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Phase Change Materials in Photovoltaics: The Assessment of System Performance in the Present Mediterranean Climate Conditions

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Abstract

The operating temperature of photovoltaics is amongst the most important parameters affecting their energy output, efficiency and life cycle. This paper is focused on the design, development and evaluation of a modified photovoltaic system, combining a photovoltaic module coupled with a phase change material. The performance of the proposed system has been assessed in the present Mediterranean climate conditions. Moreover, the life cycle assessment has been conducted to estimate its environmental burden.

The obtained results provide important findings on the benefits of the proposed system and complement the existing gap in the literature in terms of the real field experience of this configuration's operation.

Keywords

Photovoltaics; Efficiency; Phase Change Materials; Energy yield; PV-PCM system.

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I. Introduction

Globally, the energy generation mostly depends on fossil fuels. The burning of fossil fuels is nevertheless the main cause of CO₂ emissions leading to air pollution and environmental degradation. Consequently, the shift towards renewable energy sources is continuously gaining ground [1].

In recent years, the utilization of solar energy has been amongst the most promising options to meet the ever-increasing global demand for electric energy. In this sense, PV technology is a key milestone in creating sustainable energy in the future [2].

In order to strengthen further progress in PV technology, the controlling of factors influencing the performance of PV systems is vital. The operating temperature (T_m) of photovoltaics (PVs) is recognised as one of the most important parameters affecting their energy generation and efficiency. It depends on several factors such as the local climatic conditions (solar irradiation, ambient temperature, wind velocity, etc.), the thermal properties of materials used in the PV module encapsulation, the type of PV cells and the PV system configuration [3,4].

A typical commercial PV module converts only 10% to 25% of the incident sunlight into electricity with much of the remainder being either reflected or transformed into heat provoking reasonable energy losses in PV modules [5]. Specifically, for Si-based PV modules, the maximum power output drops by about 0.25 % to 0.5 % per 1°C increase above 25°C in PV cell operating temperature. These temperature coefficient values are far from negligible, as in the summer months, the temperature of the PV modules may increase to temperatures of 60-70° C, particularly in countries with high solar potential and warm climate [6, 7].

Accordingly, many researchers have investigated methods to diminish the influence of high temperature on PV performance by heat removal from PV module's surfaces. Several studies have been carried out on active cooling, such as forced air circulation, water-cooling techniques etc. [8].

In recent years, the use of phase change materials (PCMs) for the thermal regulation of PV modules has received considerable attention, since they are able to absorb large amounts of energy as latent heat at a constant phase transition temperature and by extension to be used for passive heat storage and temperature control [9].

The purpose of this paper is to provide a better understanding of this passive approach under actual Mediterranean conditions. For this scope, the research team designed, developed and evaluated a PV-PCM system concept in the

premises of the Technical University of Crete, Chania, Greece. Furthermore, a Life Cycle Assessment (LCA) of the PV-PCM prototype was performed in order to assess its environmental performance.

The obtained results provide information about the suitability of the proposed PV-PCM system and possible improvements in order to promote this effective modification of conventional PV modules.

II. Research on the PV-PCM system

To date, there were several attempts to develop a PCM-based method of PV thermal regulation. The PV-PCM system is a novel technology, combining PV modules and PCMs into a single unit, to achieve higher solar energy conversion efficiency [8].

A typical PV-PCM system is composed of a PV module and a storage container filled with PCM. The PV module converts a part of the incoming sunlight into electricity, while the rest of the radiation is transformed into heat, entering into the PCM container by heat conduction. In this way, the PV module stays cool and its solar cell energy conversion efficiency is improved. In addition, this configuration shelters the solar cells from overheating and damage [8, 9].

In a study conducted by Hendricks and van Sark, a simplified model of the PV-PCM system was formed in order to quantify the total gain in energy generation for a period of one year for both Utrecht and Malaga. According to the obtained results, a clear benefit of this PCM-based approach cannot be identified, since the yield rise per year of a PV-PCM system is only 1-3 % of the yield for the reference case in Malaga and it was not significant in Utrecht. Moreover, the economic depreciation of this investment exceeds the period of twenty years, concluding that the proposed configuration cannot be considered as deliberate. It is of interest the scenario in which the heat storage capacity was unlimited; the energy earnings increased by 72%, highlighting a huge potential in regulating the operating temperature [7].

Huang et al. [9, 10] have already experimentally studied the combination of a suitable PCM with a PV module for its thermal regulation. Their work indicated the feasibility of the PV-PCM system and the need for further research on this topic [9].

A modified PV-PCM system with small metal cells to hold two types of PCMs was designed by Huang and Hewitt. PCMs with different phase transient temperatures from 21 to 60 °C were combined to regulate the PV temperature

rising in the system. They concluded that the PV-PCM system with two types of PCMs can keep the PV at operating temperature closer to 25 °C [10].

III. PV-PCM system design procedure

In order to understand how the PCM contributes to the improvement of PV module conversion efficiency, a PV-PCM system was designed and fabricated for the experiment. Fig. 1 presents a representative diagram of the PV-PCM system concept. The backside of the PV module was coupled with a metal container filled with the chosen PCM for its protection. In this way, the PCM would absorb heat more easily from the PV module. A modified energy balance approach was used for the design of the proposed PV-PCM system.

Fig. 1. Schematic diagram of heat transfer in PV-PCM system

A. Energy balance model

The effect of factors, such as local climate conditions and module manufacturing materials, on the PV module temperature, can be estimated through the heat transfer mechanisms between the module and its surrounding environment, as described by Jones and Underwood's model [11]. Following this approach, the energy balance of the PV-PCM system is taking into account an extra element for the conduction of heat from the PV into the PCM. The heat transfer (Fig. 1) is described by the following equation [7]:

$$\frac{dT_m}{dt} = \left(\frac{P_{abs} - P_{rad} - P_{conv} - P_m}{C_m} \right) - \left(\frac{P_{cond}}{C_{PCM}} \right) \quad (1)$$

Where C_m and C_{PCM} are the specific heat capacities of the PV module and the selected PCM, respectively, P_{abs} is the solar energy that receives the PV module, P_m the energy output by the PV module, P_{rad} is the radiative heat exchange between the front surface and the sky and between the rear surface and the ground. Additionally, P_{conv} is the energy flow due to convective heat exchange between the PV module and its environment, T_m is the PV module temperature, t is time, P_{cond} presents the heat conduction from the back surface of the PV module to the PCM. The values in Table 1 [11, 14] were used to approximate the total heat capacity of the studied PV modules, since the related parameters of module's layers were not available.

Table 1. Parameter values used to calculate the heat capacity of the studied PV module

Layer	ρ_n	$C_{p,n}$	d_n	k_n	$A \cdot d_n \cdot \rho_n \cdot C_{p,n}$ [12,13]
	kg/m^3	$J/kg \cdot K$	m	$W/m \cdot K$	J/K
Glass	500	0.003	1.8	6,300	3,00
ARC	691	$1 \cdot 10^{-7}$	32	0.232	2,40
PV cells	677	$2.3 \cdot 10^{-4}$	148	497	2,33
EVA	2,09	$5 \cdot 10^{-4}$	0.35	1,404	960
Rear Contact	900	$1 \cdot 10^{-7}$	237	0.342	2,70
Glass	500	0.003	1.8	6,300	3,00
Total					14,50

B. PV-PCM system description

A prototype PV-PCM system was developed by the staff of the Renewable and Sustainable Energy Systems Laboratory (ReSEL, Technical University of Crete) in order to evaluate its performance under actual Mediterranean climate conditions in the island of Crete, Chania, Greece. The prototype (Fig. 2) consists of a tandem amorphous and microcrystalline silicon thin film (a-Si/m-Si) PV module (SHARP NA-E130L5) and a suitable metal container which is divided

into three compartments of equal volume by a partition. The dimensions of the metal PCM container were selected to fit perfectly with PV module. Rubitherm® RT 27, (melting point: 27°C and heat storage capacity: 184 kJ/kg) was used as the PCM for temperature regulation of the PV module.

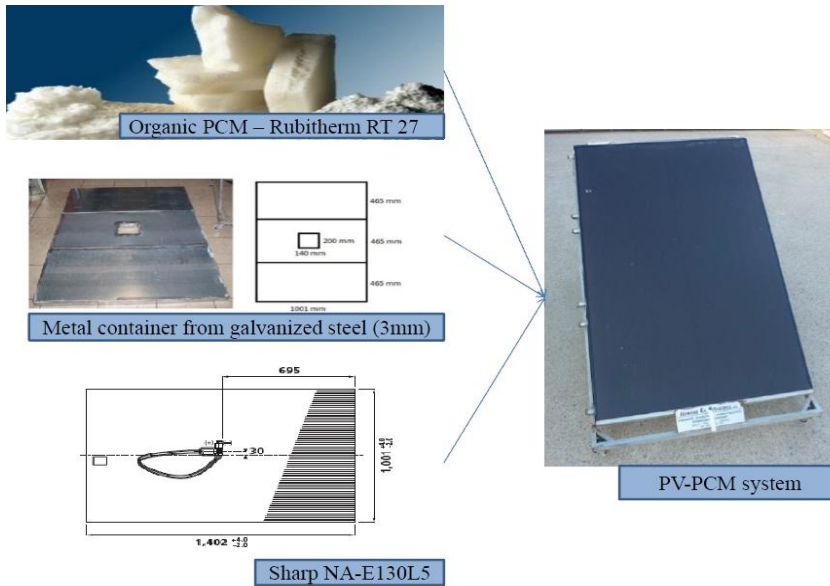


Fig. 2. The PV-PCM system prototype

C. Experimental evaluation procedure

The experiments were performed at ReSEL premises (latitude: 35°31'0 N, altitude: 24°04'0 E and about 135 m above the sea level), at the Technical University of Crete, Chania, Greece. According to the long-term data from the Chania weather station, the coldest months are January and February, characterized by monthly average ambient temperature (during daylight hours) equal to 12.9 °C and 13.2 °C, respectively. On the other hand, the warmest months are July and August when the monthly average temperature value (during daylight hours) is equal to 27.6 °C and 27.3 °C respectively. The monthly average daily solar irradiation on an horizontal surface varied from 1.9 kWh/m²/d in December to 7.35 kWh/m²/d in June, when the average monthly clearness index varied from 0.4 in January to 0.65 in July and August [3]. These data were collected during outdoor tests. The experimental electrical data, as well as the operating temperature values, were obtained during the summer period of the year 2015.

Both the PV-PCM system and the reference PV module were tested at 30° from horizontal with an azimuth angle of 0° (south facing) under actual weather conditions. The thermal performance of the experimental setup was characterized by the operating temperature recording by means of K-type thermocouples, which were attached to the rear side of the PV module and between the components of the PV - PCM system. In an attempt to achieve improved conduction and accurate temperature measurements, thermal paste was used. In Fig. 3, the positions of the thermal sensors are illustrated in detail. Using a thermal camera (IRYSIS 4000), we were able to assess accurately the PV-PCM system's thermal behaviour and to identify possible errors during its operating period.

Moreover, a pyranometer CMP3 (KippZonen) was located on the top of the experimental set-up to measure the total in-plane irradiance. Weather data were acquired from the installed weather station in the premises of the Technical University of Crete.

The I-V curve characteristic evaluation of the PV-PCM system was recorded using a validated I-V tracer (Fig. 3.), which was developed in cooperation with the Photovoltaic and Energy Systems Laboratory, Technological Institute of Crete. The device was directly linked to the PV module or PV-PCM system and provided the measurement of the I-V-curve of PV modules by means of commercial software.

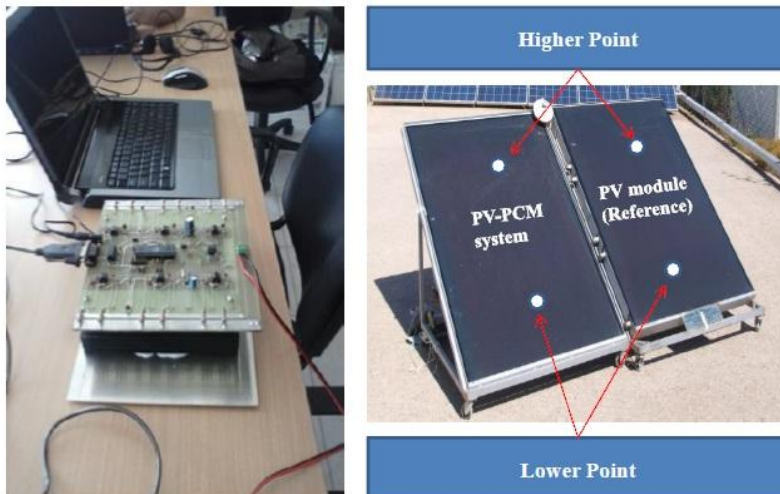


Fig. 3. View of the Experiment set up

IV. PV-PCM system life cycle analysis

A. Assumptions

A number of assumptions were made regarding the transportation to the installation site, the use phase and the disposal stages.

Specifically, the functional unit set in this LCA is 1m^2 of a thin film (a-Si/m-Si) PV module as well as 1m^2 of a metal PCM container. In addition, all the components except the PV modules are considered to be purchased from the local market, while it is assumed that the PV module is delivered to the installation by a train from Germany to Athens, then by a ship from Athens to Chania and finally by a truck from Souda port. For the use phase, the lifespan of the PV-PCM system is presumed to be 30 years. The PV output of the PV-PCM system, during its lifespan, has been calculated for the case of Chania. Moreover, a recycling rate of 70 % for PCM container material is taken into account for the analysis.

B. Life cycle inventory

SimaPro 8 and Ecoinvent database were utilized for the analysis. In Table 2, the basic data (materials/components of the studied PV-PCM system) included in the inventory analysis, are presented. The reference materials and the construction of the PV-PCM system configuration are based on reference [15].

Table 2. Basic data included in the inventory analysis

Materials/Components	Unit	PCM container	PV module (1m^2), a-Si	PV laminate, a-Si	PCM
PV laminate, a-Si	m^2	-	1	1	-
Energy	MJ	-	-	174	-
copper, at regional storage	kg	-	-	0.067	-
soft solder, Sn97Cu3	kg	-	-	0.0097	-
polyethylene, HDPE, granulate	kg	-	-	1.12	-
packaging film, LDPE		-	-	0.31	-
sheet rolling, steel	kg	-	3.14	-	-
Aluminium alloy, AlMg3	kg	-	3.35	-	-

steel, low-alloyed	kg	65	2.18	-	-
brazing solder, cadmium free	kg	-	1.5	-	-
Glass	kg	-	8	-	-
Paraffin wax	kg	-	-	-	10.9
Steel and iron waste treatment (Recycling)	kg	45.5	-	-	-

C. Life cycle impact assessment method

IPCC 2013 is utilized in order to calculate the global warming potential (GWP) of the studied PV-PCM system. In addition, ReCiPe Endpoint (H) V1.11/Europe ReCiPe H/A is also affiliated, providing results for the damage categories Human Health, Ecosystems and Resources [16].

In terms of the adopted methodologies, IPCC 2013 is an update of IPCC 2007 developed by the International Panel on Climate Change. This method is listing the climate change factors, those of IPCC, with a timeframe of 20, 100 and 500 years. ReCiPe is the successor of EI99 and CML-IA. The purpose at the start of the development was to integrate the ‘problem oriented approach’ of methodology CML-IA and the ‘damage oriented approach’ of methodology EI99 [16].

V. Discussion – Results

A. Thermal Performance

All This section presents a focused analysis of the operating temperature of the PV module with and without PCM. For the purpose of this investigation, the analysis of the recorded data related to the experiment is of increased importance. The variation of total in-plane irradiance, PV module temperature, as well as, ambient temperature and wind velocity in the tested location during a typical summer day is shown in Fig. 4.

As shown in Fig. 5, the PV-PCM system temperature values for the selected position points were recorded at an interval of 30 minutes. Comparing the average operating temperature values derived from measurements of the common PV module (at the higher position point: 54.3 °C, at the lower position point: 52.4 °C) and the PV-PCM prototype system (at the higher position point: 42.8 °C, at the lower position point: 41.4 °C), it can be seen that PCM utilisation

contributed to reduce the average PV module operating temperature by 11 °C. Besides, the temperature at the higher selected position in the PV module was observed equal to the value of 60.1 °C without PCM integration, but the rise of the temperature limited at 40.4 °C for a period of about 2.5 h due to the effect of PCM. A similar trend is observed at the lower selected position.

The use of an infrared camera allowed the direct view of the thermal performance in the PV-PCM system. Fig. 6 shows a non-uniform temperature distribution within the PV-PCM system. This fact indicates the need for conduction optimization in order to eliminate the hot-spot phenomena which can damage PV cells.

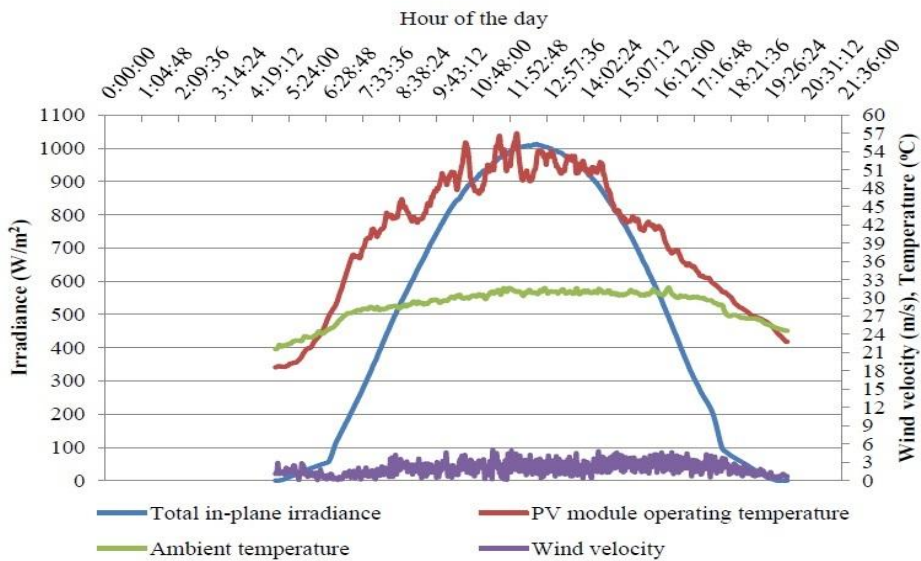


Fig. 4. PV module temperature, total in-plane irradiance (azimuth angle: 0°, inclination angle: 30°), ambient temperature and wind velocity values during a typical summer day [17]

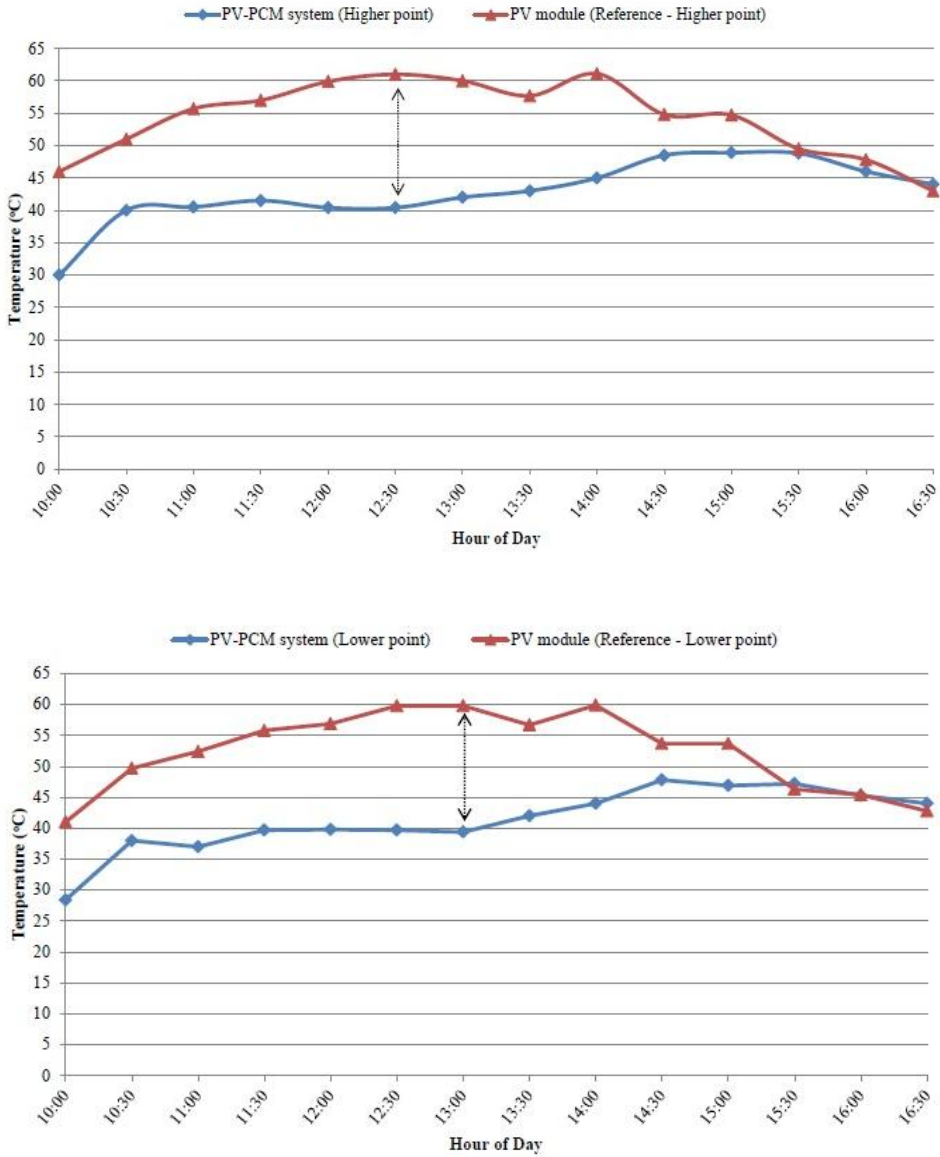


Fig. 5. Temperature comparison of the PV module with PCM (PV-PCM system) and without PCM (reference case) during a typical summer day [17]

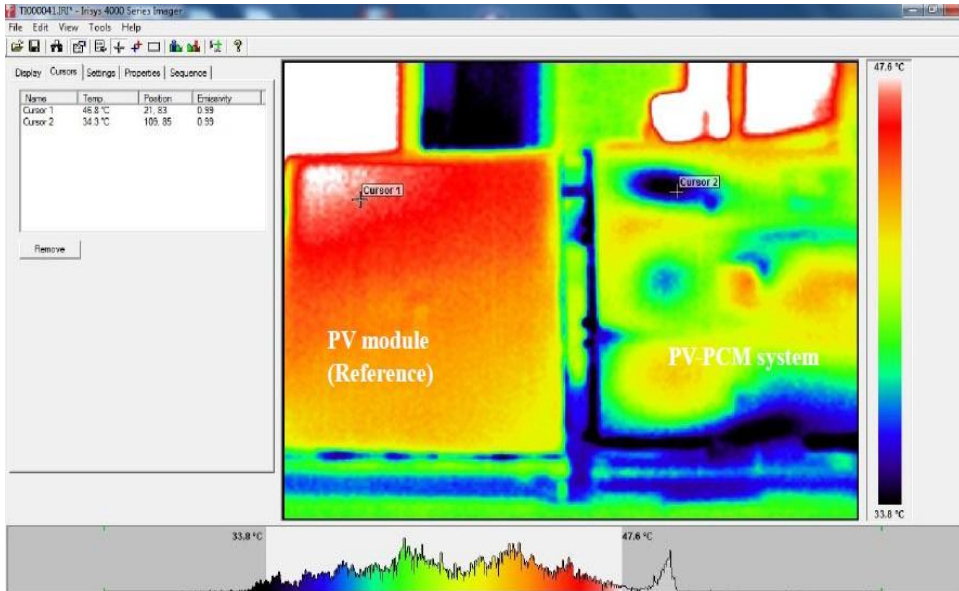


Fig. 6. Thermal image of the front surface of experimental set-up captured at 10:30 a.m. (typical summer day) [17]

B. Electrical Performance

The short-circuit current (I_{SC}) and the open-circuit voltage (V_{OC}) are the main parameters of the I - V curve of a PV module. Both I_{SC} and V_{OC} are dependent on the incoming sunlight and the PV module temperature. More specifically, a change in solar irradiance density causes a proportional change in I_{SC} value, while the change in V_{OC} is negligible. On the contrary, V_{OC} is inversely proportional to the PV module temperature. This justifies a significant decrease in energy output at higher temperatures even though I_{SC} increases nominally [14]. Furthermore, it has been verified experimentally that a rise in PV module temperature leads to a decrease in maximum output power (P_m) [3].

From the data in Fig. 8 and Fig. 9, it is apparent that the use of PCM resulted an increase in both V_{OC} and P_m due to the inverse temperature relationship, while the I_{SC} showed a negligible change. Indicatively, the conversion efficiency (at 11:00 a.m., low wind velocity, 920 W/m^2 , typical summer day) for the module without PCM was observed as 6.92 %, while with the use of PCM in the system, it increased to 7.52 %.

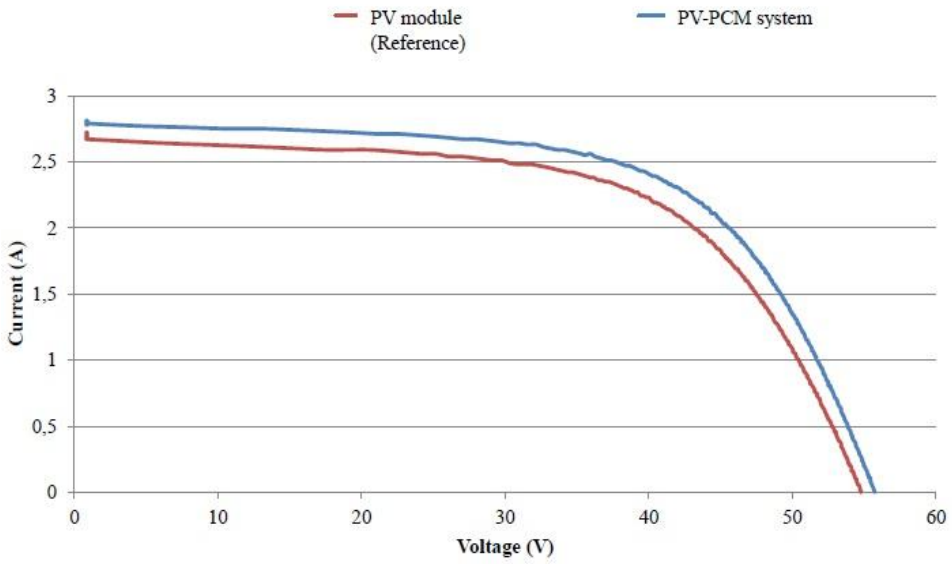


Fig. 7. I-V curve: a comparison of the PV module with PCM (PV-PCM system) and without PCM (reference case) at 11:00 a.m. (typical summer day) [17]

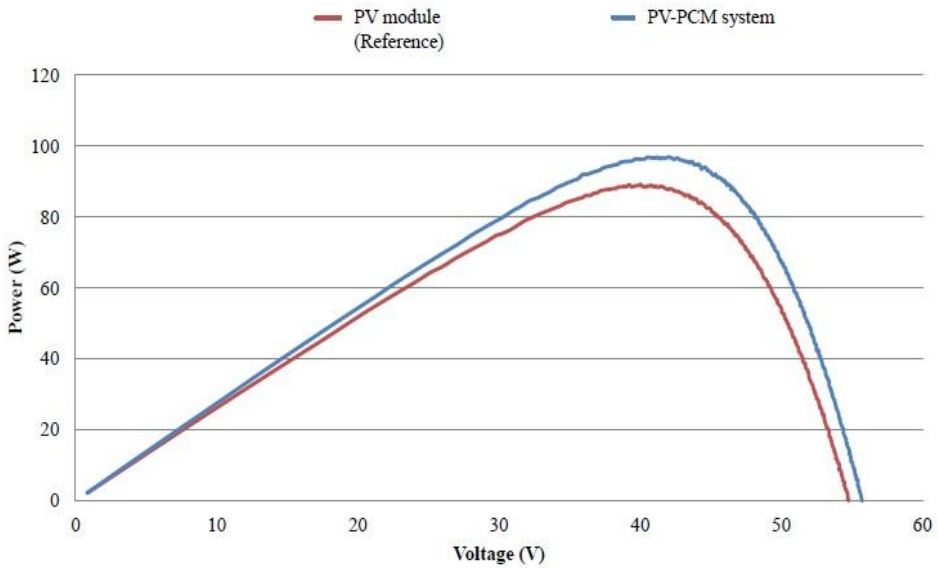


Fig. 8. P-V curve: a comparison of the PV module with PCM (PV-PCM system) and without PCM (reference case) at 11:00 a.m. (typical summer day) [17]

C. Environmental Performance

In this section, the environmental profile of the PV-PCM system is presented. In Fig. 9, the footprint of each component is illustrated. The PCM container is responsible for the greatest part of the total impact of the PV-PCM system, while PV laminate is the material with the second highest contribution. The participation of the steel component, PV laminate and Aluminium alloy to the total GWP footprint of the PV-PCM system is around 49.1%, 22% and 11.9% respectively. All the other components of the PV-PCM system prototype configuration show percentages less than 5% in terms of their contribution to the total GWP impact.

Furthermore, in Fig. 10 ReCiPe scores (Pts) for Human Health, Ecosystems and Resources are presented. By taking into account the total scores of the three categories, PV-PCM system contribution is at a higher level to avoid damages in Human Health and Resources in comparison with Ecosystems. However, it should be noted that ReCiPe footprint of the reference case is slightly better compared with the corresponding results for the proposed PV-PCM system.

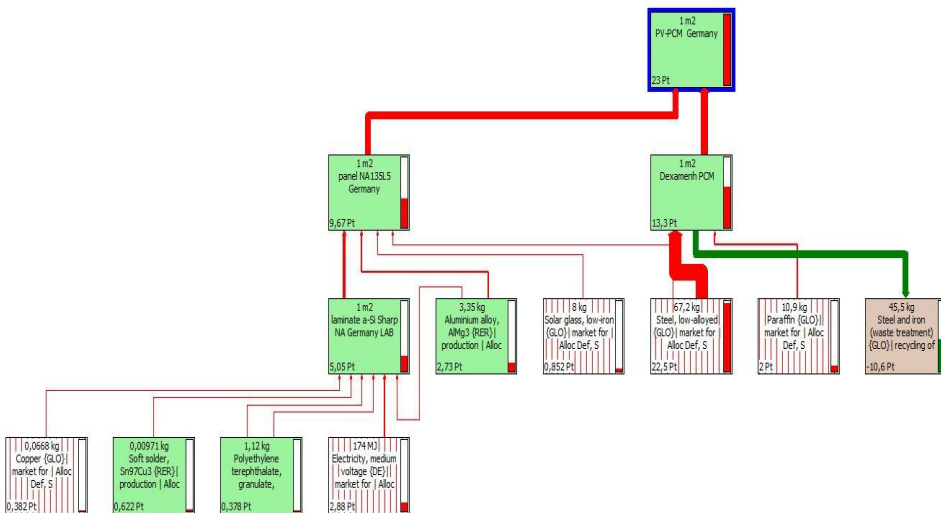


Fig. 9. LCA network model

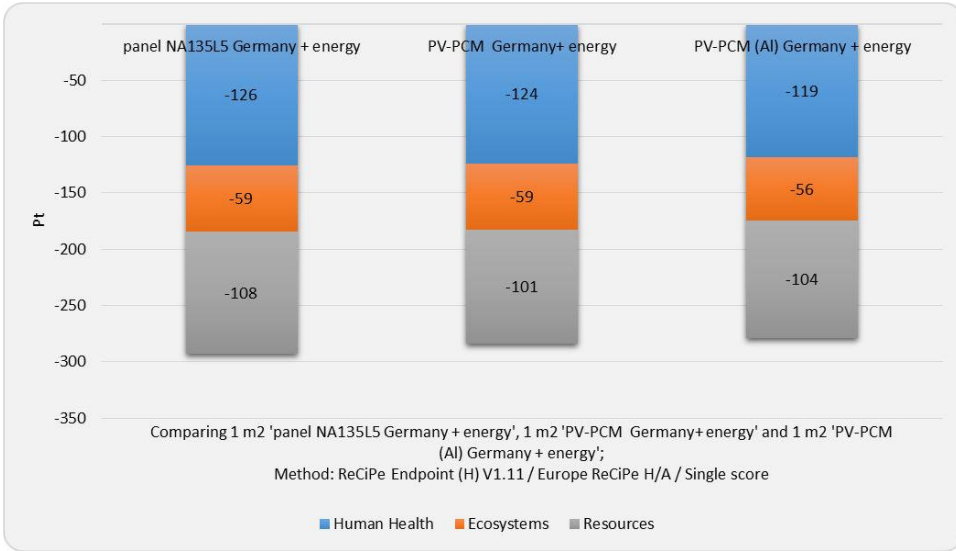


Fig. 10. ReCiPe scores (Pts) (for Human Health, Ecosystems and Resources) of the PV-PCM system compared with the reference case

VI. Conclusion

The main objective of this study was to investigate the feasibility of using PCM in order to mitigate the temperature effect on PV module's performance. For the purpose of analysis, a metal box to contain PCM was designed, fabricated and coupled with a typical PV module. The developed PV-PCM system was tested in comparison with a typical PV module of the same type (reference case) under actual Mediterranean climate conditions in the island of Crete, Chania, Greece. An average temperature reduction of 11°C was attained in the PV-PCM system as compared to the reference case; however, a non-uniform temperature distribution was noted. This initial experimental study indicated a PV conversion efficiency improvement of 8.6 % by means of using PCM. Despite these promising results, further research will take place, by optimizing heat conduction, varying the type of PCM and its thickness in order to investigate the key aspects of this PCM-based technique. The experiment proves that the utilisation of PCM could contribute to effective management of PV modules' operating temperature. Additionally, the results for the PV-PCM system show that steel components are responsible for the greatest part of the environmental impact, based on the LCA analysis. In this sense, an optimisation of the PCM container fabrication will lead to further minimise the environment burden. However, an economic impact analysis is crucial for the development of the proposed technology.

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