

Abstract

The global energy demand of the world expands with population growth which causes excessive load on conventional energy resources such as fossil fuels. Conventional energy sources are limited and cause various environmental problems such as air pollution, global warming, and sudden climate changes. Therefore, an increase in unconventional energy resources such as solar energy, wind energy, geothermal energy, and other resources must be emphasized to meet future rising energy demands and reduce the growing environmental problems. Photovoltaic (PV) technology is an excellent clean and green energy option. PV panels convert solar energy directly into electrical energy. However, most incoming radiation is wasted in the form of heat that increases the operating temperature of the PV panel and degrades its electric conversion performance. The electric conversion efficiency of the PV panel is inversely proportional to its operating temperature. Hence, the electric performance of the PV panel can be enhanced by reducing its operating temperature using appropriate cooling technique. The application of the cooling technique enhances also enhances the utilization of incoming radiation by absorbing waste heat. The phase change material (PCM) integrated PV panels (PV/PCM systems) could be a viable option to enhance PV panel's electric performance and store heat for nocturnal hours. However, the conventional rectangular PCM enclosure exhibit degradation in performance in later stages of melting process. The unsymmetrical pattern of melting in conventional enclosures leads to non-uniform temperature distribution, which degrades the electric and heat storage performance of conventional PV/PCM systems. Therefore, design modifications and innovations of PCM encapsulations are desired to improve thermoelectric performance. In this thesis, a series of new design concepts of PCM encapsulations for PV/PCM systems and bifacial PV/PCM systems working on the principle of augmented convection dominated melting regime are proposed and investigated by developing experimentally validated computational fluid dynamics (CFD) models. Various geometric and governing parameters are optimized to improve electric conversion performance and heat storage performance. Firstly, a non-rectangular PCM enclosure (same volume as the conventional enclosure) is integrated into the PV panel to take advantage of unsymmetrical melting caused by the natural convection of liquid PCM. The PV panel exhibits significant enhancement in thermoelectric performance; however, the compactness of the PV/PCM system is partially compromised. Secondly, an overhead type rectangular PCM enclosure is examined for the PV/PCM system to take the waste heat away from the PV panel and reduce the PV panel temperature. This design modification is based on the concept that the melting front can propagate in both (horizontal and vertical directions) if the enclosure is extended to an optimum height. Further, another novel enclosure design is conceived in the

form of an extended non-rectangular enclosure to investigate the effect on performance. The idea was to provide optimum distance to the melting front to travel in horizontal and vertical directions. This modified configuration exhibits better thermo-electric performance and provide compact geometry. Lastly, a more efficient bifacial PV/PCM system is proposed to enhance thermoelectric performance. This modification involves radiation reflection by an L-shape mirror system and PCM enclosure modification according to melting morphology. The bifacial PV/PCM system enhanced power output by 1.91 times that of the conventional PV system and 1.77 times that of the conventional PV/PCM system. The energy, exergy, economic, and environmental analysis were carried out for the bifacial PV/PCM system. The proposed system not only exhibits better thermo-electric performance but also help in reducing energy procurement cost and carbon emissions. All the aforesaid new designs show significant improvement in thermos-electric performance compared to conventional systems.

Chapter 2 explored the avenues to improve the electrical efficiency of photovoltaic (PV) panel by absorbing waste heat in encapsulated phase change materials (PCM) during the melting process. Previous investigators reported the melting process of PCM in a rectangular encapsulation and observed four transient regimes of heat transfer in sequence as: conduction, mixed conduction-convection, quasi-steady convection and solid-shrinking regimes. For higher heat extraction from the PV panel, longer duration of quasi-steady convection regime is desirable. However, this steady regime is suppressed in the rectangular PCM enclosure due to the nature of natural convection and consequently, the melting rate of the PCM is arrested. In this chapter, we report on electrical and thermal performance of non-rectangular PCM integrated PV panels using an experimentally validated numerical model that enhances the quasi-steady regime by more than 100% compared to the conventional rectangular design. The strategic mass distribution of PCM for better thermal management was achieved with encapsulation designs having profile of right wall varying as $y = (ax - b)^{1/n}$, with $n = 1$ (linear), 2 (parabolic) and 3 (cubic) with different lower thickness ratio. Compared to conventional design, the proposed design increased the PCM melting rate by 17% due to which PV cell temperature dropped by 11.5% and consequently, electrical conversion efficiency approaches to 12%.

Chapter 3 examines the feasibility of non-rectangular type encapsulation for PV/PCM system under variable boundary and ambient conditions (similar to real conditions). The conventional design exhibits slow melting rates and degraded thermo-electric performance due to shorter regime of convective melting (ends before maximum insolation). The unsymmetrical loading of PCM in non-rectangular enclosure encourages characterization of melting according to natural convection. The proposed non-rectangular PCM enclosure for PV/PCM systems exhibits elongated quasi-steady convection regime far beyond the maximum insolation time causing increased melting rates. Compared to conventional design, the proposed design exhibits 20% more melting and PV panel works at 92% of its rated performance. The heat loss from the proposed system is approximately half compared to conventional system that explains higher

insolation utilization ability of the system. Energy efficiency, exergy efficiency, economic, exergoeconomic, and enviroeconomic analysis are carried out for both conventional and proposed systems. The proposed system exhibits higher exergy efficiency (13.81%) and energy efficiency (73.95%) whereas conventional system exhibits somewhat lower exergy efficiency (13.66%) and a lower energy efficiency (69.77%). The economic analysis suggests that the proposed system exhibits approximately 3% lesser cost of production of electricity compared to conventional PV/PCM system. In terms of earned carbon credits, the proposed system also helps in reducing the CO_2 emissions to the environment. Hence, the proposed design of PV/PCM system would be beneficial in domestic and industrial applications.

In the chapter 4, a new design concept of overhead phase change material (PCM) enclosure design attached with a photovoltaic panel has been investigated. Various design configurations studied and based on the melting front characteristics, an optimum final design is proposed. The new design enhances the solar radiation gain (ratio of utilized to unutilized radiation) by about 17 times the conventional PV system. Higher solar radiation utilization manifests in about 10% increase in energy storage density. With strategic distribution of PCM, duration of quasi-steady regime where convection dominates, has been increased that manifested into higher melting rates of PCM compared to the conventional rectangular design. The study revealed that electrical conversion efficiency of PV panel can approach to about 12% if suitable strategies are adopted as demonstrated in this chapter. The liquid PCM has a tendency to rise against gravity force but restricted by the top wall of enclosure alongside of PV panel in conventional PV/PCM system. However, the usage of extended enclosure allows the convection current to erode the melting interface in both horizontal and vertical direction. This phenomenon accelerates the melting process as the excessive heat is being taken away from the PV panel in the extended part of enclosure. This modification in design also solves the issue of compactness of the system and also provide encouraged thermo-electric performance. This study would be useful in developing efficient PV technologies to meet the ever-growing energy needs. The findings of this investigation are reported from an experimentally validated numerical model that accurately captures the melting behavior of PCM and other thermal characteristics of the system.

Chapter 5 examines an innovative concept of extended non-rectangular phase change material (PCM) enclosure integrated with a photovoltaic (PV) panel that manifests 7.26 times incoming solar radiation than the simple PV system. In extended rectangular type enclosures, the horizontal width of the PCM encapsulation is customized with same volume of PCM is maintained in the enclosure. This will hinder the movement of melted PCM in horizontal direction and affects thermo-electric performance due to slower melting rates. Hence the enclosure design is changed to an extended non-rectangular enclosure to improve further performance. The strategic distribution of PCM is achieved by controlling certain geometric parameters such as lower thickness ratio, extension ratio and profile of right wall. With optimization of these pa-

rameters, the span of convection dominated regime is prolonged to more than 120 minutes which conceded 20.5% more melting compared to the conventional rectangular design of same PCM volume. Electric conversion efficiency can approach to 96.37% of its rated value with the application of strategies demonstrated in the paper. Moreover, incoming radiation absorbing capacity can approach to 67.35% for recommended configuration. An experimentally validated numerical model is used to report the findings of this investigation which can predict exact melting morphology and thermal behavior of the system. This study provides useful information that will be helpful in developing more efficient PV techniques that can meet the ever rising global energy demands.

Chapter 6 examines a new concept of bifacial PV/PCM (BIF-PV/PCM) system with sandwiched thermal energy storage enclosure that possesses 1.21 times power output density and 7.39 times total energy utilization density per unit land area compared to the conventional PV system. Based on the melting morphology and thermo-electric performance of the initially rectangular PCM enclosure, an optimized bifurcated non-rectangular design of the enclosure is proposed to enhance the incident radiation utilization ability by 87% more than a simple one PV/PCM system. Enhanced utilization of solar radiation manifests into 105% more melting compared to conventional PV/PCM system. With the strategic mirror reflection and bypassing the solar radiation towards the rear PV panel and strategic design of PCM enclosure to aid convection-driven melting, electric power output has been increased significantly (about 77%) compared to similar conventional PV/PCM system. The study revealed that overall system efficiency could approach about 74% if suitable strategies are adopted, as demonstrated in this chapter. Results are discussed in terms of energy utilization efficiency, exergy efficiency, power conversion efficiency, tracking melting front morphology, and its effect on heat transfer characteristics, etc. This investigation has been carried out with the help of an experimentally validated numerical model that accurately mimics the melting morphology of PCM and other heat transfer characteristics of the system. The findings of this study would help design and develop a more efficient BIF-PV/PCM system to meet exponentially increasing energy needs.

A series of novel designs of PCM encapsulation for PV/PCM systems have been investigated in the thesis using computational fluid dynamics with an objective to meet global energy demands. The efforts put in the present research certainly adds contribution to the global theme of '*Clean and green energy for all*'.