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Hybrid diagnosis to characterise the energy and environmental enhancement of photovoltaic modules using smart materials

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A B S T R A C T

Growing demands for energy, gradual depletion of fossil resources and high environmental impacts require that current energy production models be replaced by more sustainable technology. Thus, research efforts focused on improving energy efficiency and material efficiency are considered extremely relevant.

In the following work, the influence of incorporating PCMs (phase change materials) on electricity conversion efficiency discussed along with hot spot prevention and lifetime increases in BIPV (building-integrated photovoltaics). The main goal is to evaluate the operational temperature control in a BIPV with or without PCMs considering different climatic severities. A design parameter analysis was conducted, and the importance of suitable PCMs and proper system designs are revealed. Also, this study indicates that areas with different climatic severities must be considered for widespread evaluations of this technology application to impact diverse regions.

Additionally, an environmental analysis based on the LCA (life cycle assessment) methodology was performed using the SimaPro software. The results show that a positive environmental impact is generated by PCM applications because of the decreased amount of consumed resources in BIPV manufacturing, which is related to the lifetime extension resulting from the ability of PCMs to store latent heat and prevent premature physical damage to the BIPV.

1. Introduction

In recent years, the demand for energy has significantly increased because of use in sectors such as industry, transportation, construction, and electric generation and as a result of an increased quality of life in many countries. Thus, consumerism and population growth have led to an increasing demand for natural resources and raw materials [1,2]. For years, fossil fuels and nuclear energy have been dominant sources of energy [3]. However, the production of these fuels results in the depletion of fossil resources and leads to significant environmental impacts. Therefore, the current model of energy production must be substituted for a more sustainable model to reduce energy and material consumption.

In the near future, renewable energy should have increased importance [4]. Among such energies, solar energy has become a promising option in many countries [2]. The earth's surface receives an average solar irradiance that is thousands of times higher than the global energy demand. This solar energy can be transformed into electricity using PV (photovoltaic) cells, or it can be utilised as thermal energy through the use of collectors [5]. The EPIA (European Photovoltaic Industry Association), in collaboration with Greenpeace, reported an annual growth in worldwide PV power generation of approximately 40% from 2000 to 2010 [6]. A second publication, InterSolar and EPIA [7] reveals that the production from installed worldwide PV cells amounted to almost 140 GW in 2013. Moreover, this figure is predicted to grow to 345 GW by 2020 and 1100 GW by 2030.

Current designs have non-technological and technical limitations, such as the high cost of installation and distribution. Technical limitations affect the lifetime, electrical production and energetic and environmental efficiency of PV cells [8,9]. At present, the electric conversion efficiency of cells is low, between 15 and 17% on average [10]. Another problem that affects the adoption of PV cells is local overheating, which is known as a hot spot. This phenomenon occurs when the current exceeds the module's short-

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Nomenclature

α	absorbance
A	area of the photovoltaic cell (m^2)
BIPV	building-integrated photovoltaics
CM-SAF	Climate Monitoring Satellite Application Facility
CS	climatic severity
Δt	temporal interval (seconds)
ΔT_{pv}	temperature difference $T_{PV}-T_{PVPCM}$ (°C)
η_{ref}	efficiency of the photovoltaic cell (%)
η_{Tref}	efficiency of the photovoltaic cell at T_{ref} and 1000 W/m^2 (%)
η_{pv}	efficiency of the PV system without PCM (%)
$\eta_{pv/pcm}$	efficiency of the PV/PCM system (%)
EPIA	European Photovoltaic Industry Association
G	global solar irradiance incident on the cell (W/m^2)
H	latent heat of fusion (kJ/kg)
IET	Institute of Energy and Transportation
JRC	Joint Research Centre
k	thermal conductivity (W/m·K)
LCI	life cycle inventory
m_{pcm}	mass of the PCM (kg)
NASA	National Aeronautics and Space Administration
NOCT	nominal operating control temperature
NREL	National Renewable Energy Laboratory
OTA	Technological Evaluation Office
PCM	phase change material
P	power output (W)
PV	photovoltaic cells or photovoltaics
PVGIS-3	Photovoltaic Geographical Information System
Q_{acu}	heat accumulated in a specific time (J)
Q_s	heat stored in the BIPV/PCM system (J)
Q_{lat}	latent heat (J)
Q_{tot}	maximum heat the PCM can accumulate (J)
ρ_{pcm}	density of the PCM (kg/m^3)
Si	silicon
SNL	Sandia Laboratories
τ	transmittance
T_{amb}	ambient temperature (°C)
T_{fusion}	melting temperature (°C)
T_{pv}	operating temperature of the photovoltaic cell without PCM (°C)
$T_{pv/pcm}$	operating temperature of the PV/PCM system (°C)
T_{NOCT}	nominal operating control temperature (°C)
T_{ref}	reference temperature of the photovoltaic cell (°C)
TBC	Technical Building Code
U_l	global loss coefficient of the system (W/m^2·K)
v	wind speed (m/s)
w	mass composition
x	thickness of PCM layer (m)

circuit intensity because a large amount of heat must be dissipated through a small surface [11]. These hot spots have recorded temperatures of 150 °C and can even exceed 200 °C [12,13], modifying the operating performance and shortening the PV life time in the long term [14]. These scenarios are common, especially if the right conditions are not achieved to activate bypass diodes that control for temperature.

The way how PV technology is used is no longer sufficient; as a consequence, a new way of thinking is needed to convert the challenges into opportunities. New technology has been heavily promoted in generating BIPV (building-integrated photovoltaics) and construction materials. Such technology is found in walls covered with solar cells that become part of the façade as well as in windows and shutters [15]. The energy savings and environmental benefits are quite significant over the life cycle of these buildings [16,17]. However PV adoption in buildings creates new limitations apart from those previously described, such as even greater temperature increase as a result of module operation because there is a higher amount of heat loss. Besides, BIPV involves significant economic investments and location limitations [18].

Such a framework encourages advanced energy technologies based on the integral combination of new materials combined with PV modules to solve those restrictions. PCMs (phase change materials) are a suitable alternative to control the temperature. The incorporation of PCM is highlighted because of its high performance in heat exchange compared with that of water and air circulation systems, and it also shows a high capacity of latent heat absorption during phase changes. Currently, PCMs tank linked to a solar powered heat pump system was investigated considering theoretical models to analyse the variation of stored energy with time for different phase change materials [19], improvements in the geometric design of the latent heat storage tanks [20] and the thermal performance of the whole integrated system experimentally and theoretically [21]. Besides this application, these materials are commonly addressed in building added to construction elements [22,23] in systems able to storage thermal energy, which can be applied mainly in the built environment and industrial processes to recover waste energy [24]. On the one hand, PCMs do not consume electricity, do not generate noise and the maintenance costs are low [9]. On the other hand, the most important environmental indicators, such as carbon footprint, could be significantly reduced. The aforementioned has been well addressed by Roskilly et al. [25] and Norton et al. [26]. These authors highlight that from technical point of view, the PCMs can be chosen as a storage technology due to their potential capacities. In fact, they summarise a number of PCM capabilities focused from modelling and the goodness of the PCM application.

The objective of this study is to broaden the conceptual knowledge based on the use of a novel integrated system (PV + PCM) towards a low carbon energy system. It aims to promote PV energy, reduce environmental impacts, and highlight the importance of temperature control in the operation of a BIPV implementation. Excessive temperatures can reduce energy efficiency, lead to premature degradation, and increase consumption of materials for replacement. To this end, the incorporation of innovative PCM-based solutions was considered in order to thermally regulate PV installations. In addition, a theoretical model was developed to analyse the behaviour of the main variables of PV cell operation with and without PCMs, as well as the most representative climatic variables. Moreover, it performs an evaluation of the methods to adapt BIPV systems based on geographic location.

Finally, the results of environmental impacts of PCM incorporation were analysed through a set of categories that varies according to the selected method, including climate change, which is based on the analysis of the carbon footprint (kg CO_2 equivalent). This analysis was performed by means of the standardised LCA (life cycle assessment) methodology using the SimaPro software version 7.3 to assess the own models developed and supported by international reference databases. Consequently, installation designs that optimise space, material and energy consumption can be promoted to give a further continuation and expanded knowledge about research in the field of PV technology.