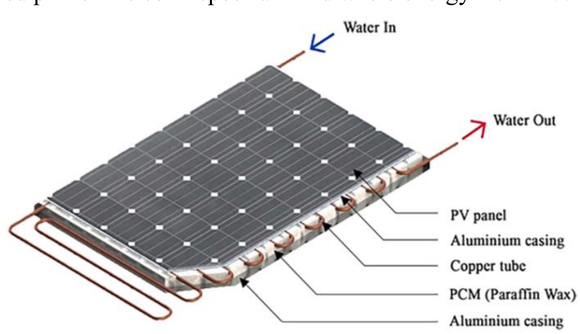

Fig. 3. Water-cooled PV/T system integrated with PCM

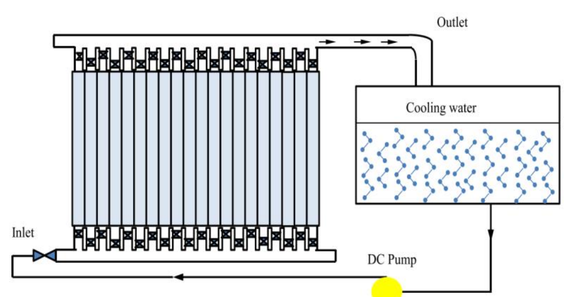

Fig. 4. Schematic representation of channels cycle

The hybrid PV/T performance improved by 9% more than traditional PV panels, and stored heat in PCM was used for household applications. Browne et al. [20] tested the three different configurations of water-based PV/T-PCM, water-based PV/T, and conventional PV panels. The heat storage capacity of the PV/T system linked with PCM was enhanced by 33% and 100% in marine and high-temperature regions, respectively. Zhou et al. [21] analyzed the PV/T system integrated with PCM having water as the coolant numerically. The effect of M and cooling water inlet temperature on performance parameters such as efficiency and TPV module.

3.2 Water-based PV/T-NEPCM system

Mousavi et al. [22] numerically examined the assessment of a water-cooled PV/T system integrated with PCM/PCM enhanced with metal (Cu) foam as the porous media. The three different types of PCMs, organic paraffin type (C15, C18, and C22), inorganic (salt of sodium phosphate), and eutectic (PA: CA) are investigated in the study. The numerical study considered the parameter for the investigation such as inlet temperature = 20 ◦C, solar orientation angle = 35 ◦, M = 0.02 kg/s and solar radiation intensity = 750 W/m^2. Melting temperature, enthalpy of melting, and specific heat capacity have all been found to impact the performance of PV/T-PCM systems significantly. The study claimed that with more reduction in thermal absorber temperature, there was a higher ηel. On the other hand, ηth increased on increasing the working fluid outlet temperature. The working fluid outlet temperature was found to be higher for organic paraffin C22, while the maximum reduction in absorber plate temperature for the inorganic salt was observed. Therefore, organic paraffin C22 has the higher ηth (83%) and inorganic salt has the higher ηel as compared to other investigated PCMs. The outdoor experiments were investigated for the performance evaluation of PV-PCM enhanced with Al2O3 system under water-cooled technique by Salem et al. [23]. The parameter considered of the ambient conditions were wind speed = 3.89–4.0 m/s, solar irradiation = 632.5–650.8 W/m^2 , ambient temperature = 35.4–37.2 ◦C and solar inclination angle = 30 ◦. The schematic channel cycle of the proposed water-cooled system in the study is depicted in Fig.4. The study concluded that there was a higher drop in PV module average temperature, thereby enhancing the performance of the NP enhanced based PV/T system. There was observed to be a reduction in TPVmodule on increasing the flow rate of coolant and concentration of NP and reducing the PCM/NP occupation in the cycle. Therefore, there was an improvement in the performance of the proposed system. Abdollahi and Rahimi [24] experimentally studied the performance of natural water cooled PV system intergraded with boehmite-enhanced PCM, which was the mixture of sunflower and coconut oil with different wt% of 18% and 82%. It was revealed that there was an enhancement in performance of the proposed system on the addition of nanomaterial in the PCM and the maximum ηel reached to be 48.23% at irradiation of 650 W/m^2. Abdelrazik et al. [25] numerically investigated the different combinations of nanomaterials and PCM integrated with PV/T at different loadings (ϕw = 10%, 20%, and 30%). The study revealed that organic RT35 and inorganic CaCl2.6 H2O were better as compared to others. MWCNT, on the other hand, was the best nanomaterial at both high nanomaterial concentration and solar concentrations. Therefore the combination of MWCNT-CaCl2.6 H2O inorganic PCM gives the best result and ηel and ηth improved by 9.3% and 18% at ϕw = 30% and solar concentration of 5 as compared to pure inorganic PCM. Islam et al. [26] experimentally investigated the energetic and exergetic performance of the different combinations of PV, PV/T, PCM, and NEPCM by employing the first and second universal laws of thermodynamics. It was observed that outlet coolant temperature is improved by 46 ◦C for the PV/T system thermal regulations by nanomaterial-enhanced PCM combination, and this system have the maximum overall energetic efficiency equal to 85% and energetic effciency equal to 12%.

IV. NF-BASED PV/T SYSTEM

4.1. NF-based PV/T-PCM system

Sardarabadi et al. [27] investigated the performance of PV/T-PCM system cooled by ZnO-water NF. The paraffin wax was used as the PCM in the study. The overall and electrical exergy efficiency of the proposed hybrid system of PCM and NF was enhanced by 23% and 13%, respectively, over conventional PV modules. Hosseinzadeh et al. [28] experimentally investigated the performance of PV/T-PCM system cooled by ZnO-water NF. The study results showed that the proposed PV/T-PCM cooled with NF has a higher overall thermodynamic performance. Therefore, the proposed system's energetic and exergetic overall efficiency was observed to be 65.71%, and 13.61% than conventional PV and PV/T-PCM cooled by water systems. Hassan et al. [29] investigated the thermal management and uniform temperature regulation of PV/T-PCM system cooled by graphene-water. The experiments were conducted at a Q = 20, 30, and 40 lpm and ϕv = 0.05%, 0.1%, and 0.15%. Fig.5 represent the molten PCM (RT35HC) filled in Al box and Cu tube serpentine flow channel networks at the backside of the module, respectively. The results revealed that the PV/T-

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PCM system cooled by graphene-water has the highest EE, TE, and ɳov 14%, 45.8%, and 60.3%, respectively at a Q = 40 lpm and ϕv = 0.1%.

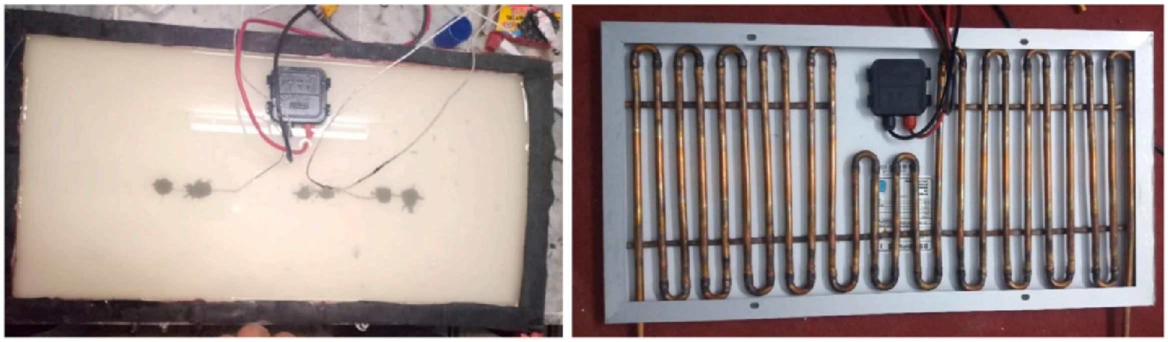

Fig. 5. (a) Molten paraffin wax filled in Al container; (b) Cu tubes serpentine channel networks inside PCM box.

4.2 NF-based PV/T-NEPCM system

Sarafraz et al. [30] examined the electrical and thermal performance of PV/T systems integrated with NEPCM and NF coolant. The EE and TE of the proposed system reached 307.9 and 276.3 W/m^2, respectively. It was noticed that there was an enhancement in overall power output with an increase in the concentration of nanomaterial from the proposed PV/T system, but it augmented the required pumping power for circulating the working fluid. Thereby, there was a reduction in equivalent thermal- electrical power. Al-Waeli et al. [31] investigated the performance of PV/T system integrated with SiC-water coolant and paraffin wax, i.e. PCM, using a mathematical model and validated experimentally. The study results revealed that ɳel and ɳth observed to be 13.2% and 71.3% from mathematical models 13.7% and 72% experimentally. Kazemian et al. [32] numerically inspected the PV/T system cooled by Al2O3-water and included it with nano-PCM. Al2O3 NP is added to both the coolant and the PCM, but the results revealed that the addition of NP in coolant was more effective than adding in PCM. The study observed that maximum thermal and electrical power outputs were 377.87 and 136.93 W/m^2 respectively, for the nano-PCM and NF coolant integrated PV/T system.

V. CONCLUSION

This paper presents and analyses a comprehensive study of recent advances and prospects on the role of nanomaterial in improving the performance of PV/T systems. The following are the major conclusions:

- Hybrid PV and solar thermal system (PV/T) is a promising technology because PV alters the ultra-violet and visible parts of the solar spectrum. While the solar thermal system used the infra-red part of the solar spectrum and waste energy from PV. Therefore, it is concluded that a PV/T system is more beneficial than having separate systems for electrical and thermal elements.
- There is an enhancement in ɳel and electricity generation on increasing the wind speed because of increased heat flow from the PV module. By which there is a drop-in module average temperature.
- Using the PCM layer in the PV/T systems reduces the enhancement in backside temperature of PV modules under solar irradiation compared to PV/T without PCM layer.
- As reported in several studies of this paradigm, there is a positive effect on the performance parameters of the PV/T-PCM system on increasing M and a decrease in the inlet temperature of the working fluid.
- The PCM type, the thickness of PCM brick, charging air flow rate, length of PCM, and the air gap between the PV cell of PV/T collector and glass cover are the controlling factors for storing the energy for TES applications. The type of PCM and charging air flow rate are the most critical factors out of these factors.
- When wind speed is increased, it improves ɳel and generates more electricity. This is primarily due to an increase in heat loss through convection as the wind speed increases. The TPV module decreased because of the increase in wind speed.

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- Thermal management with PCM is better than other thermal management techniques like heat pipe cooling, Peltier cooling, hydraulic cooling, natural and forced air circulation.

Future research directions

Although different research studies have been conducted in order to assess the role of nanomaterials on the performance of the PV/T system integrated with PCM/NEPCM, there is a need to elaborate on some areas due to complicated mechanisms and the involved processes. Therefore, future research can be extended in the following areas:

- There is a need to experimentally analyze the long-term effect of NEPCM on the PV/T system. Such type of study will explore the actual performance of NEPCM.
- An essential challenge in incorporating the metal foam in PCMs to improve the k is the total cost associated with it. Therefore, there is a need for economic analysis for the use of metal foam in PV/T systems.
- There is a need for more in-depth studies to explore the effect of various factors and variables on the k augmentation of NEPCM, understand the effect of intermolecular interactions on the enhancement of k and understand the effect of power and sonication time on the synthesis of NEPCM.
- There is a need for an in-depth study of NP agglomeration in the PCM during heating and cooling processes, and there is also a need to explore the effect of the aspect ratio of nanomaterial on the thermophysical properties of the NEPCM integrated with the PV/T system.
- As NEPCM can be used for TES applications but there is a need for further investigation of optimum concentrations of NP to address the inconsistent result on latent heat capacity and to optimize the NP concentration in PCM where the positive effect (enhancement in k) outweighs the negative effect (reduction in phase change enthalpy).
- The influences of hybrid and magnetic NF on the PV/T-NEPCM system performance should be evaluated.
- The reliability of the PV/T system integrated with NEPCM using the NF must be evaluated in terms of technical, economic, and environmental aspects.

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