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Climatic behaviour of solar photovoltaic integrated with phase change material

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ABSTRACT

In photovoltaic (PV) cells, a large portion of the solar-irradiance becomes heat which shoots the cell temperature up and decreases its electrical efficiency. The heat can be removed using phase-change-material (PCM) at the rear of the PV. In literature, the researchers have reported the performance of PV-PCM for their respective locations. However, selection criteria for climates suitable for PCM integration are not reported yet. Thus, it has been carried out in the current work. The model has been validated against the experimental measurements. It has been concluded that (i) the climates having less variations in the ambient temperature are more suitable for PCM integration. The electricity enhancement achieved by PV cooling is 9.7%. It reduces to 6.6% for the climate having large variations, (ii) Heat extraction by PCM-systems is more effective in warm climates in comparison to cold climates, (iii) PCM integration performs better in climates with low wind-speed, (iv) PCM is more effective for the climates where wind-flow is across the PV and (v) Climates having high solar-radiation is better for heat removal by PCM.

1. Introduction

Solar photovoltaic (PV) is one of the fastest growing renewable technologies. However, in PV cells, only a small portion of the solar irradiance manages to get transformed into electricity. The rest becomes heat and shoots the cell temperature up and, consequently, decreases its electrical efficiency [1]. The studies involving the use of phase change material (PCM) to cool the PV have been reviewed.

1.1. Experimental investigations

The works related to the experimental investigations of the PV-PCM system are as follows: Hasan et al. [2] have used five different PCMs: paraffin wax (RT20), capric–lauric acid (C–L), capric–palmitic acid (C–P), pure salt hydrate ($CaCl_2{\cdot}6H_2O$) and commercial blend (SP22) and found that the PV temperature can be reduced maximally by 18 °C for a solar flux of 1000 W/m^2. Indartono et al. [3] have shown the applicability of a petroleum jelly as PCM for the thermal management of the PV. Huang et al. [4] have introduced aluminium fins inside the PCM box to enhance the PV cooling and found a further reduction of 8 °C in the PV temperature. Hasan et al. [5] have studied the behaviour of the system in two climates: Dublin, Ireland and Vehari, Pakistan and found better performance at Vehari. Sharma et al. [6] have used the PCM for lowering down the temperature of building integrated concentrated PV and found 7.7% increment in the electricity. Cui et al. [7] have integrated the PCM with concentrated PV-thermoelectric system to enhance the system performance. Sardarabadi et al. [8] have pumped water through the tubes inside the PCM box to use the stored heat and reported a temperature drop of 16 °C in PV. Browne et al. [9] have also studied the utilization of the stored energy in the PCM by flowing water and reported a thermal efficiency of 20%. Huang et al. [10] have discussed the formation of the crystals in the PCM and its effect on the system performance. Researchers have reported the numerical investigations too to predict the system performance [11–14] which are presented in the subsequent sections.

1.2. Numerical investigations

There have been studies carrying out the one-dimensional thermal analysis of the PV-PCM system. The heat transfer (inside the PCM box) due to conduction only has been considered in these studies. Kibria et al. [15] have proposed an implicit scheme to model the heat balance. It is found that the mismatch of the computed values of the PV temperature from the experimental measurements remains within ± 3 °C. Brano et al. [16] have used a finite difference approach for the modelling and found a mismatch of ± 7 °C with that of the measured values.

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Nomenclature

a_i	coefficients of polynomial in Eq. (29)
C_p	heat capacity (J/kg K)
D	function used to distribute the latent heat in phase change zone
f	liquid fraction of the phase change material during phase transition
F	view factor
g	gravitational acceleration (m^2/s)
G	portion of solar irradiance converted into heat (W/m^3)
h	heat transfer coefficient due to convection (W/m^2 K)
I_T	instantaneous solar-irradiance on tilted plane (W/m^2)
k	thermal conductivity (W/m K)
L	system length (m)
L_h	heat capacity as latent (J/kg)
p	pressure (Pa)
s_f	spacing between fins (m)
t	time (s)
t_f	fin thickness (m)
T	temperature (K)
T_m	melting temperature of phase change material (K)
u	velocity of phase change material (m/s)

Greek symbols

β	tilt angle of the system (rad)
β_c	coefficient for expansion of phase change material due to temperature (/K)
δ	depth of the PCM box (m)
ε	emissivity for long wavelength radiation
η_{PV}	PV efficiency
μ	dynamic viscosity (kg/ms)
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant (W/m^2 K^4)

Abbreviation

EVA	ethylene vinyl acetate
PCM	phase change material
PV	photovoltaic

Subscripts

a	ambient
al	aluminium
b	back of the PV
g	ground
i	i^{th} layer of the PV
l	liquid phase
P	PCM
s	sky; solid phase
t	top surface
x	x direction
y	y direction

Su et al. [17] have integrated the PCM and an air channel in their study for the thermal management of the PV and found an increment of 10.7% in the overall efficiency as compared to no-PCM case. Atkin and Farid [18] have integrated the PCM and the heat sink for PV cooling and reported an increment of 12.97% in the electrical output as compared to no-PCM and no-heat sink case.

The following studies have presented two dimensional thermal analyses of the PV-PCM system considering the heat transfer due to both conduction and convection inside the PCM box since convection affects the performance of the system significantly [19]. Huang et al. [20] have introduced aluminium fins inside the PCM box to enhance the PV cooling and found a further reduction of 3 °C in the PV temperature. Khanna et al. [21–24] have investigated the performance of the system for various operating conditions and optimized the quantity of PCM for PV-PCM and Finned-PV-PCM systems. Ho et al. [25] have proposed the encapsulation of the PCM at micro level. Huang [26] has studied the effect of the use of multiple PCMs on the cooling of the PV. The PCM changes its properties during phase transition zone and, thus, Biwole et al. [27] have presented the expressions to incorporate these changes.

Ho et al. [28,29] have used a three dimensional (3-d) model to study the conduction heat transfer in the system and reported the thermal management of the PV for southern Taiwan climate. Liu et al. [30] have used 3-d model by incorporating the heat transfer due to convection and reported that the PV temperature can be reduced further by 4 °C using PCM instead of water for a day in summer at Nanjing. Huang et al. [31,32] have reported that the mismatch between the temperature values computed using 2-d and 3-d models lies within −4 °C to 2 °C.

Apart from PV cooling, there have been studies analysing the performance of PCM for other purposes: Esen and Ayhan [33] have analysed the variation of stored energy with time for various types of phase change materials for a solar assisted energy storage tank. CCHH, Paraffin, SSDH and P-Wax have been considered as PCMs. Esen et al. [34] have carried out the optimization of the storage tank. Esen [35] has analysed the PCM storage tank integrated with solar powered heat pump system. Baby and Balaji [36] have studied the PCM based heat sink for the cooling of the portable electronic devices. Srikanth and Balaji [37] have carried out the optimization of the heat sink to achieve maximum charging period and minimum discharging period.

Thus, in literature, it is found that the researchers have reported the performance of the PV-PCM system for their respective locations. However, selection criteria for the climates suitable for PCM integration are not reported yet. Thus, in the current work, various types of climates have been chosen. The objectives of the presented study are (i) to present a mathematical model for analysing the transient behaviour of the system incorporating the effect of climate, (ii) to compute the decrease in the PV temperature achieved by the cooling of PV, (iii) to compute the increment in the electricity generation achieved by the PV cooling and (iv) to compare various climates in terms of the performance enhancement achieved by PCM integration. The performance enhancements have been compared for (i) the climate having less variations in the ambient temperature with that of the climate having large variations, (ii) warm climates with that of cold climates, (iii) climate with high wind speed with that of the climate having low wind speed, (iv) climate with high wind azimuth with that of the climate having low wind azimuth and (v) climate with high solar radiation with that of the climate having low solar radiation.

2. Methodology

The systems considered for the presented work are shown in Fig. 1. First system is only-PV panel. Second system consists of a PV attached with an aluminium box containing PCM. Third system considers aluminium fins inside the PCM box. All the systems are considered to be