Increased photovoltaic performance through temperature regulation by phase change materials: Materials comparison in different climates

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Abstract

A photovoltaic–phase change material (PV–PCM) system has been developed to reduce photovoltaic (PV) temperature dependent power loss. The system has been evaluated outdoors with two phase change materials (PCMs); a salt hydrate, $CaCl_2 \cdot 6H_2O$ and a eutectic mixture of fatty acids, capric acid–palmitic acid in two different climates of Dublin, Ireland (53.33N, 6.25W) and Vehari, Pakistan (30.03N, 72.25E). Both the integrated PCMs maintained lower PV panel temperature than the reference PV panel. Salt hydrate $CaCl_2 \cdot 6H_2O$ maintained lower PV temperature than capric–palmitic acid at both the tested sites. The lower PV temperatures effected by the use of the PCMs prevented the associated PV power loss and increased PV conversion efficiencies. Both the PCMs attained higher temperature drop in warm and stable weather conditions of Vehari than the cooler and variant weather conditions of Dublin.
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1. Introduction

Silicon photovoltaics (PV) show a power drop above 25 °C with a temperature coefficient of up to $-0.65\% \, K^{-1}$ (Radziemska and Klugmann, 2002; Radziemska, 2003) depending on the type of the PV cell and the manufacturing technology (Makrides et al., 2009). Various mathematical correlations have been developed to describe the dependence of PV operating temperature on the climatic conditions and PV materials (Skoplaki and Palyvos, 2009). The operating temperature reached by PV panels and associated power drop largely depends on the climate of the site. In Germany 50% of the solar radiation reaching on a PV panel is above $600 \, W \, m^{-2}$ while in Sudan this value reaches 80% resulting different operating temperatures and associated power drop (Bücher, 1997; Amy de la Breteque, 2009). A maximum PV operating temperature of 125 °C has been reported in southern Libya (27.6N and 14.2E) resulting in a 69% reduction in the nominal power (Nassar and Salem, 2007). The advisable operating temperature limit for PV ranges from −40 °C to 85 °C (Suntechics, 2008) however in hot and arid climates, PV temperature frequently rises above this temperature range (Nassar and Salem, 2007), which results in temperature induced power failure as well as PV cell

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Nomenclature

Symbols

C	specific heat capacity of the PV–PCM system ($J\,kg^{-1}\,K^{-1}$)
ΔT	temperature drop (°C)
h_{ca}	combined convective and radiative heat loss coefficient ($W\,m^{-1}\,K^{-1}$)
v_w	wind speed ($m\,s^{-1}$)
P_s	power savings (W)
P_e	electrical power (W)
V_{oc}	open circuit voltage (V)
I_{sc}	short circuit current (A)

T_{cv}	temperature coefficient of voltage ($\%\,K^{-1}$)
V'_{oc}	improvement in open circuit voltage (V)

Abbreviations

A	area of the PV–PCM system in thermal contact with the ambient environment (m^2)
D	diameter of the PV cooling duct (m)
FF	fill factor
L	length of the PV cooling duct (m)
LHSC	latent heat storage capacity (kJ/kg)
TES	thermal energy storage (kJ/kg)

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delamination and rapid degradation (Saly et al., 2001) urging a strong need for PV temperature regulation to maximise both panel lifetime and power output.

Different passive and active heat removal techniques have been used to maintain PV at lower temperatures. Passive heat removal in free standing PV relies on the buoyancy driven air flow in a duct behind the PV (Brinkworth, 2000a). Heat removal depends on ratio of length to internal diameter (L/D) of the duct (Brinkworth, 2000b) with the maximum heat removal obtainable at an L/D of 20 (Brinkworth and Sandberg, 2006). Passive heat removal in building integrated photovoltaics (BIPV) relies on buoyant circulation of air in an opening or air channel, instead of a duct, behind the PV (Gan and Riffat, 2004). A theoretical analysis of buoyancy driven air flow in such an opening behind a façade integrated PV showed a maximum 5 °C temperature reduction in averaged monthly temperature resulting a net 2.5% increase in yearly electrical output of the (Yun et al., 2007). Though the temperature reduction and the associated prevention of power drop is very low in such PV systems, improvements can be made by boosting heat transfer through suspending metal sheets and inserting fins in the air channel and optimising distance between the walls (Tonui and Tripanagnostopoulos, 2007; Fossa et al., 2008).

Active cooling of PV mostly relies on air or water flow on the front or back of the PV surface. Effect of air flow at different inlet velocities and air gaps on front side and back side of PV temperature was modelled and a maximum 34.2 °C temperature decrease was predicted at air inlet velocity of $1\,m\,s^{-1}$ and front and back air gap of 20 mm (Mallick et al., 2007). Water flow on the front surface of a free standing PV has a decreased cell temperature of up to 22 °C along with decreasing reflection losses from PV surface yielding an 8–9% increase in electrical power output (Krauter, 2004). Water flow on the back of a façade integrated PV has theoretically shown optimum electrical and thermal performance at a water flow rate of $0.05\,kg\,s^{-1}$ for a particular system in the weather conditions of Hefei,

China at solar radiation intensities of $405\,W\,m^{-2}$ and $432\,W\,m^{-2}$ (Ji et al., 2006).

Passive cooling of BIPV with solid–liquid PCMs was experimentally and numerically evaluated using a paraffin wax as the PCM and an a rectangular aluminium container with internal dimension of (300 mm × 132 mm × 40 mm) having selectively coated front surface to mimic the PV cell (Huang et al., 2004). Temperature distribution on the front surface and inside the PCM was measured experimentally and predicted numerically with 2D and 3D finite volume heat transfer models which showed good agreement between experimental and numerical results (Huang et al., 2006b,a). Building on this work, Hasan et al. (2010), fabricated and characterised 4 different cell size PV–PCM systems to investigate performance of 5 different types of PCMs to find out the optimum PCM and the PV–PCM system for BIPV cooling application. Two PCMs, a eutectic mixture of capric acid–palmitic acid, PCM_1 and a salt $CaCl_2 \cdot 6H_2O$, PCM_2 were found promising in an aluminium based PV–PCM system (Hasan et al., 2010). A temperature drop of 18 °C was recorded for 30 min and 10 °C for 5 h at $1000\,W\,m^{-2}$ solar radiation intensity and 23 °C ambient temperature. Huang et al. (2011) evaluated the insertion of metallic fins in the rectangular PV–PCM containers previously investigated (Huang et al., 2006a,b; Hasan et al., 2010) PV–PCM and reported an improvement in temperature regulation due primarily increased natural convection which affects melting and solidification of PCM in the rectangular containments. Ho et al. (2012) conducted a simulation study of the BIPV performance integrated with microencapsulated PCM attached at PV back to cool and enhance performance of BIPV. The simulation results showed very low temperature drop from 49 °C to 47 °C of in summer and from 35 °C to 30.5 °C in winter condition using a PCM with melting point 26 °C which shows microencapsulated PCM show least effectiveness in BIPV temperature drop due to lower thermal conductivity of encapsulation materials and the lower mass ratio of PCM contained in microencapsulation. Biwole et al.