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Assessment of a Solar Powered Refrigerator Equipped with Thermal Storage for a Dairy Application

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Abstract

Typical agro-food value chains use electric refrigeration systems. However, in many non-industrialized countries, the cold chain is often not guaranteed due to lack of electricity access or unreliable electricity grids. In such cases, refrigeration systems must be equipped with electrical backups or other form of energy storage.

This study analyses the use of a commercial available vapour-compression horizontal refrigerator for small-scale cheese processing system. The studied refrigerator of 350 litres capacity is powered by photovoltaic panels, which provide electricity to a DC compressor. Encapsulated phase change materials were incorporated to the system as energy storage option, for a reliable operation at temperature at 11°C. This operating temperature is suitable for the analysed product, but it is also suitable for other agro-food applications, such as the preservation of fruits and vegetables. In particular, this study evaluates the incidence of the incorporation of Phase Change Materials on the stratification temperature inside the refrigerator, the raise temperature time of the refrigerated product, the number of on-off cycles of the compressor, the COP of the system, and the sizing of the conventional storage system with electrical batteries.

Keywords: Solar PV collectors, Compression refrigeration, Thermal energy storage, Phase change materials, Dairy sector

1. Introduction

Proper cold chain management in the agro-food sector is fundamental to preserve the quality of the products, reduce waste products, and also promote their effective commercialization (Gustavsson et al., 2012). Refrigeration systems in this sector typically use vapour-compression systems, powered by electricity, with direct expansion of refrigerant for small applications. In many developing countries, the cold chain cannot be guaranteed due to the lack of electricity supply or the frequent power outages. In such cases, refrigeration systems must be equipped with electrical backups or other form of energy storage.

In this context, several studies have analysed refrigeration systems powered by photovoltaic modules (Deshmukh and Kalbande, 2015; Katic et al., 2010) which use electrical storage and small size Direct Current (DC) compressors, eliminating the losses associated with DC / AC inverters. Energy storage plays a relevant role, especially when the cold production and energy demand are not matching (Dincer and Rosen, 2011; Lott and Kim, 2014). The use of Phase Change Materials (PCM) as a thermal energy storage option in this type of systems, can eliminate or reduce the size of the traditional electrical storage with lead-acid batteries (Pedersen and Katic, 2016). This type of electrical-storage has less useful life, generates a greater environmental impact, and in many cases has higher cost than some thermal storage options.

The integration of PCM into direct-expansion refrigeration systems can be done at the condenser as well as at the evaporator level. The integration at the evaporator level should consider factors such as the type of evaporator, its location within the cooled space, and the air diffusion system. In this regard, different studies have analysed the use of PCM in domestic and commercial refrigerators and freezers (Alzuwaid et al., 2015; Azzouz et al., 2008; Oró et al., 2012; Yusufoglu et al., 2015). In general, the results indicate that PCM provide more stable temperatures, a greater system autonomy and energy savings for refrigerators with non-regulated compressors. Most of these studies have been performed at typical operating temperatures of 4°C and -18°C, for refrigerators and freezers respectively, and in some cases without stored product; so we considered that it is convenient to carry out studies and develop models closer to the real conditions for each type of application.

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In this line, the present study analyses the performance of a horizontal refrigerator, of 350 litres of capacity, with a direct-current compressor powered by photovoltaic modules. The refrigerator will be used later in a small-scale cheese processing at an operating temperature of 11°C. This operating temperature is suitable for the analysed product, but also for other agro-food applications, such as preservation of fruits and vegetables. The refrigerator has been adapted for storing the product, as well as for the incorporation of encapsulated PCM, with a phase change temperature between 5 and 6°C. In particular, this study evaluates the incidence of the incorporation of PCM on the stratification and temperature stability inside the refrigerator, the raise temperature time of the refrigerated product, the number of on-off cycles of the compressor, the COP of the system, and the sizing of the conventional storage system with electrical batteries.

Nomenclature

H	Specific Enthalpy [kJ kg^{-1}]	η	Efficiency
Q	Heat [J]	D_t	Door open time factor [-]
q	Heat flow rate [W]	D_f	Door flow factor [-]
Q_T	Total thermal load [J]	E	Effectiveness of doorway protective device [-]
Q_{Losses}	Transmission heat gains [J]	a	Parameter "a" of photovoltaic model [-]
Q_{Pr}	Product thermal load [J]	F	Fractional state of charge of battery [-]
Q_{Int}	Heat gains due to internal equipment [J]		
Q_{Inf}	Infiltration heat gains [J]	**Subscripts**	
$Q_{Losses,d}$	Transmission heat gains for a day [J]	ex	Exterior
Q_{Useful}	Useful heat [J]	in	Interior
m	Mass [kg]	p	Time interval
T	Temperature [K]	Ref	Refrigerator
A	Area [m^2]	air	Air
x	Thickness [mm]	PCM	*Phase change material*
W	Electricity consumption [J]	s	Solid
w	Power [W]	l	Liquid
V	Voltage [V]	S	Series
I	Current [A]	P	Parallel
I_{SD}	Inverse saturation current of the diode	F	Photovoltaic
t	Time [s]	i	Initial
c_p	Specific heat [J kg^{-1} K^{-1}]	f	Final
k	Thermal conductivity [W m^{-1} K^{-1}]	r	Regulator
h	Convection heat transfer coefficient [W m^{-2} K^{-1}]	b	Battery
U	Global heat transfer coefficient [W m^{-2} K^{-1}]	d	Discharging
COP	coefficient of operation [-]	c	Charging

2. Methodology

2.1 Description of system and analysed application

The studied system is located in the district of Nyanza (Kenya), with a latitude of 0.08°N, longitude of 35.06°E, and 1914 m of altitude. The system consists of a horizontal refrigerator (Fig.1), which will be installed in a processing room, under controlled temperature between 21 and 25°C. The refrigerator is equipped with a direct current (DC) Compressor, with refrigerant R134a. The system will be powered by a multi-crystalline photovoltaic module, and has two types of energy storage: (1) Electrical storage with conventional lead-acid batteries, with a charge controller, and (2) Thermal energy storage with phase change materials, arranged next to the interior walls of the spaced refrigerated, since the evaporator is embedded in them.

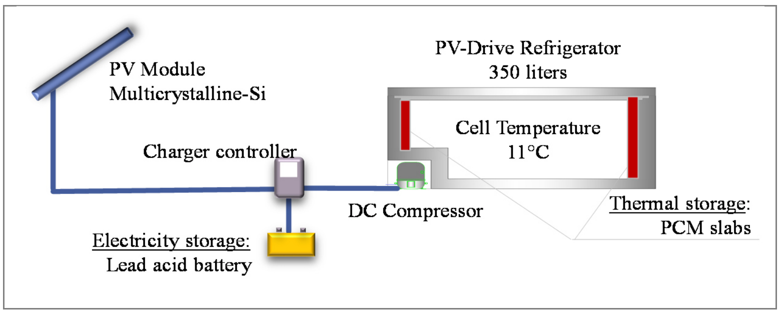


Fig. 1: Scheme of the system

The refrigerator was adapted to store the product (cheeses), incorporating four vertical structures that allow to process up to 16 kg of cheeses, and using forced convection with two small power fans installed in the upper area of the refrigerator.

2.2 Experimental setup for testing refrigeration cell

For performing this study, the refrigerator was tested in a climatic chamber taking measurements before and after installing the PCM. Taking into account that in real conditions the refrigerator will operate in an air-conditioned room, the tests were performed for an ambient temperature of 25°C and a relative humidity between 40 and 60%. During the tests, water was used as a refrigerated product, and in a later stage, a specific mixture will be used to simulate the system in conditions closer to the application.

The experimental setup is shown in Figure 2. The horizontal refrigerator, 350 litters capacity, is equipped with a direct current compressor, Secop BD 35F, with refrigerant R134a and a Danfoss 101N21C controller. The power supply in the test was performed at 12 volts, using a regulated source voltage. The phase change material (PCM) was incorporated in the internal side of the refrigerator, since the evaporator of the refrigerator is embedded in the wall.

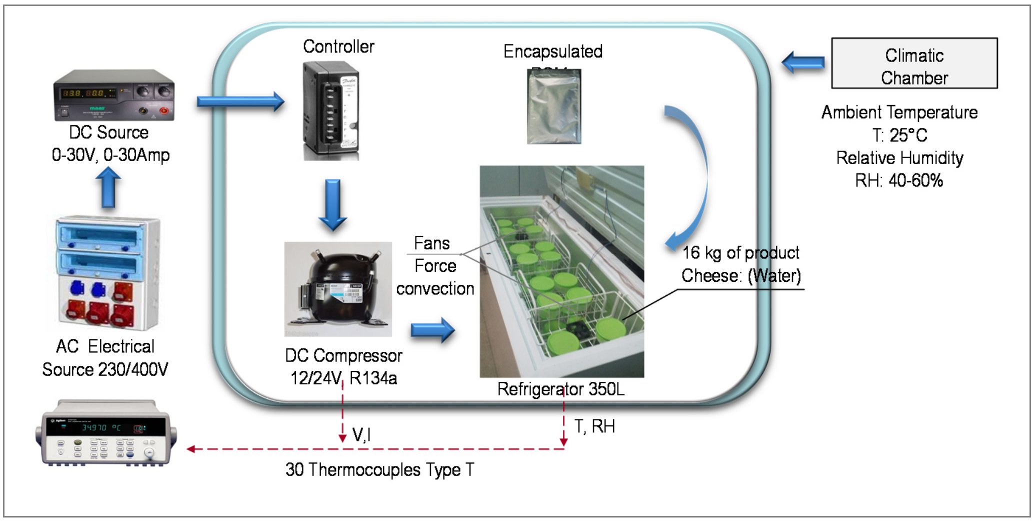


Fig 2: Experimental setup of refrigerator cell

The PCM-encapsulation consists of polyethylene bags with an aluminium layer, placed on a 1mm steel-sheet (Fig 3(a)) attached to the inner side of the refrigerated space (Fig 3(b)), since the evaporator is embedded in the refrigerated space walls. The melting temperature of the PCM, manufactured by Rubitherm, is between 5 and 6 ºC and the operating temperature inside the refrigerator is 11±2°C. The PCM slab has a thickness of 8mm, and the final mass installed was 8.9 kg.

(a) Detail of phase change material on one of the walls of the refrigerator. (b) Refrigerator with PCM next to Evaporator-Wall (c) Refrigerator, inside of the climatic chamber at the laboratory

Fig. 3: Details of the experimental setup of integration of PCM

In total, 30 T-type thermocouples were used to measure the temperatures in the product (cheese), PCM, and refrigerator walls, and ambient temperature. Current and voltage measurements were also taken in order to quantify the electrical consumption, with a measurement interval of 1 minute. Table 1 summarizes the number and types of sensors used in the experimentation.

Tab. 1: Resume of sensors used in the experimental setup of refrigeration cell

Type of sensor		Number of sensors	Location
Temperature sensors	T-type thermocouples	10	Interior walls of refrigerator
		10	Product
		9	Encapsulated PCM
		1	Climatic chamber
Electricity sensors	Voltage: Voltage Regulated Source Output	1	CC Circuits
	Current: Hall effect sensor, Arduino ACS712	2	CC Circuit 1: Compressor, CC Circuit 2: Fans
Humidity sensors	Relative humidity sensor	1	Climatic chamber

2.3 PCM selection and integration

The integration of PCMs in domestic and commercial refrigerators and freezers can be carried out through active and passive solutions. Active solutions are often more effective than passive ones in the heat transfer process; however, passive solutions are simpler for implementation.

Passive integration solutions can be done at the condenser as well as at the evaporator level. The integration at the evaporator level should consider factors such as the type of evaporator, its location within the cooled space, and the air diffusion system.

In relation to this, several previous studies have analysed different options such as: The installation of a PCM slab next to the external side of the evaporator and embedded in the wall of the refrigerator (Azzouz et al., 2008; Yusufoglu et al., 2015); the arrangement of PCM slabs inside freezers with internal evaporator (Oró et al., 2012), the arrangement of PCM next to the condenser, and also the arrangement of PCM in the refrigeration circuit (Cheng et al., 2011). In the case studied, the refrigerator has a wall evaporator, so the integration option adopted consists of placing a slab of the PCM on the inner wall of the refrigerator.

Tab. 2: Main Characteristics of Phase Change Material (PCM) Selected

Description	Value
Manufacturer	Rubitherm
Reference of the substance	RT5HC, Organic
Type of Substance	Paraffin, C5-C20
Phase change Temperature Range [°C]	5 to 6
Thermal storage capacity [kJ/kg]	250 (-2 to 13°C)
Specific heat capacity (solid) [J kg^{-1} K^{-1}]	2000
Specific heat capacity (liquid) [J kg^{-1} K^{-1}]	2000
Density (solid, -15°C) [kg m^{-3}]	880
Density (liquid, 20°C) [kg m^{-3}]	760
Thermal conductivity (solid) [W m^{-1} K^{-1}]	0.2
Thermal conductivity (liquid) [W m^{-1} K^{-1}]	0.2

Since the temperature required for the refrigerated product is 11 ° C, the evaporator temperature should be about 0 ° C, in order to provide a suitable temperature difference for an effective heat transfer process. In this case, the phase change temperature of the PCM should have a value between the evaporator temperature and the required product temperature. This ensures that the PCM material changes phase, without cooling the refrigerated product below the required temperature range.

In this way, the PCM finally selected is the RT5HC manufactured by Rubitherm, with a phase change temperature between 5 ° C and 6 ° C. Table 2 presents the main characteristics of this material. The material is organic (Paraffin, C5-C20), and does not have a single-phase change temperature, as it happens, in pure substances. The main advantages of this type of PCM compared to the hydrated salts are the greater stability, and that the crystallization process requires less sub cooling of the material.

2.4 Data analysis and simulation

2.4.1 Scenarios considered

The experimental data provide information about the system for two scenarios: (1) Refrigerator without PCM and (2) Refrigerator with PCM. For both scenarios, two types of day were analysed: (1) "Initial day", in which the product is cooled from an initial temperature (25°C) to the required final temperature (11°C) , and (2) "Maintenance day" type, in which the product is only maintained within the required operating temperature range (11±2°C).

Base on the experimental data, two electrical power demand profiles were created for a full month of operation (With PCM and Without PCM). The month selected for analysis was November, since this month has the lowest photovoltaic production. The TRNSYS 16 software was used as a simulation tool for photovoltaic production, and other complementary analysis was carried out by using Matlab.

2.4.2 Total thermal load

Total thermal load (Q_T) was calculated according to ASHRAE (eq.1), which includes: Transmission heat gains or losses through the refrigerator enclosures (Q_{Losses}), the Product thermal load (Q_{Pr}), the heat gains due to internal equipment (Q_{Int}) and the infiltration heat gains (Q_{Inf}).

$$Q_T = Q_{Losses} + Q_{Pr} + Q_{Int} + Q_{Inf} \quad \text{(eq.1)}$$

Transmission heat gains or losses through the refrigerator enclosures (Q_{Losses}) were estimated according to equation 2 (ASHRAE, 2010; Azzouz et al., 2008), where U_{Ref} corresponds to the global heat transfer coefficient of the refrigerator, A_{Ref} corresponds to the refrigerator area, $\Delta T_{Ref,\,p}$ is the temperature difference between the inside face of the cooler and the outside air at each time interval (p), and the Δt corresponds to the time step of the measurement or simulation.

$$Q_{Losses} = \sum_{p=0}^{P} U_{Ref} . A_{Ref} . \Delta T_{Ref,p} . \Delta t \quad \text{(eq.2)}$$

The overall heat transfer coefficient of the refrigerator was estimated according to equation 3, where x_n and k_n correspond to the thickness and thermal conductivity of the wall layer "n", and h_{int} and h_{ext} correspond to the interior and exterior convection heat transfer coefficients.

$$U_{Ref} = \frac{1}{\frac{1}{h_{ex}} + \frac{x_1}{k_1} + \frac{x_1}{k_1} + .. + \frac{x_n}{k_n} + \frac{1}{h_{in}}} \quad \text{(eq.3)}$$

The layers considered on the refrigerator wall are presented in Table 3. The overall coefficient U_{Ref} is 0.4712 $Wm^{-1}K^{-1}$ without PCM and 0.4623 $Wm^{-1}K^{-1}$ with PCM.

Tab. 3: Properties of the materials of the enclosures of the refrigerator

Layer Number	Material	Thickness [mm]	Thermal Conductivity [$Wm^{-1}K^{-1}$]
1	Steel	1.5	50

2	Polyurethane	60	0.050
3	Aluminium	1	230
4	PE film	0.15	0.33
5	PCM	8	0.2
6	PE film	0.15	0.33
7	Steel	1	50

The heat extracted from the product (Q_{Pr}) includes only sensible heat for this application, since the refrigerated product does not change phase. Q_{Pr} is calculated by applying the basic expression of equation 4, where C_p and m correspond to specific heat and mass of the material, while T_i and T_f are the temperatures corresponding to the initial and final time of the evaluated period.

$$Q = C_p.m.(T_i - T_f) \qquad \text{(eq.4)}$$

In relation to the heat gains due to internal equipment (Q_{Int}), the calculation considered two small power fans (1.8W) used for forced convection inside the refrigerated cell. Finally, the infiltration heat gains (Q_{Inf}) were estimated for a full day of operation of the refrigerator, applying equation 5 (ASHRAE, 2010), which includes the transmission heat gains in the enclosures for a stable day of operation ($Q_{Losses,d}$), the door open time factor (D_t), the door flow factor (D_f), and the effectiveness of doorway protective device (E).

$$Q_{Inf} = Q_{losses,d}.D_t.D_f(1 - E) \qquad \text{(eq.5)}$$

2.4.3 Power demand profiles

The profiles of the electric power demand were defined based on experimental data for the two scenarios analysed (With PCM and without PCM). To do this, the power was calculated by multiplying the voltage (V) and current (I) measurements at each time step.

2.4.4 Heat transferred in the PCM

The total heat transferred in the PCM (Q_{PCM}) was estimated multiplying the mass of the installed PCM by the variation of enthalpy for each time step, from the initial to the final one, according to the equation 6.

$$Q_{PCM} = \sum_{p=1}^{P} m_{PCM}.\Delta H_{PCM,p} \qquad \text{(eq.6)}$$

The specific enthalpy, , was calculated as a function of the temperature of the phase change material, according to equation 7 (Ozisik, 1993), where C_p is the specific heat capacity of the PCM, L is the specific heat of fusion, and the mushy region is between the temperatures T_s and T_l. When the temperature is lower than T_s, the material is in solid state, and when the temperature is higher than T_l, the material is in a liquid state.

$$H = \begin{cases} C_pT & for\ T < T_s\ Solid\ region \\ C_pT + \dfrac{T - T_s}{T_l - T_s}L & for\ T_s \le T \le T_l\ Mushy\ region \\ C_pT + L & for\ T > T_l\ Liquid\ region \end{cases} \qquad \text{(eq.7)}$$

2.4.4 PV production

The photovoltaic production profile was calculated by using the component 194 available in the dynamic simulation software TRNSYS 16. This component uses the 5-parameter model (Duffie and Beckman, 2013), that consists of a voltage generator, a diode connected in parallel that represents the semiconductor material, a series resistance, and a parallel resistance.

$$I = I_F - I_{SD}.\left(e^{\frac{V+I.R_S}{a}} - 1\right) - \frac{V + I.R_S}{R_P} \quad \text{(eq.8)}$$

The output current of the photovoltaic module (I) is calculated by applying equation 8, where it is necessary to know the 5 parameters of the model: (1) The series resistance (R_S), (2) parallel Resistance (R_P), (3) the current produced by photovoltaic effect (I_F), (4) the inverse saturation current of the diode (I_{SD}), and finally the factor "a". These parameters can be calculated by using the manufacturer specifications at standard reference conditions according to Eckstein (1990) and De Soto et al (2006).

2.4.5 Electric battery and regulator

The electric battery as well as the load regulator/controller were simulated using the algorithm applied in the "Type 48b", available in the dynamic simulation software TRNSYS 16. In this model, the charging of battery is carried out by applying a global efficiency value (η_b); the regulator charges the battery while the fractional state of charge *(F)*, is between a minimum value (F_d) and a maximum value (F_c). In addition, the battery bank can be discharged when the fractional state of charge is below of a specific value (F_b). On the other hand, a direct current (DC / DC) conversion is performed on the regulator/controller with a global efficiency value (η_r). Table 4 presents the parameters used in the analysed case.

Tab. 4: Values of Fractional state of charge and efficiencies applied in the electric battery and the regulator model

Description	Value
Minimal value of Fractional state of charge (F_d)	0.3
Maximum value of fractional state of charge (F_c)	1.00
Fractional of Fractional state of charge for starting discharging the battery bank (F_b)	0.85
Charging battery efficiency (η_b)	0.85
Regulator efficiency (η_r)	0.95

2.4.6 Performance indicators

The system performance was analysed by reviewing the following variables and indicators: (1) the temperature stratification of the refrigerated product, (2) the number of on-off cycles of the compressor, (3) the rise temperature time and (4) the coefficient of operation of the system (COP). In addition, the process of charging and discharging of PCMs was also studied.

The temperature stratification of the product was revised from the experimental data, using the information of nine thermocouples in the refrigerated product arranged at three different heights and at different points in the refrigerator.

The rise temperature time was measured by turning off the power supply and quantifying the total time in which the temperature of the refrigerated product reaches the maximum permitted value. These measurements were made according the standard EN 62552 for household refrigerating appliances (IEC, 2013).

$$COP = \frac{Q_{Useful}}{W} \quad \text{(eq.9)}$$

The coefficient of operation (*COP*) of the system was calculated by applying equation 9, where Q_{Useful} corresponds to the effective heat extracted by evaporator, and W corresponds to the electricity consumption of the refrigerator during the period of time evaluated. The effective heat extracted by the evaporator was estimated by adding the heat extracted from the product, the heat gains by transmission through the enclosures, and the infiltration heat gains. In this case, the experimental temperature data measured minute by minute are used and equations 2 to 5 are applied.

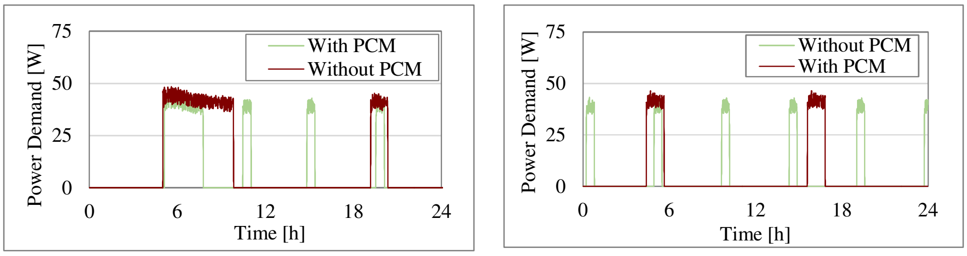
In relation to the charging and discharging processes of the PCM, the transferred heat was also calculated from experimental temperature data and applying equations 6 and 7.

3. Results and discussion

3.1 Power demand

The electric power demand of the refrigerator was measured during 48 hours for the two analysed scenarios (with PCM and without PCM). According to these data, the power demand profile were elaborated for two types of days: (1) "Initial day" (Fig 4a), in which the product is cooled from an initial temperature of 25 ° C to the required final temperature of 11°C, and (2) "Maintenance day" (Fig 4b), in which the product is only maintained within the required operating temperature range (11±2°C).

The average power for the "Without PCM" scenario is 38.7W, with a minimum of 33.2W and a maximum of 45.8W, while the average power for the "With PCM" scenario is 41.6W with a minimum of 35.9W and a maximum of 48.4W. This implies that the incorporation of PCM in the refrigerator increases the average power demanded in 7%.



a) Initial day (b) Maintenance day

Fig. 4: Power demand profile for Initial and Maintenance day, with and without PCM

In relation to the electricity consumption, when the refrigerator does not have PCM, the values obtained are 709 kJ and 410 kJ for the "Initial day" and "Maintenance day" respectively. When the PCMs are incorporated in the refrigerator, these electricity consumption values are 929 and 396 kJ for the "Initial day" and "Maintenance day" respectively. Finally, for the analysed month of operation of the system, there is a slight reduction of 1.5% in the electricity consumption when the PCM are installed.

3.2 PV Production

Taking into account the daily demand for electrical energy, the proposed photovoltaic installation consists of a single multi-crystalline type module, 50Wp in STC (37WP in NOTC). The azimuth of the module is 0°, and the slope is 15°, this value is slightly higher than the latitude in order to improve the maintenance conditions. Fig 5 shows the production of the photovoltaic module, simulated in TRNSYS 16, for the month analysed (November). The average daily production of electricity is 870 kJ, with a minimum of 692 kJ on the 30th of the month, and a maximum of 1024 on the 3rd of the month.

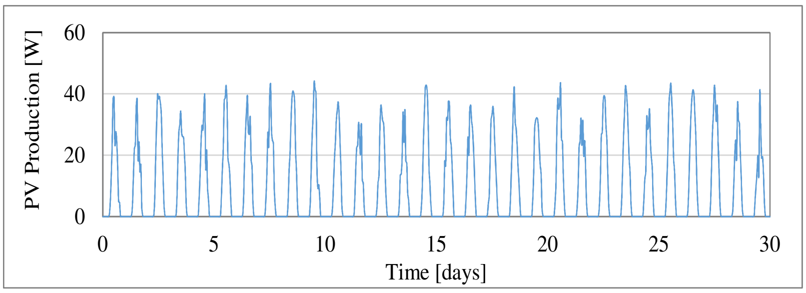
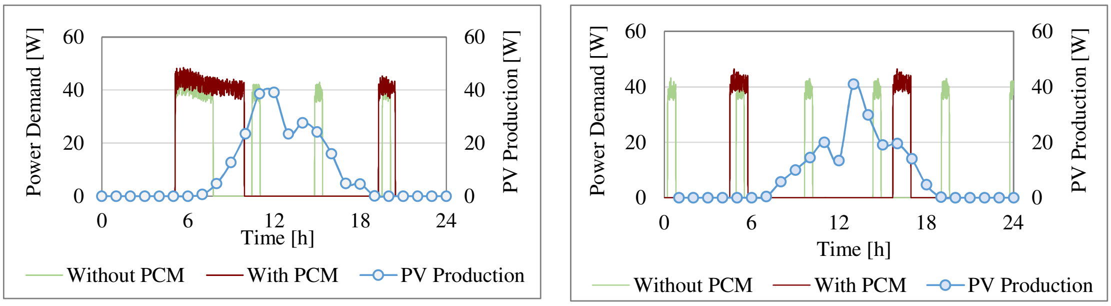


Fig. 5: Electricity production of the photovoltaic installation for analysed month

The electricity production does not match the demand, as shown in Figures 6a and 6b for the “Initial day” and the "Maintenance day" type respectively. Therefore, the installation must incorporate energy storage (thermal or electric) as is usually for the off-grid photovoltaic installations.

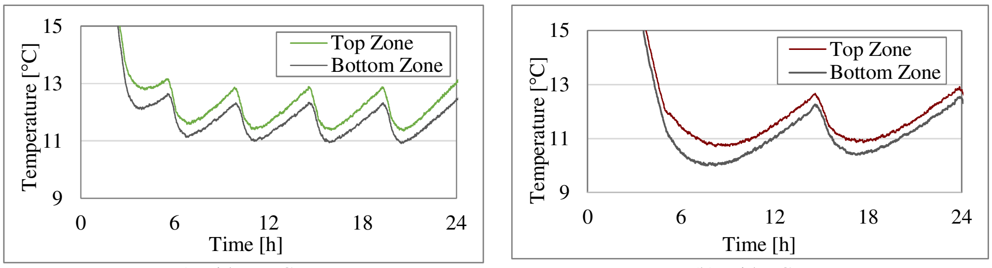


a) Initial day (b) Maintenance day

Fig. 6: Mismatch between electric production and power demand for initial and maintenance day

3.3 Evolution and stratification of product temperature

Figure 7 shows the evolution of the temperature in the top zone of the refrigerator as well as in the bottom zone, for the analysed scenarios (With PCM and without PCM). According to this information, the product temperatures in both refrigerator zones (top and bottom) are maintained within the required operating range (11 ± 2 ° C). The maxim temperature difference between the top and bottom zones is 5% for the “Without PCM” scenario and 6% for the “With PCM” scenario for the Maintenance cycles.



a) Without PCM (b) With PCM

Fig. 7: Product temperature evolution for Initial day

The data allow concluding that the influence of PCMs on stratification of product temperature is low. However, the temperature of the refrigerated product in the "With PCM" scenario is lower than the temperature in the “Without PCM” scenario. This difference of temperature between both scenarios reaches a value of 1.5°C.

The lower temperature of the "PCM" scenario is because the PCM is at a lower temperature than the product, so when the compressor stops, the heat transfer process continues until the equilibrium is reached. Therefore, it is advisable to take into account this behaviour in order to improve the control of the product temperature in the Scenario "With PCM".

3.4 Number of on-off cycles of the compressor

There are two types of operating cycles In the operation of the refrigerator: The "Initial Cycle" in which the product is cooled from the initial temperature (25 ° C) to set temperature (11 ° C); and the "Maintenance Cycle" in which the product is maintained in the required temperature range (11 ± 2 ° C). In both cycles, the compressor is “on” until the set-point temperature is reached, and then it continues “off” until the product temperature reaches the maximum allowed value.

According to the power demand profiles presented item 3.1, it is possible to verify that the number of off-on operations of the compressor are reduced from 4 to 2 for the "Initial Day" of operation, and from 5 to 2 for the "Maintenance Day" type. This implies that during the studied month, the number of off-on operations of the compressor decrease 59.7%, from 149 to 60 operations. This fact has a positive impact in the useful life of the compressor.

3.4 COP of the system

The COP was calculated according to 2.4.6, when the useful heat extracted by the evaporator was estimated by adding the heat extracted from the product, the heat gains by transmission through the enclosures, and the infiltration heat gains. The calculations were carried out for the "Initial" and "Maintenance" cycles, and for the two analysed scenarios (With PCM and Without PCM). Table 5 summarizes the results for the two analysed scenarios.

Tab. 5: COP of System

Cycle	COP Without PCM	COP With PCM
Initial cycle	2.19	1.90
Maintenance cycle	1.83	1.99

We can see that the scenario “With PCM” has a lower COP than the scenario “Without PCM” for the Initial cycle. However, the result is just the opposite when the maintenance cycle is analysed. This is because the smaller number of off-on operations of the compressor finally have a positive impact on the efficiency of the system, as some previous studies have verified.

3.5 Charging/discharging process in PCM

The charging and discharging process of PCMs can be analysed by monitoring the temperature in the encapsulation bags of PCM. Figure.8 shows the evolution of the average temperature of the PCMs located in the top, middle, and bottom zones of the refrigerator wall.

This information indicates that the PCMs located in the top and middle zones of the refrigerator wall reach the temperature required to change the phase (less than 5°C), and can storage sensible and latent thermal energy. However, the PCMs located in the bottom zone of the refrigerator wall do not reach the required temperature and only storage sensible thermal energy. This result makes necessary to adjust the integration solution of the PCMs in the bottom zone of refrigerator wall; one option can be to install insulation material in this part instead of the PCMs, and another option can be to use a PCM with a different phase change temperature.

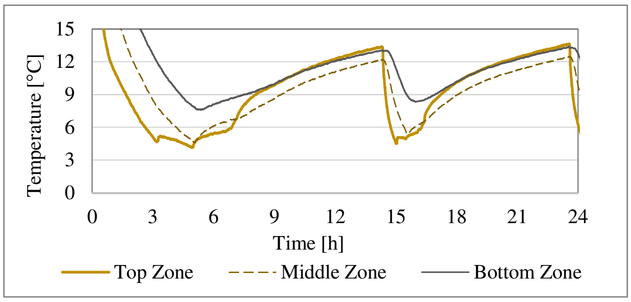


Fig. 8: Temperature evolution in the PCM

In relation to the energy rate transferred during the charging /discharging process of the PCM, the values obtained for the maintenance cycle were 177 W for charging process, and 44 W for the discharging process. These values can also be improved by other actions, such as the use of materials with better thermal conductivity to carry out the integration of PCMs.

3.6 Raise temperature time

The raise temperature time, correspond to the time from the compressor stops (off), until the refrigerated product reaches the maximum allowable temperature. The measurements were made according to “The Rise Temperature Test” included in the standards EN 62552 for household refrigerating appliances (IEC, 2013). Table 6 presents the duration of the different cycles (“Initial” and “Maintenance”), according to the state of the compressor ("on" and "off") and for each analysed scenario ("With PCM" and "Without PCM").

Tab. 6: Cycle duration time and raise temperature time

Description	Without PCM [h]			With PCM [h]		
	On	Off	Total	On	Off	Total
Duration of Initial Cycle	2.63	2.72	5.35	4.78	9.38	14.16
Duration of Maintenance Cycle	0.55	4.07	4.62	1.18	8.08	9.26
Raise Temperature Time		5.01	5.01		11.31	11.31

In general, the incorporation of the PCM in the internal side of the refrigerator increases the duration of the different cycles as well as the raise temperature time of the refrigerated product. According to these data, the raise temperature time changes from 5.01 h to 11.31 h; that means an increase of 126%. Thanks to this, the size of the energy storage with the electric batteries can be reduced as item 3.7 exposes.

3.7 Sizing of electrical battery

In order to sizing the electric storage with lead-acid batteries, we first consider the results of daily electrical consumption, presented in 3.1, and secondly we select a four-day autonomy for the system. According to this, for the “Without PCM” scenario, a battery bank should have a capacity 2345kJ, which correspond to 51Ah C20 for a voltage of 12V and a discharging time of 13.1h.

On the other hand, for the "With PCM" scenario, the initial capacity of the battery bank would be 2263kJ, which can be adjusted, taking into account the increase of the raise temperature time of the refrigerated product in this scenario. In this way, the capacity of battery bank can be reduced to 1996 kJ, which correspond to 46 Ah C20, for a voltage of 12V and a discharging time of 18.5h.

The result means a decrease of 10% in the size of the electric battery bank when the “With PCM” scenario is compared with the “Without PCM scenario”. This reduction is low, and the system should be optimized in order to improve the performance of the thermal storage with PCM.

Because of this, the experimental results will be used for validating a model and analysed different parameters in the system, such us the thickness of the PCM slab, the thickness of the insulation, and the velocity of the fans for the force convection.

4. Conclusions

This study analysed the performance of a commercial horizontal refrigerator, of 350 litres of capacity, with a direct-current compressor powered by a photovoltaic module. The refrigerator will be used later in a small-scale cheese processing at an operating temperature of 11°C. The system has an electrical storage with a lead-acid batteries and also the refrigerator incorporates a thermal storage with an inner slab of PCM, next to evaporator-wall, with a thickness of 8mm and phase change temperature between 5 and 6°C.

The analysis considers two scenarios, one is the refrigerator “Without PCM” and the other is the refrigerator “With PCM”. From the experimental data, two electrical power demand profiles have been created for a full month of operation (With PCM and Without PCM). The month selected for analysis was November, since this month has the lowest photovoltaic production throughout the year.

The incorporation of PCM, does not have a high impact in the stratification of product temperature, nevertheless the temperature of the refrigerated product is lower when the Refrigerator has the PCM slab. This is because the discharging process of the PCM continues once the compressor stops in each cycle. Taking into account, this behaviour the control system of product temperature can be improved.

Regarding to charging process of PCM, it was possible to verify that the PCM located in the top and middle zone of the refrigerator wall reach the temperature required for the freezing and took advantage of the latent energy storage; however, the PCM located in the lower do not reach the required temperature. This result makes necessary to adjust the integration solution of the PCMs in the bottom zone of refrigerator wall in order to improve the analysed thermal storage option.

The PCM gives more inertia to the system, since the number of daily on-off cycles of the compressor, has a reduction of 59.7% for an analysed month. This fact has an indirect positive impact in the useful life of the compressor and in the electricity consumption. With regard to this electricity consumption there is an increase of 31.0% in the “Initial cycle” and a decrease of 3.5% in the “Maintenance cycle”. Finally, for the full-analysed month, there is a slight reduction of 1.5% in the electricity consumption.

As far the raise temperature time concern, this value increases 126%, going from 5.01h to 11.31h. This implies that conventional energy storage with electric batteries can be reduced about 10% for the analysed application. This reduction is low, and the system should be optimized.

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