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Global analysis of photovoltaic energy output enhanced by phase change material cooling

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HIGHLIGHTS

- Phase change materials (PCMs) can passively cool PV panels to increase energy output.
- A global numerical analysis of PV energy output with PCM cooling is presented.
- The most promising locations for PCM cooling are in the tropics.
- A relative performance improvement of over 6% is possible in some regions.
- A sub-optimal PCM melting temperature still produces a beneficial energy output enhancement.

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ABSTRACT

This paper describes a global analysis to determine the increase in annual energy output attained by a PV system with an integrated phase change material (PCM) layer. The PCM acts as a heat sink and limits the peak temperature of the PV cell thereby increasing efficiency. The simulation uses a one-dimensional energy balance model with ambient temperature, irradiance and wind speed extracted from ERA-Interim reanalysis climate data over a 1.5° longitude × 1.5° latitude global grid. The effect of varying the PCM melting temperature from 0 °C to 50 °C was investigated to identify the optimal melting temperature at each grid location. PCM-enhanced cooling is most beneficial in regions with high insolation and little intra-annual variability in climate. When using the optimal PCM melting temperature, the annual PV energy output increases by over 6% in Mexico and eastern Africa, and over 5% in many locations such as Central and South America, much of Africa, Arabia, Southern Asia and the Indonesian archipelago. In Europe, the energy output enhancement varies between 2% and nearly 5%. In general, high average ambient temperatures correlate with higher optimal PCM melting temperatures. The sensitivity to PCM melting temperature was further investigated at locations where large solar PV arrays currently exist or are planned to be constructed. Significant improvements in performance are possible even when a sub-optimal PCM melting temperature is used. A brief economic assessment based on typical material costs and energy prices shows that PCM cooling is not currently cost-effective for single-junction PV.

1. Introduction

The addition of phase change material (PCM) to a solar cell has been proposed as a method to increase solar PV energy output by keeping the temperature of PV cells close to the ambient [1]. The PCM is a layer of high latent heat capacity which acts as a heat sink, absorbing heat that is transferred from a PV cell. Solar cell efficiency is dependent on cell temperature, with a drop in efficiency of 0.45% (relative) for every 1 °C rise in cell temperature for crystalline silicon [2]. Therefore, any mechanism which reduces the cell temperature, particularly at times of high irradiance, will increase cell efficiency and PV energy output. Alongside phase change materials, existing cooling methods proposed include water and air cooling. Water cooling may be unsuitable due to the weight of water required to deliver appropriate cooling [3]; furthermore, in many locations where solar energy has great potential such as deserts, water is scarce. If either air or water cooling is activated, this introduces a maintenance burden that could increase operating costs and system downtime.

The potential for improvement by using a PV/PCM system has been demonstrated in numerical simulations [1,4], laboratory tests

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[1,5,6] and in outdoor studies [5,7,8]. In terms of outdoor testing of PV/PCM systems, it was estimated that efficiency from a PV/PCM system would be improved by 7.5% at peak solar hours due to a 17 °C difference in temperature between an aluminium flat plate and an aluminium box containing PCM [5]. A PV/PCM panel tested outdoors in Pakistan resulted in a PV cell temperature that was 21.5 °C lower than the reference at the peak time of the day [7]. These figures are maximum temperature differentials as the PCM and non-PCM systems change temperature at different rates due to the difference in thermal masses. However over the course of the day it was calculated that PV energy output would be improved by 6.8% compared the reference cell, estimated from the cell manufacturers' data of a 0.5% K^{-1} decline in efficiency and the temperature difference between the cells at each point during the day. In the cooler climate of Ireland in mid-September, the power output increase was approximately 3.8% with the same PCM. During an experiment in Western India it was demonstrated that PCM cooling could be very promising for use in concentrating solar PV cells [8].

This paper evaluates the global potential for PCM-assisted cooling by measuring the absolute and relative increases in electrical output from a silicon solar cell using a numerical simulation. The simulation is performed globally using typical climatological data for each region. For sites of current and future interest for solar PV, the dependence in energy output on PCM melting temperature is analysed. The locations where PCM-assisted cooling is likely to lead to significant energy output increases are therefore identified.

2. Model PV/PCM cell

The model PV/PCM cell consists of a solar cell layered on top of an aluminium box containing PCM (Fig. 1). The heat transfer through a PV/PCM cell is modelled performed using a one dimensional finite difference energy balance method with a one hour timestep. The energy balance scheme consists of the incoming solar energy less the heat lost to the surroundings in the form of convection and radiation and energy extracted in the form of electricity (Fig. 1). Conductive heat exchange occurs between each component of the PV/PCM cell.

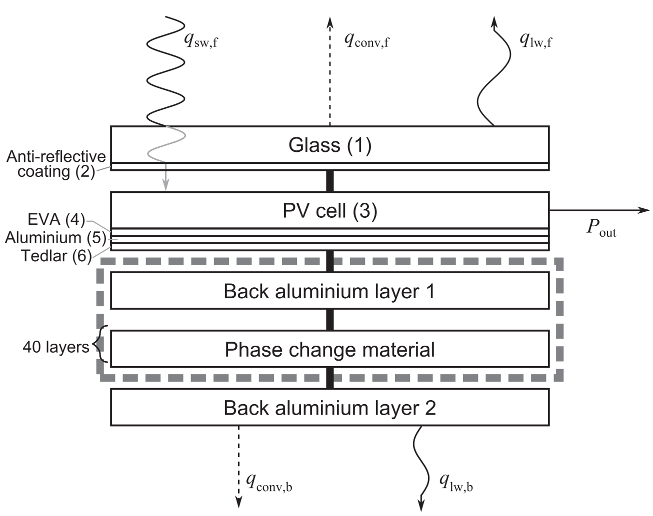

Fig. 1. Energy balance diagram showing the energy fluxes into and out of the PV/PCM system. The thick black lines represent conductive heat exchange. Subscripts are defined as follows: sw = shortwave, lw = longwave, conv = convective, f = front, b = back. P_{out} is the electrical energy generated by the cell. The dotted grey box encompasses the components of the PV/PCM system that are omitted from the reference PV system. Numbers in brackets refer to the subscripts given to each layer in Table 1 and Eqs. (1)–(6).

2.1. PV cell

The PV cell is based on that of Armstrong and Hurley [9] and has 6 separate layers numbered 1–6 in Fig. 1 and Table 1. Given the small heat capacity of some of the layers, the glass and anti-reflective coating are treated as one combined thermal mass, referred to hereafter as the *glass* layer, and the PV cell, EVA layer, aluminium rear contact and Tedlar backing are combined into another separate thermal mass, referred to hereafter as the *cell* layer. The combining of small thermal masses improves the numerical stability of the model by avoiding division by very small numbers.

The total heat capacity (J K^{-1}) of the glass layer is given by

$$C_{glass} = A(\rho_1 c_{p1} z_1 + \rho_2 c_{p2} z_2) \quad (1)$$

and thermal conductance (W K^{-1}) is given by

$$G_{glass} = \frac{A}{z_1/k_1 + z_2/k_2} \quad (2)$$

where A is the area of the cell. The heat capacity and thermal conductance of the PV cell layer is similarly given by

$$C_{cell} = A(\rho_3 c_{p3} z_3 + \rho_4 c_{p4} z_4 + \rho_5 c_{p5} z_5 + \rho_6 c_{p6} z_6) \quad (3)$$

and

$$G_{cell} = \frac{A}{z_3/k_3 + z_4/k_4 + z_5/k_5 + z_6/k_6} \quad (4)$$

2.2. Aluminium casing

The PV cell described is attached to an aluminium box which sandwiches the PCM following the experimental methods of Huang et al. [5]. It was shown that a highly conductive material for the PCM housing such as aluminium is more effective than an insulating housing such as Perspex [10]. Heat losses through the sides of the PCM box are assumed to be negligible compared to the front and back of the box based on a cell size of $A = 1$ m^2.

Both top and bottom aluminium sheets have heat capacity and thermal conductance G_{alu} given by

$$C_{alu} = A\rho_{alu} c_{p,alu} z_{alu} \quad (5)$$

and

$$G_{alu} = \frac{Ak_{alu}}{z_{alu}} \quad (6)$$

with $z_{alu} = 5$ mm and values of ρ, c_p and k the same as for the back-contact aluminium given in Table 1.

2.3. Phase change material

PCMs can either be isothermal or undergo a small phase change temperature range. Various materials have been exploited as PCMs, including salt hydrates, fatty acids and paraffin waxes

Table 1
Heat transfer parameters of the PV panel, from references within [9]. ρ: material density (kg m^{-3}), c_p: specific heat capacity (J kg^{-1} K^{-1}), z: material thickness (m), k: thermal conductivity (W m^{-1} K^{-1}).

Subscript	Layer	ρ	c_p	z	k
1	Glass covering	3000	500	0.003	1.8
2	Anti-reflective coating	2400	691	1.0×10^{-7}	32
3	PV cells	2330	677	2.25×10^{-4}	148
4	EVA	960	2090	5.0×10^{-4}	0.35
5	Aluminium (cell)	2700	900	1.0×10^{-5}	237
6	Tedlar	1200	1250	0.0001	0.2