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Sun-Powered Refrigerator: Design, Testing, and Limitations

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ABSTRACT

The availability of vaccines, medicines, and perishable goods in remote or off-grid areas remains a formidable challenge. Integrating solar photovoltaic (PV) systems with refrigeration technology has emerged as a promising solution to address this critical need. This paper comprehensively explores a sun-powered refrigerator capable of maintaining temperatures between +2℃ and -20℃, essential for preserving vaccines, medicines and perishable products in remote areas. A solar PV panel is mounted on the refrigerator's top surface, harnessing renewable energy to power the refrigerator. This solution also enhances portability, making it well-suited to remote and resource-constrained regions. The results of initial experimental tests aim at validating feasibility and efficacy of the sun-powered refrigerator and assessing the refrigerator's performance under varying operating conditions. Detailed insights into the design, construction and limitations are provided, shedding light on its potential as a sustainable solution for vaccines and medicines storage in underserved areas. Solar availability, storage capacity, and backup power sources are carefully examined to provide a comprehensive understanding of the practical considerations and constraints involved. This paper contributes to scientific literature on renewable energy applications and aims to inform policymakers, healthcare practitioners, and technology developers about the potential and challenges of solar-powered refrigeration solutions for resource-limited areas.

1. INTRODUCTION

Vapor Compression Refrigeration (VCR) systems are the most commonly utilized and easily accessible options for the storage of temperature-sensitive products. The challenge of ensuring the availability of vaccines, medicines, and temperature-sensitive products in remote or off-grid regions is complex and requires addressing the issue of unreliable electricity access in a constructive manner, since the safety and functional properties of perishable products can be affected by inadequate cooling facilities. In addition, improvements in energy consumption of refrigeration systems are crucial for the refrigeration industry to reduce its environmental impact. During last decades, the scientific community has focused its attention on new emerging refrigeration technologies, such as solid-state refrigeration [1, 2], new refrigerants [3] able to reduce the so-called direct emissions (related to refrigerant leakages). In particular, to address fluorine-based environmental impact, current scientific literature focuses on solutions involving the use of natural refrigerants such as carbon dioxide [4-6] or isobutane (R600a) [7], showing promising energy and environmental performances. In addition, renewable power sources and energy recovery [8] are spreading as promising solutions to reduce indirect emissions (related to the production of electric energy to power refrigeration systems) both in static and transport refrigeration sectors. Integrating solar photovoltaic (PV) systems with refrigeration technology has become a promising solution to meet the critical need for cooling [9] thanks to its supply-demand matching characteristics (during periods of higher solar radiation, the demand for cooling increases). Moreover, solar cooling is an environmentally conscious solution, since it contributes to decreasing reliance on fossil fuels, reducing or eliminating the indirect emissions of refrigeration systems. PV solar cooling systems utilize electricity generated by the PV modules to power the cooling operations, resulting in a system where solar energy drives cooling [10]. Solar PV cooling, also called solar-assisted vapor compression refrigeration, comprises four essential components: PV modules, a battery pack, an inverter or a charge regulator, and a VCR system. The specific cost of PV panels is decreasing over time, and their efficiency is continuously improving, so vapor compression cycles combined with PV panels represent the most attractive solution in economic [11] and technical [12] terms. Several experimental studies have evaluated the effectiveness of vapor compression solar cooling systems, including both alternating current (AC) and direct current (DC) cases [13-15]. The difference between AC and DC systems is related to the device acting as the interface between the PV modules and the load, i.e. performing the DC-AC or DC-DC conversion, respectively. In particular, when considering an AC refrigeration system, a hybrid inverter with specific characteristics for photovoltaic purposes (performing the Maximum Power Point Tracking-MPPT, for example) must be used. In the case of DC-powered refrigeration units, no AC/DC conversion is required, and a charge controller should be used in order to modify the PV panel operating voltage to meet the battery needs (if present) and power the load properly. In this case, the efficiency in the DC/DC conversion is greater than that of AC/DC conversion, reducing the power losses [16] and increasing the available electric energy provided by the PV panels. In addition, several researchers have conducted theoretical investigations and feasibility studies regarding PV solar cooling systems [9, 17-19]. Feasibility is proven, both technically and economically, and its application is currently under study also in the refrigerated transport sector [20]. However, drawbacks like the necessity of batteries (thermal or electrical) and the higher investment costs with respect to standard solutions prevent the extension of these systems. The battery pack is necessary to achieve maximum emission savings by allowing the use of green energy during insufficient solar energy periods, such as at night. At the same time, a PV array output deviates from the maximum power point without an inverter or a charge regulator [21], causing an inefficient use of solar energy. Charge and discharge cycles during operation can cause a premature degradation of the battery because of an increase in temperature [22]. However, in the case of solar-powered VCR systems, batteries do not reach dangerous conditions, so a thermal management system is not required (differently from automotive cases).

Even if the current scientific literature is rich in studies regarding PV solar cooling systems, it needs to be pointed out that PV panels powering a refrigeration unit (both refrigeration and air conditioning systems) are usually dislocated with respect to the VCR system. This solution allows having no limits to the available solar surface but strongly reducing the compactness and portability of the system.

This study presents and thoroughly analyses a compact solar-assisted refrigerator, developed inside the spinoff ARES S.r.l. (SU.P.E.R. - SUn PowEred Refrigerator project). The photovoltaic panel is mounted on the rooftop of a DC refrigerator, making it suitable for transportation and deployment in remote areas. The results of initial experimental tests aim to validate the sun-powered refrigerator's feasibility and efficacy in operating without the need for a backup power source, and assess the refrigerator's performance under varying operating conditions. The experimental results are also discussed in terms of opportunities and limitations of the proposed system.

2. PROTOTYPE DESCRIPTION

The refrigeration system considered in this study is a commercial VCR refrigerator operating with 60g of R290, a non-toxic but flammable natural refrigerant characterized by a low GWP (Global Warming Potential) value. The original VCR unit is a refrigerator with a hot-wall design, meaning that the condenser is embedded within the insulated walls, and features a DC-powered variable-speed compressor. It allows the selection between refrigerator mode and freezer mode. The difference between the two modes is given by the internal set-point temperature, which can be set in the range between 2℃ and 12℃ for refrigerator mode, and between -20℃ and -10℃ in freezer mode. The supply voltage can be either 12 V or 24 V so that the system can be easily powered through photovoltaic panels. The DC compressor supply is managed by means of a dedicated power controller, which regulates the compressor's speed. The controller works in the Adaptive Energy Optimization - AEO mode, adjusting the compressor's speed to minimize energy consumption according to the required cooling power [23]. The characteristics of the base refrigerator are summarized in Table 1.

Table 1. Refrigerator characteristics

Parameter	Value
Operating voltage	12 V/24 V
Compressor nominal power	89 W @ 0℃ & 3000 rpm
Cooling volume	166 L
Operating temperature	+2℃ – +12℃ (Refrigerator) -20℃ – -10℃ (Freezer)
Voltage supply range	10 V – 17 V/17 V – 31.5 V
Environmental operating temperature	+10℃ – +43℃
Dimensions	872×917×709 mm
Insulated walls thickness	11 cm
Weight	47 kg
Refrigerant	R290 (60 g)

In this study, the above-described VCR system is modified to be powered correctly by solar-photovoltaic technology. Precisely, a foldable monocrystalline PV panel with a peak power of 160 W is placed on the rooftop of the refrigerator through a self-designed structure, as shown in Figure 1 in folded (a) and unfolded (b) configuration.

(a) (b)

Figure 1. Prototype with folded (a) and unfolded (b) PV panel

The PV panel has an available solar surface greater than that of the rooftop of the refrigerator, as can be noted in Figure 1. It consists of four sub-modules, which can be overlapped when needed, guaranteeing compactness during transportation. A foldable PV panel has been chosen among alternatives based on the maximum power production, which relates to the available surface exposed to solar irradiation.

Since the VCR system operates under hysteretic conditions, alternating ON and OFF phases causes a mismatch between the electric energy produced by the PV panel and that required by the refrigeration unit. In addition, the PV panel's power production can exceed that the refrigerator absorbs. Therefore, optimising solar energy utilization requires a battery to store exceeding energy. The battery employed in the proposed prototype is a 12 V, 100 Ah lead-acid battery, the size of which is chosen to guarantee the correct electricity supply for at least one day without solar radiation, considering a maximum depth of discharge equal to 50%. As briefly described in the introduction section, in the specific case considered in this study, the refrigerator is DC-powered, so no AC/DC conversion must be performed. However, a charge regulator with MPPT function is required to adapt the PV panel voltage to the load (in this case, near 12 V) and charge the battery when possible. Table 2 summarizes the characteristics of the photovoltaic system employed, including the PV panel, the battery and the charge regulator.

Table 2. PV panel, charge regulator and battery characteristics

Component	Parameter	Value
Photovoltaic panel	Nominal power	160 W
	Open circuit voltage	21.4 V
	Short circuit current	9.6 A
	Maximum power voltage	18.2 V
	Maximum power current	8.8 A
	Cell type	Monocrystalline silicon
	Weight	5.6 kg
	Unfolded dimensions	157×68×2.5 cm
	Folded dimensions	42×68×2.5 cm
	Cell chemistry	Lead-acid
Battery	Capacity	100 Ah
	Nominal voltage	12 V
	Weight	21.92 kg
	Dimensions	353×175×190 mm
	Battery voltage	12 V/24 V
Solar charge regulator	Nominal charge current	10 A
	Max short circuit current	13 A
	Maximum conversion efficiency	98%
	Maximum PV open circuit voltage	75 V
	Dimensions	10×11.3×4 cm
	Weight	0.5 kg

The previously described components added to the base refrigerator aim to make the system independent from the electric power grid. However, since the proposed system is intended for use outdoors under direct solar radiation, it needs to be considered that radiative heat exchange is a non-negligible part of the thermal load. To reduce the thermal load experienced and, consequently, the electric energy needed for operation, the lateral surface is covered with a layer of high-reflectance aluminium tape, while the top of the refrigerator is covered by the PV panel. Solar radiation causes the PV panel to heat up, reducing its conversion efficiency and contributing to radiative heat exchange. To counter this, an air gap is included between the PV panel and the refrigerator's top surface to allow external air to flow and cool down the panel.

3. TESTING PROCEDURE

In this study, four experimental tests have been performed to prove feasibility and highlight the proposed PV-powered system's drawbacks and limitations. Four different set-point temperatures are considered in the experimental campaign to evaluate the system's potential for different applications. In particular, internal temperatures of -20°C, -10°C, 0°C and +4°C, with a hysteresis of ±1°C, are tested to cover a wide range of medical products applications (e.g. 2–8°C for common medical products, between -25°C and -15°C for Moderna COVID-19 vaccine [24]). To consider the worst operating conditions, no products are stored in the refrigerator during the tests, since they act as thermal masses increasing the thermal inertia of the whole system. The internal air temperature is brought to the desired set-point temperature before beginning each experimental test, which starts at 17:00 in full-charged battery conditions and lasts 24 hours. The chosen starting time is intended to face nighttime as soon as possible, as solar radiation decreases and the external temperature starts to decrease after 18:00. Furthermore, in this condition, the PV panel power production is almost negligible, so most of the energy required to power the VCR system is provided by the battery.

The tests are performed in a temperature-controlled laboratory room to avoid dependence on actual daily climatic conditions. A remotely controlled DC power supply simulates the PV panel's dynamic behaviour. In particular, the well-known single diode model, given by Eq. (1), is employed to calculate the V-I and V-P curves, and consequently the maximum power point, according to climatic conditions (external temperature and solar irradiance) provided by the PVGIS-SARAH database.

$$I_{PV} = I_{ph} - I_{sat}\left(e^{\frac{V_{PV}+I_{PV}\cdot R_s}{\eta \cdot V_t}} - 1\right) - \frac{V_{PV} + I_{PV}\cdot R_s}{R_h} \qquad (1)$$

where, I_{ph} is the photoinduced current, I_{sat} is the diode's saturation current, V_{PV} and I_{PV} are the PV panel voltage and current, respectively. V_t is the thermal voltage of the PV cell (related to the PN junction) depending on the cell's temperature, R_s and R_h are series and shunt resistances used in the equivalent circuit, respectively, and η is the ideality factor of the diode. All these parameters are evaluated based on the specific PV module datasheet. A schematic of the above-described testing device is shown in Figure 2.

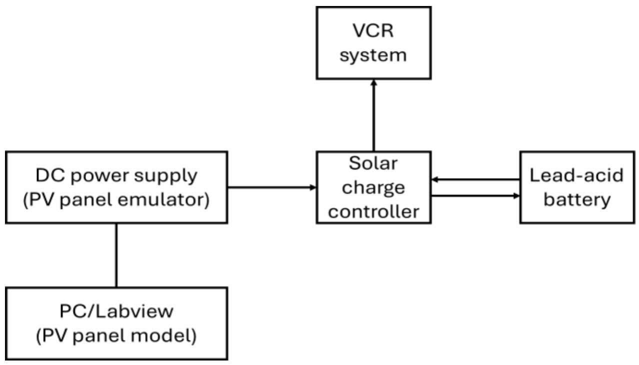


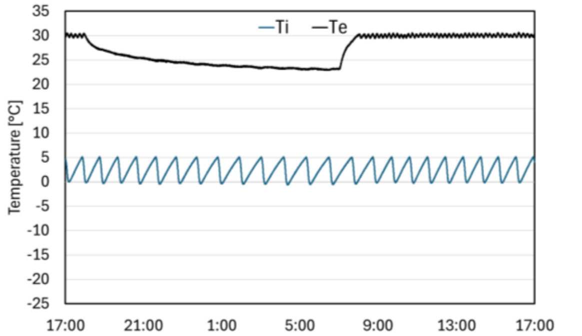
Figure 2. Schematic of the testing device

In this experimental campaign, climatic conditions of Fisciano (Salerno, Italy) on a generic day in July are considered to test the worst conditions in terms of thermal load and energy consumption. The external temperature is varied through an electric heater to maintain 30°C during the day (with a hysteresis of ± 0.5°C), while night-related attenuation is simulated by turning the heater off.

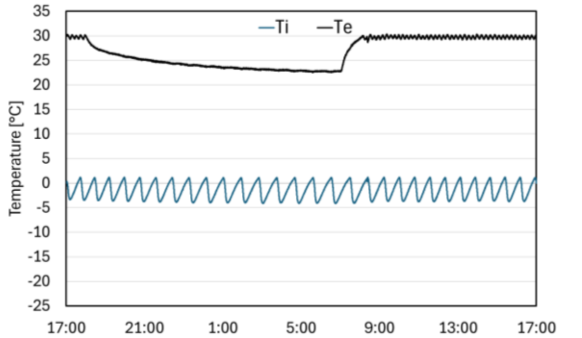
During the tests, external and internal temperatures are measured through two four-wire RTDs Pt100 with an accuracy of ±0.1°C. Electric energy measurements are also performed to evaluate energy fluxes across the charge regulator. In particular, an energy meter is used to measure both voltage and current related to the PV panel, the battery and the VCR system's compressor, with an accuracy of ±10mV and ±10mA, respectively.

4. RESULTS AND DISCUSSION

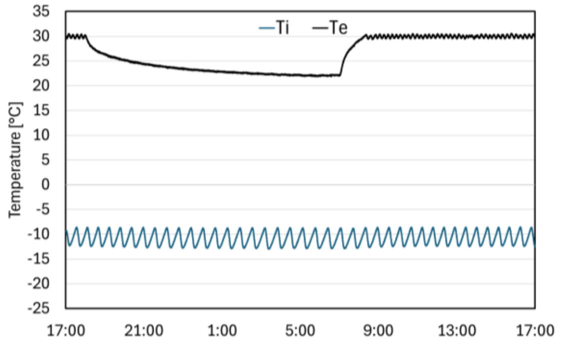
Figure 3 shows the internal and external air temperatures measured during the tests.



(a)



(b)



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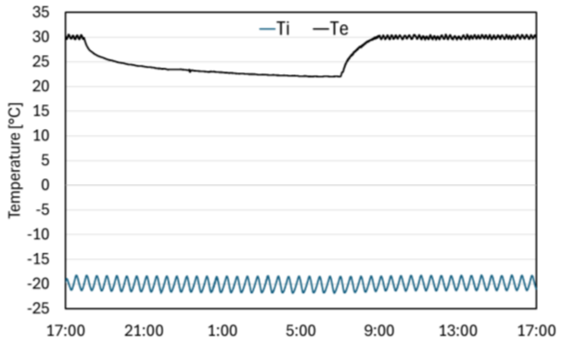
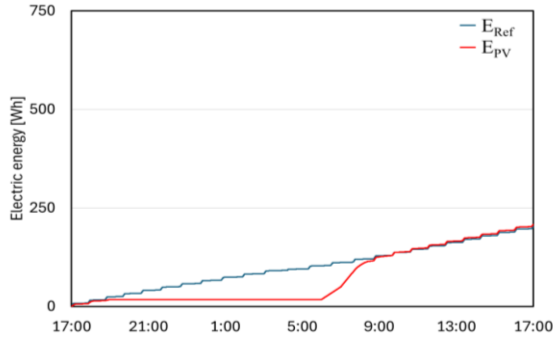


(d)

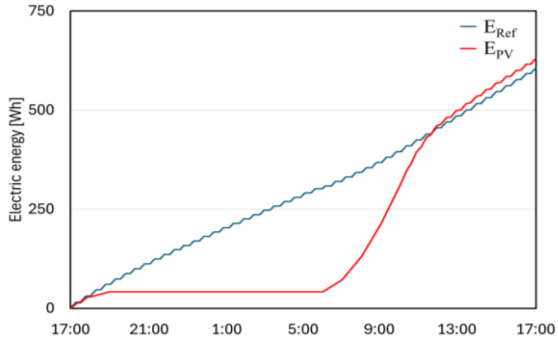
Figure 3. Temperature measurements during the experimental tests at +4°C (a), 0°C (b), -10°C (c) and -20°C (d)

As previously described and shown in Figure 3 (a-d), the external air temperature (Te) is set to 30°C during daytime hours and decreases during nighttime. The measured external temperature agrees with the climatic data used to model the PV panel. The results obtained from all the experimental tests have proven that the PV-powered system can maintain the desired internal air temperature (Ti) during the whole duration of the tests. Of course, this is an already-expected behaviour since the battery is sized to guarantee an entire day of operation without the contribution of the PV panel.

Figure 4 shows the cumulative electric energy produced by the PV panel (E_{PV}) and absorbed by the VCR system (E_{Ref}). In particular, the best-conditions and the worst-conditions tests are shown (i.e. +4°C and -20°C, respectively).



(a)



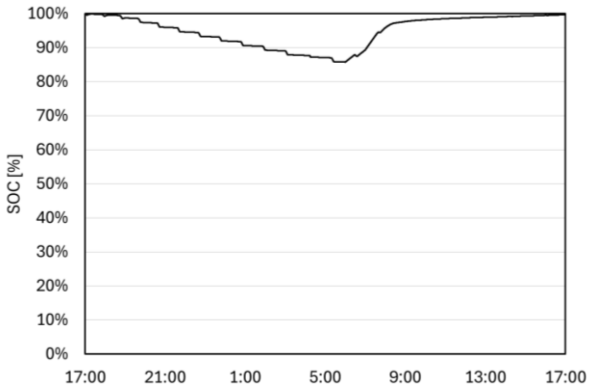
(b)

Figure 4. Cumulative electric energy during the experimental tests at +4°C (a) and -20°C (b)

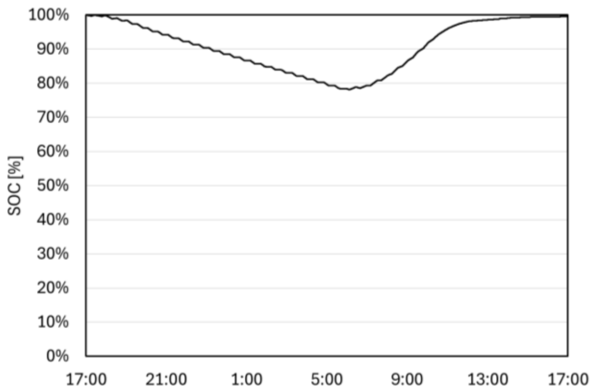
As shown in Figure 4, the PV panel does not produce electric energy during nighttime, so the cumulative plot shows a horizontal line. In the early morning hours, PV production increases according to the hourly irradiance value. The PV panel cannot cover the electric energy demand during nighttime and early morning hours, making the battery an indispensable device. At the end of the tests, the electric energy produced by the PV panel is greater than that absorbed by the refrigerator. This means that the PV system (panel and battery) can power the VCR system properly in both the best-case and worst-case tests (and, consequently, the two intermediate conditions as well). The PV panel's electric energy production in 24 hours is always higher than that the refrigerator absorbs since the charge regulator's conversion efficiency must be considered. Since the electric energy demand is totally covered by the PV panel's production, the actual State of Charge (SOC) of the battery should be evaluated to understand its behaviour during the tests. Figure 5 shows the SOC of the battery during the best-conditions (+4°C) and worst-conditions (-20°C) tests.

As shown in Figure 5, the battery is discharged during nighttime and starts to be recharged in early morning hours. The minimum SOC (SOC_{min}) equal to 78% is reached during the -20°C test, as expected, while in the tests at +4°C the minimum SOC is equal to 93%. When considering the 0°C and

-10°C tests, a minimum SOC of 91% and 86%, respectively, can be found. Anyway, in each test the PV panel is able to produce all the required energy and consequently the battery is fully recharged after 24 hours in each test performed.



(a)



(b)

Figure 5. SOC of the battery during the experimental tests at +4°C (a) and -20°C (b)

As shown by the results obtained, the system is able to operate in off-grid conditions without absorbing energy from the power grid. Considering the Italian energy mix, corresponding to an emission factor of 331 $g_{CO2,e}$/kWh, the reduction in greenhouse gas emissions can be evaluated. Table 3 summarizes the results obtained for each test.

Table 3. Summary of the results

Parameter	Test #1	Test #2	Test #3	Test #4
$T_{set\text{-}point}$ [°C]	+4°C	0°C	-10°C	-20°C
$E_{el,PV}$ [Wh]	208	254	407	631
$E_{el,Ref}$ [Wh]	203	247	395	608
End-of-test SOC [%]	100			
SOC_{min} [%]	93	91	86	78
Emission savings [$g_{CO2,e}$]	67	81	130	201

As shown in Table 3, the PV panel's electric energy production varies based on the specific test considered, since instantaneous power production depends on the balance between PV panel, battery and load. In addition, climatic data also affect the energy production. In this study, climatic conditions of July are considered, since they represent the worst case in terms of thermal load and energy consumption. However, it is worth noting that it is also the month with highest solar radiation, so the PV panel production is also maximized. Therefore, further tests in different climatic conditions should be carried out. The system has proven to be able to operate without the need for the electric power grid, resulting in a zero-direct environmental impact refrigeration system. Anyway, the battery is able to power the system for only one day (considering a maximum DOD of 50%), and two days (considering a maximum DOD of 100%). This means that even with a high-capacity battery (12 V, 100 Ah), in the case of more than two consecutive low-solar radiation days, the system could not be able to properly power the VCR system, leading to product waste and the need for a backup power source (electric power grid). This solution, unfortunately, would make the system not deployable in remote and undeserved areas. In addition, the battery considered in this study is already characterized by a high weight and dimensions, reducing the system's actual compactness. These limitations can be both overcame by employing a thermal energy storage system in addition to the battery. Phase change materials, in particular, could be well suited to this application, being able to increase the PV panel electric energy production to its maximum and reducing the needed battery size.

5. CONCLUSIONS

In this study, the feasibility of a compact solar-powered refrigerator is analysed. The proposed system consists of a commercial cockpit DC-powered refrigerator, with the addition of a PV panel mounted on its top surface, a solar charge controller and a lead-acid battery to store electric energy. Four experimental tests at different set point temperatures have been conducted in order to evaluate the dynamic behaviour of the whole system for 24 hours considering July climatic conditions. The set point temperatures are chosen according to medical products storage temperature range. Results have shown that the system is able to operate independently from the electric power grid. The PV panel can produce all the required electric energy during the 24 hours, so that the battery is fully recharged after the 24 hours. These results prove the feasibility of the system and its efficacy in storing medical products in remote and undeserved areas in the worst climatic conditions in terms of thermal load. In addition, the proposed components also allow the system to be a possible solution towards sustainability in the cold chain, since 100% of the required electric energy is provided by a renewable energy source, leading to $CO_{2,e}$ savings of 67-201 $g_{CO2,e}$. Anyway, the energy required by the refrigerator varies according to the climatic conditions, as well as the PV panel's electric energy production, so further experimental tests at different environmental conditions are required. In addition, the system still requires a battery with high capacity, size and weight to face low-solar radiation conditions, reducing the actual compactness of the whole system. A possible solution to this limitation is to employ phase change materials as thermal energy storage system, allowing an increase in the PV panel's energy production and reducing the size of the battery.

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NOMENCLATURE

E electric energy, Wh

I	current, A
R	electric resistance, Ω
Te	external air temperature, °C
Ti	internal air temperature, °C
V	voltage, V
V_t	thermal voltage of the PV cell, V

Greek symbols

η	ideality factor of the diode

Subscripts

h	shunt
min	minimum
ph	photoinduced
PV	photovoltaic panel
Ref	refrigeration system
s	series
sat	saturation
set-point	set point

Acronyms

$CO_{2,e}$	equivalent carbon dioxide
DOD	depth of discharge
SOC	state of charge
VCR	vapor compression refrigeration