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ScienceDirect

Solar Energy 105 (2014) 561–574

SOLAR ENERGY

www.elsevier.com/locate/solener

Application of a phase-change material to improve the electrical performance of vertical-building-added photovoltaics considering the annual weather conditions

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Received 11 January 2013; received in revised form 28 January 2014; accepted 21 April 2014
Available online 20 May 2014

Communicated by: Associate Editor C. Estrada-Gasca

Abstract

The performance improvement of a vertical PV module with the application of a phase-change material (PCM) in a device known as a PV/PCM module was examined in an experiment. The PCM could prevent the PV module from overheating by absorbing a considerable amount of heat during the phase change. A simulation was also carried out to analyze the annual electric energy generation with changes in the installation direction of the PV/PCM module and the melting temperatures and thicknesses of the PCM. Through an analysis of the results, the optimal melting temperatures and thicknesses of the PCM according to the installation directions were introduced.

When the amount of vertical solar radiation was high and when the outdoor air temperature was moderate, the electric power output of the PV module was increased by at most 3% using the PCM. However, during the winter, the effect of the PCM was decreased.

The optimal melting temperature was determined to be 298 K in all installation directions. The optimal PCM thickness varied slightly depending on the installation direction of the PV/PCM module. The amount of electric power generation was increased by 1.0–1.5% compared to that of the conventional PV module. It is hoped that the results will used as important reference data for the improvement and commercialization of PV/PCM modules.

Keywords: PCM; BAPV; PV/PCM module; Electrical conversion efficiency; Melting temperature; Annual weather conditions

1. Introduction

With the increasing interest in renewable energy, the application of the photovoltaics (PV) system has increased. Building-added photovoltaic (BAPV) systems, which are installed directly onto building exteriors, have widely been used because they do not require an additional site.

The PV module of a BAPV system is usually installed on a building roof, where it is most exposed to solar radiation. However, the number of PV installations on vertical wall surfaces also has increased in an effort to use solar energy more actively. When the PV module is installed on a vertical wall surface, it is important to eliminate the heat caused by the generation of electric energy. If the heat is not released effectively, the PV module becomes overheated and the energy generation efficiency is decreased. This problem has been pointed out by several past studies.

Brinkworth et al. (1997), Meneses-Rodriguez et al. (2005) reported that a PV module decreases in efficiency by 0.5% with a 1 K increase in the temperature from 298 K. Krauter et al. (1999) stated that a PV module attached to a building surface decreases the energy generation efficiency by 9.3% compared to PV modules that are

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http://dx.doi.org/10.1016/j.solener.2014.04.020
0038-092X/

Nomenclature

A	the PV surface area (m^2)
C	the combined incidence angle modifier for the PV cover material
C_p	the specific heat of the PCM (J/kg K)
I_T	the total amount of solar radiation on the PV surface (kJ/h m^2)
$I_{T,\mathrm{ref}}$	the total amount of solar radiation on the PV surface at the conditions under which the reference PV efficiency was measured (kJ/h m^2)
m	the mass of the PCM (kg)
P_{PV}	the electric power produced by the PV/PCM module (W)
q_{conv1}	the convective heat transfer that occurred in the glass cover for the PV cell (W/m^2)
q_{conv2}	the convective heat transfer that occurred in aluminum plate 2 (W/m^2)
$q_{n,s}$	the heat absorbed or released in layer n (W/m^2)
q_{n1-n2}	the heat transfer between layer $n1$ and layer $n2$ (W/m^2)
$q_{\mathrm{pcm},s}$	the heat absorbed or released by the PCM (W/m^2)
$q_{\mathrm{pcm,phase\ change}}$	the heat required for the phase change of the PCM (W/m^2)
q_{rad1}	the radiative heat transfer that occurred in the glass cover for the PV cell (W/m^2)
q_{rad2}	the radiative heat transfer that occurred in aluminum plate 2 (W/m^2)
q_{sol}	the solar radiation absorbed by the glass cover for the PV cell (W/m^2)
R_{n1-n2}	the thermal resistance between layer $n1$ and layer $n2$ (m^2 K/W)
t	the time (s)
T_n	the temperature of layer n (K)
T_{PV}	the PV cell temperature (K)
T_{ref}	the cell temperature in the reference conditions (K)
X	the ratio of the liquid and solid state of the PCM (0: completely liquid; 1: completely solid)
ΔX	the change in X
η	the overall efficiency of the photovoltaic system
$\eta_{I,\mathrm{coef}}$	the coefficient that describes the change in the PV efficiency as a function of the incident solar radiation
η_{ref}	the overall efficiency of the photovoltaic array under the reference condition
$\eta_{T,\mathrm{coef}}$	the coefficient that describes the change in the PV efficiency as a function of the cell temperature
$(\tau\alpha)_n$	the transmittance/absorptance product of the PV cover for solar radiation at a normal angle of incidence

not attached to buildings. This is due to the high PV module temperatures, as building surfaces prevent excess heat from being removed.

To solve this problem, many experiments have been conducted to decrease the PV module temperature and to increase the energy generation efficiency. Hasan et al. (2010) introduced six methods to lower the PV module temperature; natural ventilation, mechanical ventilation, water circulation, the use of a heat pipe, the use of a thermoelectric device that converts heat energy to electric energy, and the use of a PCM.

Moshfegh and Sandberg (1996), Sandberg and Moshfegh (1996, 1998), Liao et al. (2007), Gan (2009) examined the air movement due to the buoyancy and the heat transfer phenomena produced in the space between the PV module and the wall surface using numerical simulations and experiments. They also evaluated the performance change of the PV module according to the temperature. In particular, Teo et al. (2012) increased the performance efficiency of the PV module by 4–5% by installing an air duct behind the module and removing heat by ensuring good air flow through the duct.

Krauter (2004) used water circulation on the surface of the PV module to decrease the temperature of the module. By means of water circulation, it was possible to prevent the accumulation of dust on the surface and to reduce the temperature of the module. The temperature of the PV module was decreased by as much as 295 K, while the energy generation efficiency was increased by 10.3%.

Some researchers provided systems which could increase the energy generation performance by absorbing and recycling the excess heat from the PV module. Pei et al. (2012) proposed a photovoltaic/thermal system which combined solar radiation and a solar heat system. This system used a heat pipe to decrease the temperature of the PV module while simultaneously providing hot water. Le Pierres et al. (2008) considered using a thermoelectric device which could convert heat energy to electric energy.

In the studies discussed above, a mechanical fan, pump, or other type of energy-consuming equipment was used to remove heat from the PV module. However, this study focused on a more passive method using a phase-change material (PCM), which does not require additional energy after installation. The PCM stores or releases the heat through a phase change from liquid to solid or from solid to liquid at the melting temperature. Using this characteristic, the PCM can increase the energy generation efficiency by preventing the overheating of the PV module though the absorption of heat during the day and the release of heat during the night. Moreover, compared to the natural ventilation method, the PCM is not significantly influenced by the speed and direction of the wind, giving it greater potential to decrease the PV module temperature.