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Energy and environmental performance of photovoltaic cooling using phase change materials under the Mediterranean climate

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ABSTRACT

The energy and environmental performance of photovoltaic (PV) panel cooling, when using phase change materials (PCMs), was examined. Actual, long-term field data were collected from a PV and a PV-PCM system, both operating under Mediterranean conditions (Greece). The energy analysis revealed that even though cooling increases (9.4%) the panel's energy output, PCM cooling is associated with a high initial energy investment, leading to low energy-return-on-investment values (1.79) compared to PV (4.94). High energy payback times were observed for the PV-PCM (~14 years) compared to the PV system (~5 years). Furthermore, the life cycle assessment methodology revealed that PCM cooling increases PV's total environmental footprint by 21.9%. However, in the Greek context, the additional electricity attributed to PV cooling leads to significant environmental gains through fossil-fuel-dependent electricity substitution. Cooling can also decrease the rate of cell degradation and prolong PV useful life, leading to additional environmental gains. Due to PCM's initial high energy investment, other cooling technologies should also be examined since, apart from improving electricity output and stability, cooling can also reduce PV's impact on land use, increase the power sector's decarbonization, and address global warming's impact on PV performance by reducing temperature fluctuations and extremes on the panel's surface.

1. Introduction

Over the last decades, solar energy has emerged as a promising technology to address, at least partly, both the growing global energy demand as well as the environmental concerns of fossil fuel power generation [1]. Among the diverse solar applications, photovoltaic (PV) technology is broadly accepted as a mature and environmentally sustainable technology for electricity generation [2,3]. Compared to electricity generation from fossil fuels, PV electricity emits less CO_2 and other air pollutants such as NOx, SO_2, and CO [4]. As a result, PV systems have been adopted at unprecedented scales, with solar PV farms installations being also on the rise, i.e., the global cumulative PV power capacity in 2021 was 942 GW_p [5], and this number is projected to double (1.99 TW_p) by 2026 [6].

Even though solar technology is a mature renewable energy source (RES), there is still ample room for further research and development and particularly regarding the factors affecting PV efficiency and, by extension, environmental performance [7–9]. Among them, the PV panel temperature is considered a crucial factor since through its proper control the panel's performance, useful life, and environmental profile can be improved [10,11]. Specifically, a typical PV module converts from as low as 5% to as high as 40% of the incident solar radiation into electricity [12], with the remaining amount being reflected or transformed into heat, i.e., the temperature of the panel is increased. The latter leads to energy losses (e.g., for temperatures above 25 °C the peak power output of Si-based PV modules decreases by around 0.25%–0.5% per °C rise [13,14]) and also reduces the panel's lifespan due to thermal degradation. During warm periods the temperature on the surface of PV panels can rise up to 50 °C, or higher, affecting PV's nominal efficiency and power output [15], while global warming is expected to further affect their performance [16].

To control the temperature of PV panels/modules, and thus improve their efficiency in electricity generation, different cooling methods, employing different fluids such as air (e.g., active cooling using air blowers [17] or fin-based passive cooling [18,19]), water (e.g., microchannels [20], water spraying [21,22], or water flow (pumping) [23,24]), and solid/liquid phase change materials (PCMs) [25] have been experimentally studied. Among them, PCMs have emerged as a promising cooling method to improve, even up to 20%, the power output of

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Nomenclature

List of abbreviations/acronyms

a-Si/μc-Si	micro-amorphous silicon
AC	Alternating current
AOD	argon-oxygen decarburization
CED	Cumulative energy demand
CML	Centrum voor Milieukunde Leiden
CO_2	Carbon dioxide
CO	Carbon monoxide
CO_2 eq	Carbon dioxide equivalent
Cu	Copper
DC	Direct current
E	Energy generated – kWh
EBPT	Energy payback time
EDC,d/m	Daily/monthly PV power output
EROI	Energy return on energy invested
FU	Functional unit
GWp	Gigawatt-peak
IR	Ionizing radiation
ISO	International organization for standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
nEL	PV module's electrical efficiency
NOx	Nitrogen oxides
PCM	Phase change material
PE	Polyethylene
PM	Instantaneous maximum PV power generation
PR	Performance ratio
PV	Photovoltaic
PVT	Photovoltaic thermal
R&D	Research and development
RES	Renewable energy source
ReCiPe	RIVM and Radboud University, CML, and PRé Consultants
Si	Silicon
SO_2	Sulphur dioxide

List of symbols

%	Percentage
$	US dollar

List of units

A	Ampere
^oC	Degree Celsius
CFC11 eq	Trichlorofluoromethane equivalent
Co-60 eq	Cobalt 60 equivalent
CO_2eq	Carbon dioxide equivalent
G	Giga
h	hours
I	Current
K	Kelvin
kBq	kilobecquerel
kJ	kilojoule
kW_p	kilowatt-peak
kWh	kilowatt-hour
L	Litre
m^2	Square meter
m^2a	Square meter annual
m^3	Cubic meter
N eq	Nitrogen equivalent
NOx eq	Nitrogen oxides equivalent
kg	kilogram
$PM_{2.5}$ *eq*	Particulate matter (that have a diameter of less than 2.5) equivalent
P eq	Phosphorus equivalent
Pt	Eco-indicator point
SO_2 eq	Sulphur dioxide equivalent
1,4-DCB	1,4-Dichlorobenzene
T	Terra
V	Volt
Wp	Watt peak

PV panels [26]. Research has focused on optimizing the design and operational aspects of PV-PCM systems [26,27]; however, little attention has been paid to the environmental sustainability of such systems. Specifically, general economic-environmental evaluations for PV passive [28] and active [29] cooling systems under Croatia's climate have been carried out, with PCM increasing the environmental impacts of passive cooling systems [28]. In the same spatial setting (Croatia), the environmental sustainability of a biobased (pork fat) PCM system for the cooling of a photovoltaic-thermal (PVT) collector was also examined, and the biobased PCM was associated with very low environmental impacts [30]. When the amount of avoided CO_2 from Egypt's energy mix, when using PV, PV-PCM, and PV-PCM-composite (blended with aluminium foam) for electricity generation was examined, the latter was found more promising due to its increased electricity output, followed by the PV-PCM [31]. The environmental performance of PCMs in building-integrated PVs under Spain's climate has also been examined, with the extended lifespan of the PVs due to cooling providing additional environmental benefits [32]. Different LCAs for PCM thermal applications, i.e., excluding solar power generation, have also been carried out [33]. For example, in building-integrated solar thermal systems PCM cooling has been found to improve thermal energy production, nonetheless at the expense of the total environmental footprint [34]. However, when the environmental credits from the improved energy profile were considered, then, despite the increased environmental impact from their integration, the overall life cycle impact of building-integrated PCMs is reduced [35]. This might well be the case for integrated PV-PCMs systems.

Therefore, it appears that PCM cooling can increase PV's power output, but, at the same time, PCM cooling itself has its own environmental impact, which should also be considered to make informed decisions. To this end, full life cycle assessment (LCA) studies, which include the demolition and disposal phase of the PV-PCM system, are required to identify the environmental sustainability of such systems. However, as was discussed above, and as was also highlighted in the results of a bibliometric analysis on the core research of PV-PCMs (Fig. S1 in the Appendix), the body of knowledge on the environmental sustainability of such systems when using LCA is rather limited. Not only this, but LCA studies based on real measurements, such as the one presented here, are required to verify and complement existing LCA studies, such as ones based on simulations [32] and experimental setups [28]. Consequently, the research gap filled by this work is the combination of an experimental study of a PV-PCM system with the LCA methodology, under mild Mediterranean climate.

2. Materials and methods

2.1. PV-PCM system description

An integrated PV-PCM system was constructed and tested at the premises of the Technical University of Crete in Chania, Greece, i.e., the system operated under Mediterranean climatic conditions. The prototype consisted of a thin film (a-Si/μc-Si) PV module (SHARP NA-

E130L5), along with a galvanized steel container that housed the PCM. A standalone PV was also emplaced next to the PV-PCM system (Fig. 1). The container comprised three compartments of equal volume, where the PCM was injected. It is noteworthy that paraffin was the PCM used to regulate the PV module temperature, as obtained from Rubitherm (RT 27), and this material has also been examined under the local conditions for building insulation [36]. A detailed analysis of the PCM selection criteria, PCM effective quantity estimation, and PV-PCM design approach can be found elsewhere [37], while a brief overview of the technical specifications for the PV panel and the selected PCM is given in Table 1.

2.2. Experimental set-up

The PV-PCM pilot system under study, along with a standalone PV (reference system) was tested under real-field conditions and for a year-long period (Fig. 1). Daily measurements were recorded from 8:00–18:00, using a 10-min interval. Over the entire reference period, i.e., July 2016–June 2017, an increased amount of energy-related data and operational temperature readings were collected and analyzed, enabling the performance assessment of the PV systems under study. Both the PV-PCM system and standalone PV were evaluated at a 30° tilt angle from horizontal with an azimuth angle of 0° (south-facing). In order to investigate the thermal profile of the PV panels understudy, the operating temperatures were measured using four K-type thermocouples, positioned at the back of the PV panels. Furthermore, an IRYSIS 4000 thermal camera was used to record the entire thermal behaviour of the systems. To measure total in-plane irradiance, a pyranometer (CMP3 by Kipp & Zonen BV) was placed on top of the experimental set-up. Apart from solar irradiance, wind, ambient temperature, and humidity typically affect the PV panel temperature, thus, a time lag between solar irradiance and PV temperature can be observed [38]. Therefore, these parameters should also be monitored when assessing the performance of PV panels. For this reason, the relevant records from a nearby weather station, which, among others, include wind speed and direction, humidity, and ambient temperature, were also collected. Regarding the electrical measurement system, a tested I–V tracer and a computer were used to convert the PV panel's current and voltage outputs to signals. This monitoring system was causally attached to the standalone PV or PV-PCM system, while measurements were collected and processed

Table 1
Characteristics of the PV panel and the chosen PCM, as part of the PV-PCM system under study [37].

PV panel (Sharp NA-E130L5)		PCM (Rubitherm RT27)	
Parameter	value	Parameter	Value
Nominal power	130 Wp	Melting area	25 °C–28 °C (typical:27 °C)
Open-circuit voltage	60.4 V	Heat storage capacity	184 kJ/kg
Short-circuit current	3.41 A	Specific heat capacity	2 kJ/kg·K
Voltage at point of max. power	46.1 V	Density solid at 15 °C	0.88 kg/L
		Density liquid at 40 °C	0.76 kg/L
Current at point of max. power	2.82 A	Volume expansion	12.5%
Module efficiency	9.3%	Max. operation temperature	50 °C
Dimensions	1402 mm x 1001 mm		
Temperature coefficient of voltage	−0.30%/°C		
Temperature coefficient of current	+0.07%/°C		
Temperature coefficient of power	−0.24%/°C		

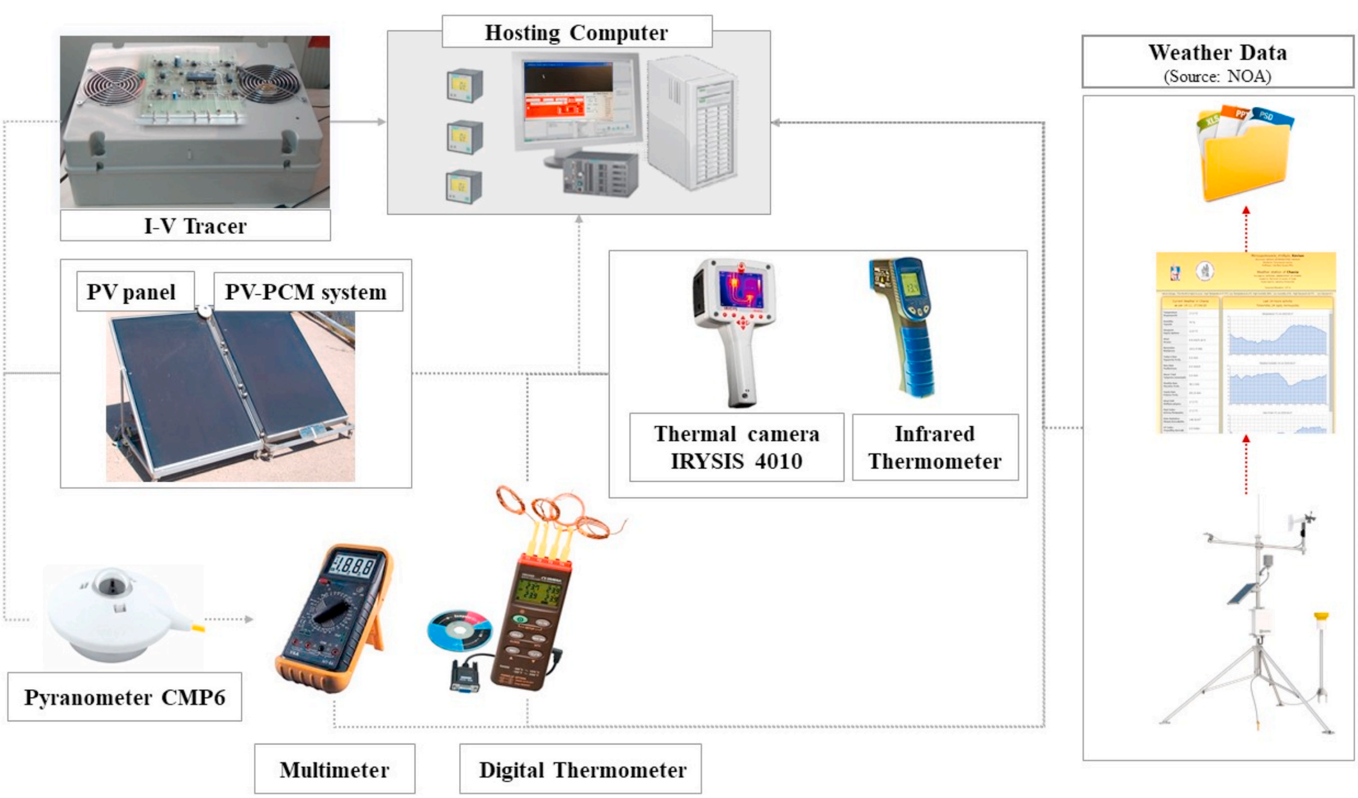

Fig. 1. The standalone and the PV-PCM experimental set-up.

using the RealTerm terminal program (version 3.0.0.24) [37].

2.3. PV energy performance indicators

To evaluate the energy performance of the standalone PV and of the PV-PCM system, a set of indicators were employed, including the instantaneous maximum PV power generation (P_M), the electrical efficiency (n_{EL}), the daily/monthly PV power output ($E_{DC,d/m}$), and the performance ratio (PR) (section S1, Appendix). Furthermore, the cumulative energy demand (CED) was also estimated for each system using the corresponding life cycle impact assessment (LCIA) method, as discussed below. CED was then used to estimate the energy payback time (EBPT), i.e., how much time is required for compensating CED, and the energy return on energy invested (EROI), i.e., the total produced energy divided by the CED, which are both common indicators for solar PV systems [39].

2.4. Environmental analysis

2.4.1. Goal and scope

The goal of this LCA study is twofold. First, to identify the environmental performance of a typical PV-PCM system operating under Mediterranean conditions, and second, to assess the potential environmental gains, if any, attributed to its improved electricity output. To this end, actual LCI data were collected from a standalone PV and an integrated PV-PCM system constructed and operating in the island of Crete, Southern Greece. This is the geographical coverage of this LCA study, which also includes the Mediterranean basin and areas with similar climatic conditions. The time-related coverage is 2021, while average technology was assumed to be used. Finally, solar energy harnessing is a popular field not only for researchers, but also for the energy industry, decision and policymakers, as well as the public, since solar energy can play an important role in the power sector's decarbonization and in the fight against climate change. All the above constitute the intended audience of this LCA study.

2.4.2. Functional unit

A basic element of an LCA study is its functional unit (FU), which is a reference to which all system flows (input and output LCI data) are normalized and expressed [40]. In this case, the FU was set as the generation of 1 kWh of electricity. Electricity generation is the main function of PV systems and, as such, this FU also provides context to the literature. It also enables the comparison of the system under study with the same PV panel that operates without cooling (standalone PV). Furthermore, this FU can also be used to identify the environmental gains from using the additional electricity that is produced from PV cooling instead of using electricity from Greece's fossil-fuel-dependent energy mix. In this sense, here, a cradle-to-grave (raw materials extraction, manufacturing, use, and disposal), rather than a cradle-to-gate LCA, is carried out.

2.4.3. System boundary

The system boundary describes which flows are included in the LCA study, i.e., are inside the system boundary, and which are not, i.e., are external to the system boundary. In this work, all main flows for raw material extraction, manufacturing, operation, as well as for the demolition of the PV-PCM system are included in the analysis (Fig. 2). Specifically, the PV panel, as a material, is included in the analysis, as is its transportation, by ship and truck, from Italy where it is manufactured to Crete, Greece, where it was installed. The PCM, the inverter, and the cabling are also inside the system boundary, along with their transportation from Germany, where they were manufactured, to Crete, Greece. For the PCM container, its main material, i.e., stainless steel, along with its welding, was considered, while local transportation was taken into account since the container was manufactured near the installation site. The thermal grease is also inside the system boundary and its transportion from China to Crete, Greece was also considered. The foundation required for the system's installation is included in the analysis, which is also the case for land use and land-use change, i.e., inside the system boundary. Operation and maintenance (O&M) activities, i.e., personnel transportation to the site and PV panel washing, are also included in the analysis. Finally, the decommission of the system, after the end of its useful life, is inside the system boundary, along with

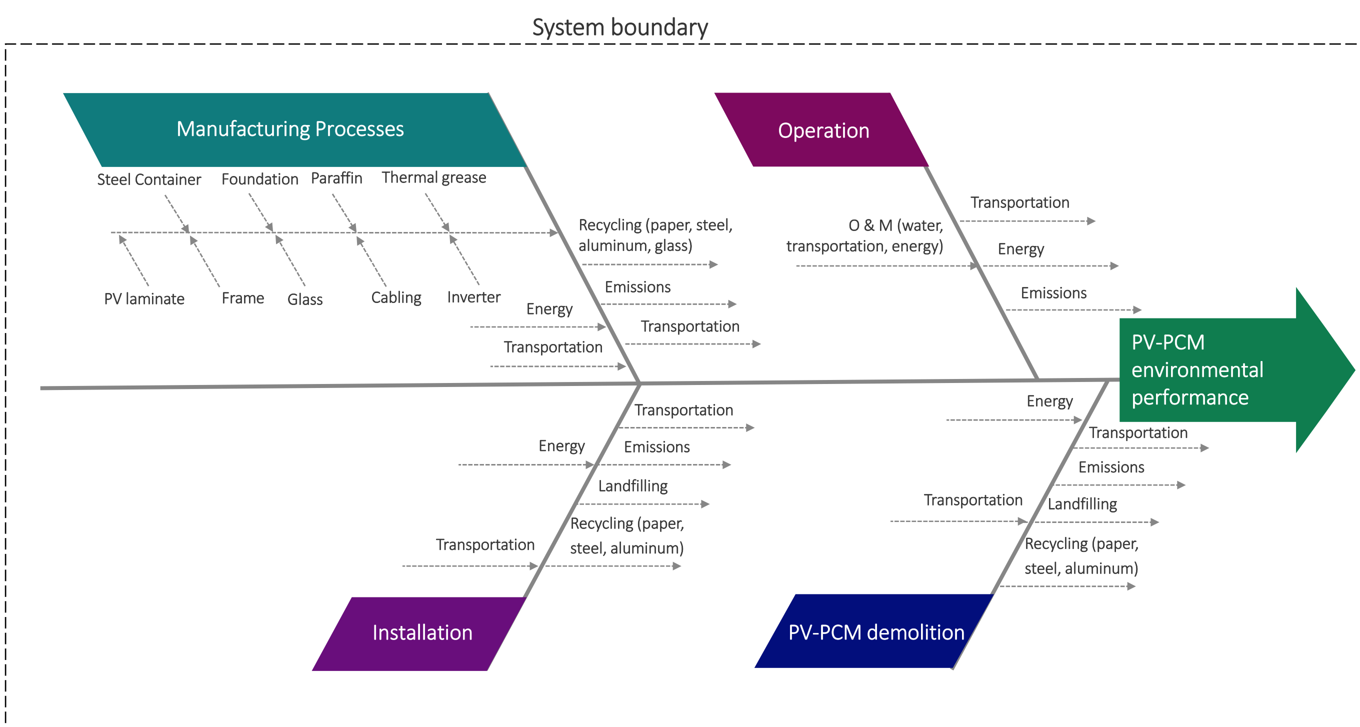

Fig. 2. The system boundary of the PV-PCM system under study.

the landfilling of the inert waste and the recycling of the recyclable materials, i.e., metals, cabling, and glass.

2.4.4. Life cycle inventory

The life cycle inventory (LCI) is one of the main stages of the LCA study, since the depth and breadth of the analysis and the accuracy and reproducibility of the results are dependent on transparent and accurate LCI data. For this reason, here primary LCI data were collected from an integrated PV-PCM system (Fig. 2 and Table S1 in the Appendix). Specifically, to include all main flows (inputs and outputs) for the manufacturing and disposal/recycling of the PV laminate, ecoinvent's data for an a-Si PV laminate was used as a proxy and adapted accordingly. In detail, the panel under study (SHARP NA-E130L5) is produced in Italy. Therefore, for laminate manufacturing, the raw materials, such as copper, were adapted either to the European or the global context, whereas the electricity consumed during manufacturing was assumed to originate solely from Italy's energy grid and the heat (district or industrial) and the water to the European context. The waste (e.g., plastics) and wastewater streams were assumed to correspond to the Italian, European, or global context, depending on ecoinvent's availability for spatial data. Furthermore, for the PV frame, i.e., excluding the laminate, the materials input for the SHARP NA-E130L5 panel were used. For the PV panel (laminate and frame), transportation 700 km were ascribed by maritime and 500 km by road transport, while for the packaging material cardboard was assumed to be used.

For the PCM (RT 27, Rubitherm) ecoinvent's data for paraffin were adapted to the German context, i.e., electricity was assumed to originate solely from Germany's energy grid, while the heat (district or industrial) and the water consumed during manufacturing were assumed to correspond to the European context. The LCI data and more information on the paraffin manufacturing process can be found elsewhere [41]. Furthermore, 1800 km were ascribed to road transport and 300 km to maritime transport. The same transportation distances were ascribed to the cabling and the inverter. Regarding the latter, it should be noted that 18 panels were assumed to be connected to one inverter and, therefore, the 1/18th of a 2.5 kW inverter (95% efficiency) was allocated to the PV panel. For the PV panel's mounting system, ecoinvent's data for the installation of an open-ground module was used.

For the PCM container and the PCM mounting system, hot-dipped galvanized steel was considered, which was sourced and arc-welded locally. The thermal grease that was used in the PCM container was taken directly from ecoinvent, as epoxy resin, while 7500 km were ascribed to maritime transport (China to Greece) and 50 km to road transport (local transportation). O&M, which includes personnel transport and panel washing, was assumed to be carried out on a biannual basis. As such, 30 km were ascribed per visit by means of a small passenger car, where 410 panels were assumed to be inspected and washed per visit, using 6 L of tap water per panel.

Finally, for the waste management scenario, it was assumed that after its lifespan, the PV panel, along with the rest of the system, would be dismantled and recycled and/or landfilled locally. Specifically, the demolition of the foundation system is already included in ecoinvent's data and therefore the relevant transportation distances and the recycling or landfilling of the main materials were considered (Table S1, Appendix). A recycling rate of 70% for the recyclable materials was considered, with the remaining 30% assumed to be landfilled, along with the non-recyclable materials. It should be noted that ecoinvent's LCI data for metal and glass recycling do not include important inputs, such as electricity consumption. To this end, relevant LCI data for glass [42] and metal [43] recycling were used to complement ecoinvent's data, assuming that recycling is taking place in Greece, i.e., electricity originates from Greece's energy mix.

2.4.5. Life cycle impact assessment

LCIA methods are classified into two broad categories, i.e., resource-based (focus is placed on resource consumption (input) from nature, e.g., CED) or emission-based (focus is placed on one (e.g., USEtox) or multiple (e.g., ReCiPe) emissions (outputs) to nature) [44]. Here both a resource-based, i.e., CED, which shed light on the direct and indirect energy consumption of the standalone PV and the PV-PCM system throughout their life cycles, and an emission-based, i.e., ReCiPe 2016, which covers a broad range of different categories, were used. Specifically, ReCiPe 2016 is a harmonized, multi-issue LCIA method that can translate environmental emissions and resource extractions into a limited number of environmental impact scores, using characterization factors. It can express results both at midpoint (focusing on single environmental problems that are found earlier in the cause-effect chain) and endpoint (relating to the damage at three areas of protection, i.e., human health, ecosystem quality, and resource scarcity) level [45]. At the midpoint level ReCiPe 2016 uses 18 midpoint impact categories, while at endpoint level, the damage to human health, ecosystem quality, and resource scarcity are examined [46]. Finally, endpoint results can be further normalized and weighted as to obtain the total environmental footprint in the form of one single indicator, i.e., a single score, which, even though it introduces uncertainty and subjectivity (in weighting), is particularly helpful in comparative assessments [47], such as herein. In ReCiPe 2016, single scores are expressed in Eco-indicator points (Pt), where 1000 Pt correspond to the annual environmental load of an average European inhabitant. Here, the Hierarchist perspective was used in ReCiPe with an average weighting set, while for the environmental modelling the software program SimaPro (version 9.3) was employed.

3. Results and discussion

3.1. Energy performance

First, the obtained experimental results for the energy performances of the standalone PV and the PV-PCM are briefly discussed. Specifically, the mean and maximum deviation of the operating temperature values of the PV panels ($\Delta T_{m\ (PV/PV\text{-}PCM)\_peak}$, $\Delta T_{m\ (PV/PV\text{-}PCM)\_avg}$), as a result of the PCM integration, are shown in Fig. 3. It should be noted that the deviation between the operating temperature values of the standalone PV and the PV-PCM system was observed to be particularly limited during winter and summer, while it was higher during spring and autumn. More specifically, the values of the relevant indices, i.e., $\Delta T_{m\ (PV/PV\text{-}PCM)\_peak}$, $\Delta T_{m\ (PV/PV\text{-}PCM)\_avg}$, for December were 9.4 °C and −0.8 °C respectively, which were observed to significantly increased in May, as shown by the respective values of 26.1 °C and 12.6 °C (Fig. 3).

The total monthly energy yield of the standalone PV and the PV-PCM system is shown in Fig. 4. Results indicate that the PV-PCM system generated more electricity than the standalone PV during the year-long reference period. Specifically, the annual alternating current (AC)

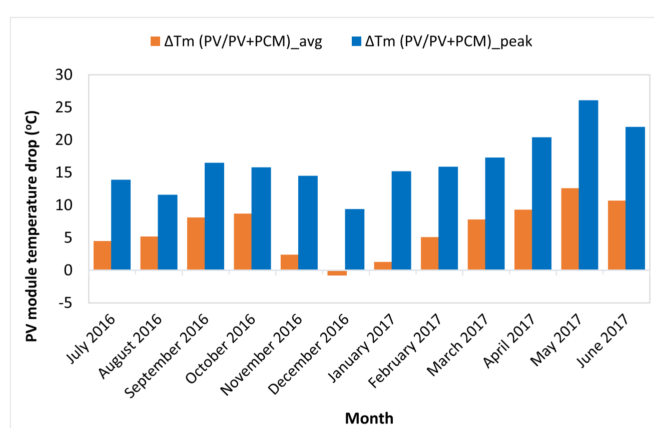

Fig. 3. Mean and peak monthly temperature decrease gained by PCM cooling.

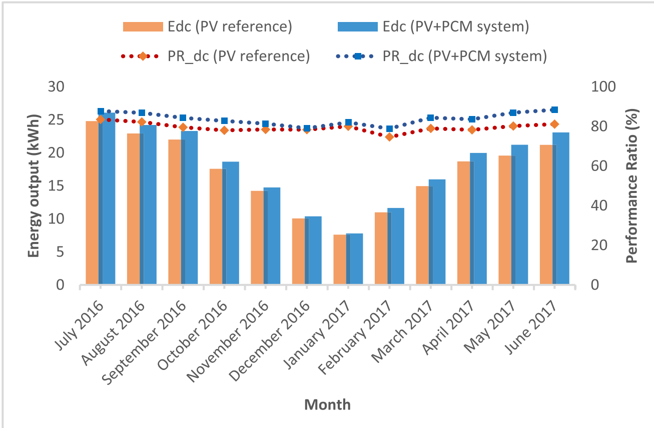

Fig. 4. Total monthly energy production ($E_{DC,m}$) and monthly variation of the performance ratio ($PR_{DC,m}$) of the standalone PV and the PV-PCM system.

electricity yield of the PV-PCM system was 215.1 kWh instead of 202.7 kWh (Table S2, Appendix), i.e., 6.1% higher than the standalone PV. Regarding their long-term efficiency due to thermal degradation, for the standalone PV, a 0.6% annual degradation rate was considered for the first 10 years, whereas afterwards, the mean annual degradation rate is assumed to increase to 1% until the end of its useful life (25 years). For the PV-PCM system, the literature suggests that the annual degradation rate would be constant at 0.6% [28,32], whereas our year-round measurements for the island of Crete, Greece, suggest that this value could be nearer to 0.5% and this value was considered here. In this sense, for a typical 25-year lifespan, the standalone PV will generate 4401 kWh, whereas the PV-PCM will generate 4814 kWh, i.e., a 9.4% increase in electricity output which translates to an additional 413 kWh over a 25-years reference period (Table S2, Appendix).

Furthermore, the increase in the energy yield of the PV-PCM system greatly varies depending on the month and season, with the minimum being in December (3% increase) and the maximum in June (8.9% increase) (Fig. 4). Specifically, in the winter months, energy generation was significantly lower due to the lower sunshine duration (sun hours) compared to summer, whereas during the summer apart from more sun hours temperatures are also higher thus cooling is more beneficial. The results are in line with the literature since, for example, in an experimental study in Benha, Egypt, it was identified that PCM cooling improved PV's electrical efficiency by 3.7% in winter but by 9% in summer [31]. Finally, the average monthly value for the performance ratio ($PR_{DC,m}$) of the standalone PV and the PV-PCM system was observed to be in the range 74.6–83.5% and 83.8–88.4%, respectively (Fig. 4).

3.2. Cumulative energy demand, energy payback time, and energy return on investment

As was expected, the CED of the PV-PCM system is significantly higher (2.69 MWh) compared to the standalone PV (0.89 MWh). The reason is twofold. First and foremost, PCM, i.e., paraffin, is responsible for this much higher score compared to the standalone PV, since it contributes more than half (55.6%) on the PV-PCM CED score. This was expected, since paraffin is a petroleum wax that is produced from the crude oil distillation process [48]. Furthermore, paraffin production from crude oil is energy-intensive, since for the production of 1 t of natural paraffin 1.08 t of crude oil (raw material) is required, while 25.83 kWh of electricity and 4.8 GJ of heat are also consumed [41]. For electricity and particularly for heat generation, fossil fuels (e.g., natural gas) are burned, and this is reflected in PCM's CED score. Second, the material of the PCM housing unit, i.e., stainless steel, also contributes to the PV-PCM's total CED score, but to a lesser extent (11.9% of CED's total score). Specifically, among the existing manufacturing industries, iron and steel have the highest global energy consumption [49] since mineral resources (iron ore) need to be mined (explosives and machinery are used), crushed (energy and machinery are used), processed (blast and electric furnaces are energy-hungry), and refined (e.g., using an argon-oxygen decarburization (AOD) vessel which is also energy intensive) [50]. The relatively low contribution of the PCM housing unit is partly attributed to the fact that steel recycling was included in the system boundary.

Regarding the EPBT scores, results suggest that it will take around 5 years for the standalone PV system to payback its initial energy investment, whereas for the PV-PCM system, this period is significantly higher at around 14 years. In a case study in Egypt, the EPBT for a standalone PV and a PV-PCM system was estimated at 4 and 5 years, respectively [31]. The latter is much lower than the EPBT value estimated here. However, the comparison of different PV-PCM systems cannot be direct since different set-ups with different inputs are used. For example, in the case study in Egypt, a 20 W PV was assessed when using 4.56 kg of PCM and 1.3 kg of aluminum for the container, while the lifespan was restricted to 10 years [31]. Here, a 130 Wp PV was examined along with 46.2 kg PCM (replaced once, i.e., total mass 92.4 kg) and 76 kg stainless steel for the container, whereas the lifespan was 25 years. Even though the CED value for the PCM appears high, other studies have suggested even higher values for fossil-fuel derived PCMs, such as 250 MJ kg^{-1} for octadecane [51], which implies that PV-PCM systems are associated with elevated CED and, by extension EPBT values, as was the case herein. This also highlights the need for more studies on different PV-PCM systems and configurations, as was the case with the standalone PV's where a wide range of EPBT values has been reported, spanning from 1.96 to 9.6 years and 1.24 to 6.05 years for the monocrystalline and polycrystalline technology respectively [52]. Finally, as was expected the EROI for the standalone PV was 4.94 whereas the corresponding value for the PV-PCM system was significantly lower at 1.79.

Therefore, both EPBT and EROI indicators suggest that PCM cooling comes with a hefty energy footprint, highlighting the need for using less energy-intensive PCMs. To reduce the high energy footprint of fossil-fuel-based PCMs, biobased PCMs, including waste biomaterials, could be used as replacements. For example, it has been reported that the CED value of a fossil-fuel-derived PCM (octadecane) is an order magnitude higher than its bioderived (coconut oil) counterpart [51]. Biobased materials can also be blended with fossil-fuel-based materials, e.g., composites of beeswax and coconut oil blended with paraffin [53], which apart from improving PV electrical efficiency, can also reduce the energy and possibly the environmental footprint of PCM cooling. However, even though biobased PCMs are less energy intensive and possibly more environmentally friendly than fossil-fuel-based PCMs, more research and development (R&D) is required before they reach maturity [54]. For example, in a case study between beeswax (biobased) and fossil-fuel-based (Rubitherm RT 44 HC) PCMs for the passive cooling of electric vehicle batteries, the latter was found more effective [55], whereas even though pork fat appears to be promising for integration in PVT-PCM systems more R&D on its long-term properties is required [30]. Finally, since here PCM was assumed to be replaced during the 25 years lifespan of the PV-PCM system, recyclable PCMs, as have been proposed elsewhere [56], could be used to reduce the energy and most likely carbon footprint of PCM cooling.

3.3. ReCiPe at midpoint level

3.3.1. Characterization

First, ReCiPe's results for the standalone PV and the PV-PCM system are presented at the midpoint level and per FU, i.e., per 1 kWh. Regarding the environmental impacts of the PV modules, their manufacturing is energy-intensive (e.g., the reduction of silica to silicon requires large amounts of energy), while large quantities of minerals and metals (e.g., silicon, cadmium, and copper) are also mined, processed, and consumed, leading to relevant emissions [1]. As a result, the PV laminate affects the categories that are related to abiotic resource depletion, due to mineral extraction from the earth's crust [57]. The PV frame and cabling also consume metals (e.g., copper extraction and processing for cable production [58]). The ecotoxicity and human toxicity categories are mainly affected by emissions generated from the processing of these minerals (e.g., tailings from minerals extraction and emissions from fossil fuel burning [57]) as well as from the landfilling of PV laminates after the end of their lifespan [59].

Regarding the environmental impacts of the PV-PCM system, it was identified that the scores of the standalone PV are lower in most impact categories and particularly in the categories of global warming, ozone formation, acidification, fossil resource scarcity, and water consumption (Table 2). These categories are mainly affected by PCM's raw material, i.e., paraffin, and, to a lesser extent, by the material of the PCM container, i.e., stainless steel. As mentioned above, paraffin is a fossil-fuel-derived (petroleum) material, and this is directly reflected in the categories of global warming, fossil resource scarcity, and water consumption. Similarly, stainless steel's environmental impacts are traced back to the energy and raw materials consumed for its production, mainly affecting the fossil resource scarcity category, while a wide array of different emissions are generated [50], affecting most of the remaining categories. The thermal paste mainly affects the ecotoxicity and, to a lesser extent, the toxicity impact categories. Hoverer, the integration of PCM cooling improves the PV's power output and, therefore, a smaller amount of the PV-PCM system is allocated per FU compared to the standalone PV. This is reflected in its lower scores on water ecotoxicity, human toxicity, and land use categories (Table 2).

Finally, the comparison of the results of different LCA studies cannot be direct, since different systems, with different inputs, assumptions, and LCIA methods, are examined greatly affecting the presented results [60]. However, in a case study of a PV-PCM system in Croatia, using an aluminium container for the PCM and the CML 2001 LCIA method, PCM cooling was found to increase PV's total score on global warming by 71.3%, acidification by 104.8%, eutrophication by 34.7%, human

Table 2
ReCiPe 2016 results at midpoint level (characterization) for the generation of 1 kWh of electricity from a PV-PCM and a standalone PV system.

Impact category	Standalone PV	PV-PCM	Percentage increase
Global warming (kg CO_2 eq)	4.40E-02	7.21E-02	63.9%
Stratospheric ozone depletion (kg CFC11 eq)	2.16E-08	2.46E-08	13.9%
Ionizing radiation (kBq Co-60 eq)	3.47E-03	3.73E-03	7.5%
Ozone formation, Human health (kg NOx eq)	1.19E-04	1.84E-04	54.6%
Fine particulate matter formation (kg $PM_{2.5}$ eq)	1.14E-04	1.38E-04	21.0%
Ozone formation, Terrestrial ecosystems (kg NOx eq)	1.22E-04	1.87E-04	53.3%
Terrestrial acidification (kg SO_2 eq)	2.96E-04	3.84E-04	29.7%
Freshwater eutrophication (kg P eq)	4.20E-05	4.68E-05	11.4%
Marine eutrophication (kg N eq)	3.04E-06	3.44E-06	13.2%
Terrestrial ecotoxicity (kg 1,4-DCB)	1.25E+00	1.27E+00	1.6%
Freshwater ecotoxicity (kg 1,4-DCB)	1.69E-02	1.64E-02	−3.0%
Marine ecotoxicity (kg 1,4-DCB)	2.17E-02	2.11E-02	−2.8%
Human carcinogenic toxicity (kg 1,4-DCB)	1.14E-02	1.15E-02	0.9%
Human non-carcinogenic toxicity (kg 1,4-DCB)	2.51E-01	2.49E-01	−0.8%
Land use (m^2a crop eq)	3.62E-02	3.35E-02	−7.5%
Mineral resource scarcity (kg Cu eq)	1.06E-03	1.21E-03	14.1%
Fossil resource scarcity (kg oil eq)	1.24E-02	3.94E-02	217.7%
Water consumption (m^3)	8.43E-04	1.29E-03	53.0%

toxicity by 16.1%, photochemical ozone depletion by 180.6%, while the categories ozone layer depletion and abiotic depletion were practical unaffected [28]. Here, a different LCIA method was used, i.e., ReCiPe 2016, which considers a wider range of midpoint categories, and results were expressed per kWh produced, but for the global warming category, a similar increase in its score (63.9%) was observed, while PCM cooling increased acidification by 29.7%, eutrophication by 11.4% (freshwater) and 13.2% (marine), human toxicity by 0.9% (carcinogenic), and ozone depletion (stratospheric) by 13.9%. Note that, among others, CML 2001 estimates the total eutrophication potential, i.e., it does not discriminate between terrestrial, marine, and freshwater eutrophication [61], while even the results of different versions of the same LCIA method (e.g., ReCiPe 2008 and ReCiPe 2016) are typically not comparable. However, the global warming category gives consistent interpretations in both CML and ReCiPe [62] and hence the observed agreement here. For the standalone PV, the results are also in agreement with the literature, since the results for the carbon footprint (global warming category) of the PV panel are on par with the results for a commercial ground-mounted PV farm in the Greek setting, i.e., 4.27E-02 [63] instead of 4.40E-02 kg CO_2 eq per kWh here. Finally, as mentioned above, biobased PCMs can not only reduce the energy footprint of PV-PCM systems but, most likely, also their environmental footprint. This was the case when pork fat was used in a PVT-PCM collector under the Mediterranean climate, where the PCM (pork fat) itself was not the main contributor to the environmental impacts of the system [30].

3.3.2. *Normalization*

To identify the relative importance of the abovementioned midpoint scores (Table 2), normalization was applied using ReCiPe's 2016 global normalization factors (reference year 2010). The normalized results reveal that the midpoint categories that are affected the most, in both the standalone PV and the PV-PCM system, are marine and freshwater ecotoxicity, followed by human carcinogenic and then non-carcinogenic toxicity, and lastly terrestrial ecotoxicity (Fig. 5). The remaining midpoint impact categories exhibited very low to negligible normalized scores.

Even though PV panels do not generate noise or emit chemical pollutants during use, their manufacturing requires large quantities of raw materials and is power-hungry [1], while their installation also affects land use [64]. Therefore, the large normalized scores on the ecotoxicity impact categories can be mainly traced back to the PV laminate production process, which is responsible for heavy metals emissions such as arsenic, cadmium, chromium, lead, mercury, and nickel [1]. The human toxicity categories are mainly affected by emissions from the metals production chain [57]. In addition, the manufacturing and landfilling of the PV balance of system components (i.e., inverter, cabling, supporting infrastructure, etc. but not the PV panels themselves) is also responsible for the release of toxic and carcinogenic substances and contaminants into the air, water, and soil [59], further affecting the ecotoxicity impact categories.

Overall, it appears that the normalized scores of the cooling system (PCM and container) are much smaller than the scores of the PV panel across midpoint impact categories. More importantly, the use of PCM colling improves electricity output and, therefore, a slightly lower amount of the PV-PCM system, compared to the standalone PV system, is allocated per FU. To account for its decreased electricity output compared to the PV-PCM system, the LCI of the standalone PV system should be higher (9.4%), including the data for land use and land-use change. On the other hand, the PCM cooling system is affecting most impact categories to the extent that cannot be compensated by the greater electricity output of the PV panel, apart from the water ecotoxicity categories, which enjoy a relatively high reduction in their normalized score (Fig. 5).

3.3.3. *ReCiPe at endpoint level and the effect of displaced electricity*

At the endpoint level, results were first expressed in ReCiPe's three

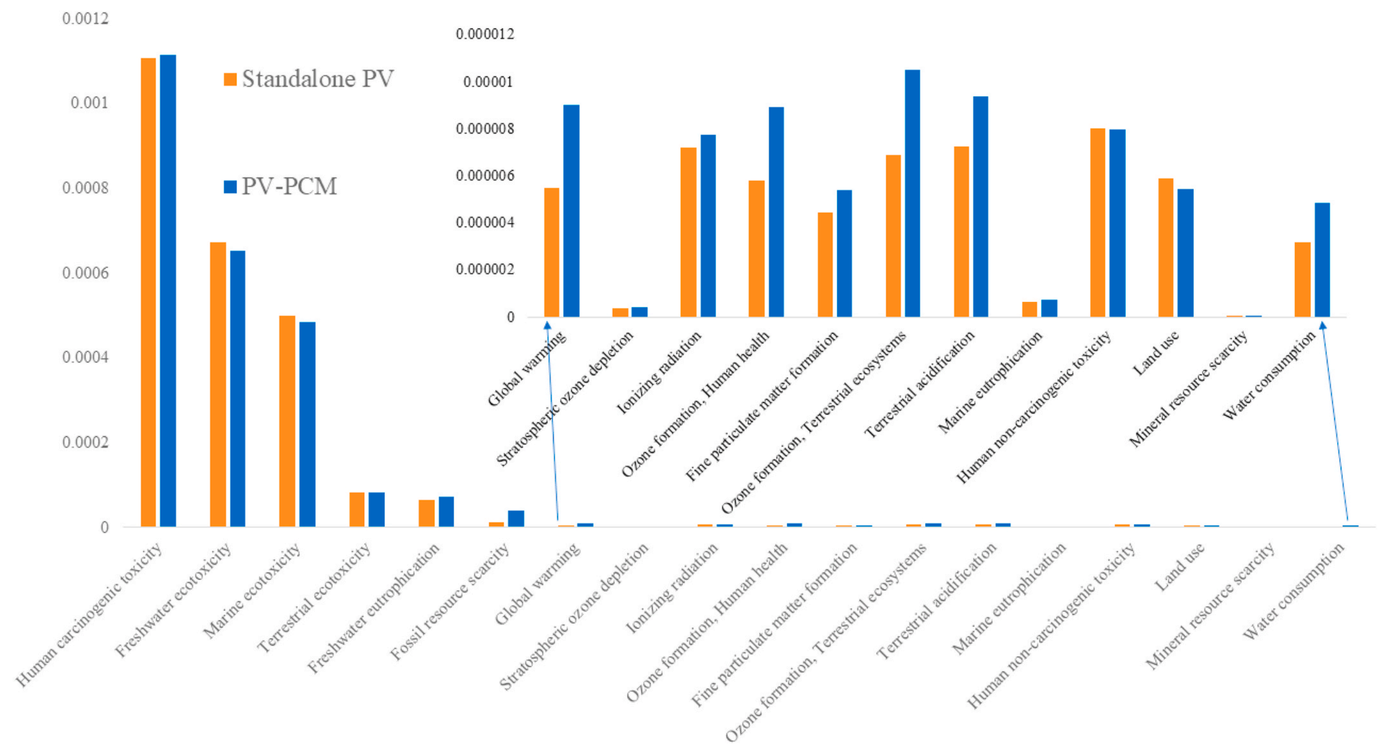

Fig. 5. The normalized scores of ReCiPe's 18 midpoint impact categories for the standalone PV and the PV-PCM system.

damage categories, i.e., damage to human health, ecosystem quality, and resource scarcity. These correspond to the three respective areas of protection considered in ReCiPe 2016. To accommodate an easier comparison between the standalone PV and the PV-PCM system, results were then expressed into a single score (Fig. 6). Specifically, it was identified that PCM cooling does not drastically affect the environmental sustainability of the PV panel, since the total environmental footprint of the PV-PCM unit 21.9% higher than that of the standalone PV system (no cooling) or 18.9% per FU . This increase in the total environmental footprint is attributed to i) paraffin (13.2% contribution to PV-PCM's total environmental footprint), and ii) stainless steel used in the PCM housing (8.1% contribution to PV-PCM's total environmental footprint). It should be noted that a smaller amount of the PV-PCM system is allocated per FU compared to the standalone PV and this is also reflected in the results. The thermal grease, which is used in the PCM housing, has a much lower (1.5%) contribution to PV-PCM's total environmental footprint. Finally, the transportation process contributed, in both cases (standalone PV and PV-PCM), less than 1%. This was expected, since emissions from PV modules transportation are inconsequential when compared to the emissions generated during PV module manufacturing [1]. Even though the comparison of the results of different LCA studies cannot be direct, the increase in the total environmental footprint due to PCM cooling appears to be in line with the literature since, in a case study in France, PCM cooling increased the total environmental footprint of a building-integrated solar thermal system by 21.4% [34].

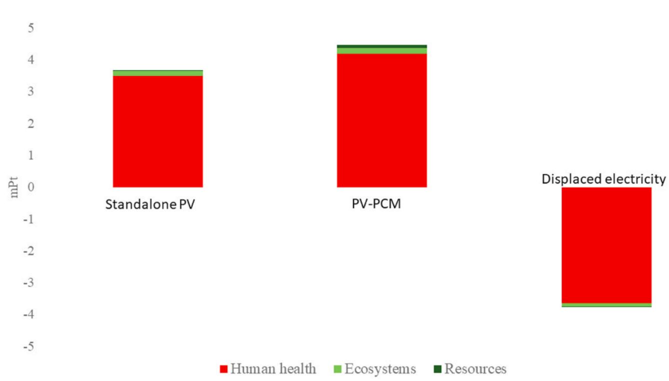

Fig. 6. The total environmental footprint of the standalone PV, the PV-PCM, and the effect of the displaced electricity.

Furthermore, among the three examined damage categories, human health was affected the most in both the standalone PV and the PV-PCM. For the human health category, the damage pathways include the increase in respiratory disease, cancer, other diseases/causes, and malnutrition [46]. In both the standalone PV and the PV-PCM, the observed scores are mainly traced back to human toxicity (carcinogenic and non-carcinogenic) midpoint impact categories. Also cabling, and to a lesser extent, the inverter, contribute to this category. Copper is the main material for cabling, and its mining and processing greatly affects the human toxicity impact categories through heavy metals and other toxic emissions, e.g., from leakages from disposed copper mine tailings and of the overburden material [58]. The higher score of the PV-PCM system, compared to the standalone PV, in the human health damage category is traced back to paraffin and stainless steel (housing unit), with the welding process of the latter and its transportation having a negligible contribution. As mentioned above, iron ore mining is associated with toxic emissions (e.g., tailings), while steel production is energy intensive. Therefore, emissions from fossil fuel extraction and burning directly affect the toxicity impact categories and, thus, the human health damage category. Paraffin is also produced from fossil fuels (oil), while energy, mainly for heat production, is also consumed during its production. For the ecosystem quality category, the damage pathways include the damage to freshwater, terrestrial, and marine species and can be mainly traced back to the high scores of the ecotoxicity impact categories for the reasons mentioned above. Finally, the resources damage category is affected by the metals and the fossil fuels that are consumed/depleted. For example, the raw materials (iron, copper etc) and the fossil fuels that are consumed for the manufacturing of the PV and the PCM unit directly affect the mineral and fossil resource scarcity impact categories and, therefore, the resource scarcity damage category.

However, even though PCM cooling comes with a higher initial environmental footprint, it also improves the PV's electricity output, and therefore additional electricity will be displaced from national grids. This will credit the PV-PCM system with avoided emissions and, therefore, improve its overall environmental performance. However, as electricity decarbonizes, these environmental credits will reduce. Here, the displaced electricity from the Greek energy mix, assuming only the current mix and not possible future decarbonized mixes, was considered through system expansion. It was identified that when considering Greece's current energy mix, the avoided emissions have a great potential to reduce the total environmental footprint of the PV-PCM system. The largest reduction was observed in the damage category human health (84.6%), followed by ecosystems (48.5%), however, even with the environmental credits from the displaced electricity, the damage resources remain way above (228.9%) than the standalone PV. Since human health had the largest overall weighted score, its reduction had the largest impact, while ecosystems had only a small effect on the total score of both systems. The large score of the displaced electricity is traced back to the fact that electricity in Greece is fossil fuel dependent, as is also the case for the global energy mix. i.e., the average global energy mix currently comprises 3.06% oil, 23.32 natural gas, 36.38% coal, 10.35% nuclear, 15.63% hydro, 10.39% renewables, and 0.87% others (pumped hydro and non-renewable waste) [65]. Therefore, the environmental credits are traced back to avoided emissions from fossil fuel extraction, processing, and burning, which have a large impact on the human health damage category [66].

Overall, results suggest the positive environmental effect of displacing fossil fuel-based electricity with renewable energy, in this case, solar energy. As a result, when the displaced electricity is included in the analysis, the environmental footprint of the PV-PCM could be reduced by as much as 84%, over a 25-year period and when only considering the current but not the future energy mix in Greece. As such, when the displaced electricity is considered, it appears that the PV-PCM system is more environmentally friendly than the standalone PV (Fig. 6). Specifically, with the current electricity mix, it will take around 5 years for the PCM cooling system to compensate for its initial environmental footprint, while thereafter environmental gains are expected to be achieved when compared to the standalone PV. The importance of displaced electricity was also highlighted in another case study in Egypt, where it was identified that additional CO_2 emissions are avoided due to improved PV electricity generation from PCM cooling [31].

Therefore, it appears that in the Greek context (electricity displaced from the current Greek energy mix), the integration of PCM cooling in PV panels can act as an environmentally sustainable avenue to increase both electricity output and renewable energy penetration to the energy grid. Furthermore, cooling can be beneficial for reducing the impact of PV panels on land use and land-use change, since solar PV farms are notorious for the large areas that they occupy during installation and operation and, by extension, for their impact on land-use and land-use change [64]. Therefore, the improved electricity output from PV cooling provides an opportunity to reduce the impact of solar energy on land use and use and land-use change, which could have major implications for future large-scale solar installations. Finally, PV cooling could sustainably mitigate the impact of climate change on the solar energy output by reducing temperature extremes and fluctuations on the panel's surface attributed to global warming. However, as has been noted elsewhere, the energy savings in building-intergraded PCMs are insufficient to compensate for their high cost [35]. Similarly, for PV-PCMs commercial applications, the PCM cost should either drop significantly or novel and more cost-effective PCM should be developed [28] and biobased PCMs could play an important role in this regard [54].

3.3.4. *Sensitivity analysis*

To identify the effect of the source of energy that is used during PCM manufacturing, as well as the effect of electricity output and useful life of the PV panel that is cooled, sensitivity analysis was employed. Specifically, PCM's environmental impacts are greatly traced back to the heat input and, to a lesser extent, by the electricity that is consumed during its manufacturing. Therefore, a scenario where the electricity and the heat input comes from renewable sources, i.e., hydropower and biomass respectively, was examined. In this scenario, the total environmental footprint of the PCM, as a material, is greatly reduced (46.2%). However, due to PCM's high lifespan and its overall low environmental footprint compared to the PV panel, it appears that the environmental performance of the PV-PCM system only slightly improves, since the total environmental footprint of the PV-PCM system reduces by only 6.7%.

Nonetheless, it was identified that the PV-PCM system is more sensitive to changes in the electricity output and useful life, which are dictated by the reduction of the PV's thermal degradation rate due to cooling. Specifically, our year-round measurements suggest that PCM cooling improves the electricity output of the typical a-Si PV panel by 9.4%. However, the effect on the electricity production output greatly depends on PV type and geographic location, with different values being reported in the literature. Here, a plausible worst- (3% improvement [67,68]) and a best-case (12% improvement [69,70]) scenario were considered. In the worst-case scenario, it was assumed that the PV-PCM system would produce 4533 kWh of AC electricity over the 25 years reference period, whereas in the best-case scenario would produce 4929 kWh (AC) in the same time span. Our measurements suggest that 4813.5 kWh (AC) would be produced over the 25 years period (Table S2, Appendix), and this is referred to as the base-scenario. It should be noted that the best- and worst-case scenarios refer to different PV technologies, different system set-ups, and different geographies; however, results can provide insight for future PV-PCM installations. Compared to the base-scenario, in the best-case scenario the environmental performance of the PV-PCM system increases by 6.2%, whereas in the worst-case scenario decreases by 2.3%. However, in both cases the standalone PV has a better environmental performance (Fig. 7).

When the additional electricity (132 kWh and 528 kWh more than the standalone PV in the worst- and best-case scenario, respectively, over a 25-year useful life) is considered, then the importance ofcooling in improving PV electrical efficiency becomes clearer. Specifically, even in the worst-case scenario, cooling renders the PV-PCM system more environmentally friendly than the standalone PV through avoided emissions attributed to electricity displacement from Greece's current fossil-fuel-dependent energy mix (Fig. 7). The importance of displacing fossil-fuel-dependent electricity has also been highlighted in another case study in Egypt, where the PV-PCM achieved higher CO_2 avoidance rates compared to the standalone PV [31].

Regarding the PV's useful life, in the base-scenario it was considered that the lifespan of the PV-PCM system would be 25 years, as is the case

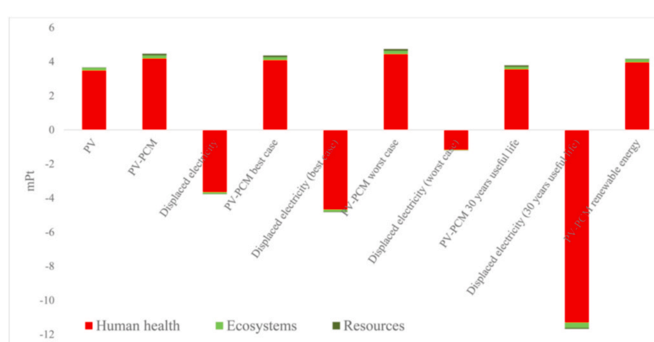

Fig. 7. The results for the PV, PV-PCM, and displaced electricity along with the results of the sensitivity analysis for the PV-PCM best and worst-case case scenario and the extended (30 years) useful life, along with the corresponding displaced electricity.

for the standalone PV. However, our year-round measurements suggest that PCM cooling can greatly reduce PV's thermal degradation rate, thus, most likely, extending its useful life to 30 years would be plausible. This implies that it will be economically viable to harness solar energy for an additional 5 years after the standalone PV solar farm has been decommissioned. In this case, an additional 866 kWh would be generated over this 5-years timespan, bringing the total electricity output of the base-scenario from 4813.5 kWh (25 years) to 5679.5 kWh (30 years). Furthermore, for the 30 years of useful life, only the PCM would require an additional replacement, and this was also considered in the extended lifespan scenario. In this case, the total environmental footprint of the PV-PCM is nearly identical (around 3% higher) to the standalone PV footprint, since a smaller amount of the PV-PCM system is allocated per FU. However, the environmental credits from the avoided emissions from displaced electricity are much higher, suggesting the great potential of PV cooling (Fig. 7). In other case studies, such as in a building-integrated PV-PCM system in Spain, extended lifespans up to 48 years, instead of 30 years herein, were reported [32] suggesting the large potential of PCM cooling.

4. Conclusions

The environmental performance of an integrated PV-PCM system was comprehensively examined using the life cycle assessment methodology. Actual life cycle inventory data were collected from a system constructed and operating in Crete, Greece, i.e. under the Mediterranean climate. The integration of PCM cooling in a typical a-Si PV panel was found to increase the total environmental footprint of a standalone ground-mounted solar PV system by 21.9%. However, PCM cooling improves electricity output by around 9.4% during a 25-year lifespan. It can also increase the PV panel's useful life (by at least 5 years), and this can greatly improve the environmental sustainability of the PV-PCM system, as was identified through sensitivity analysis. The increased electricity output leads to reduced scores on the midpoint impact categories that are affected the most by the PV technology, i.e., the eco-toxicity and toxicity categories. More importantly, the additional electricity attributed to PCM cooling can grossly reduce the environmental impacts of the PV technology, since currently the Greek energy mix, as well the global average energy mix are fossil fuel dependent.

When the displaced electricity from the Greek energy mix was considered, then it appears that the PV-PCM system is more environmentally friendly than the standalone PV (no cooling) owing to avoided emissions. As a result, it appears that the environmental credits from the increased electricity output can compensate for the initial environmental footprint of the PCM cooling system in about five years, leading to environmental gains thereafter. When considering increased PV electricity output and lifespan, attributed to PCM cooling, additional environmental credits are ascribed to the PV-PCM system. Furthermore, the increased electricity output is also beneficial for land use and land-use change, since large-scale solar PV farms are notorious for such impacts. PCM cooling could also mitigate the impact of climate change on the solar energy output by reducing temperature extremes and fluctuations on the panel's surface attributed to global warming. Nonetheless, based on the existing body of knowledge, significant price reductions or novel and more cost-effective PCMs should be introduced to enable the wide-scale commercialization of this technology. Furthermore, the PCM itself has a very high energy footprint, which also translates to elevated scores in most of the examined categories. The different energy efficiency indicators employed herein also implied that PCM cooling comes with a hefty initial energy penalty compared to the standalone PCM. As such, research should focus on more energy and environmentally friendly materials, such as biobased PCMs or on other means of cooling such as wind and water.

CRediT author statement

Spyros Foteinis: Conceptualization, Investigation, Data curation, Methodology, Software, Writing - original draft. **Nikolaos Savvakis**: Methodology, Investigation, Data curation, Validation, Writing - review & editing. **Theocharis Tsoutos**: Conceptualization, Funding acquisition, Supervision, Project administration, Formal analysis, Validation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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