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Techno-Economic Assessment of an Air-Multiple PCM Active Storage Unit for Free Cooling Application

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Abstract: A latent energy storage (LES) unit is presented in this paper for free space cooling and ventilation application. The unit includes multiple phase change materials (PCM) to advance the thermal performance of common LES units. It is composed by metallic rectangular panels containing commercial paraffins with melting temperatures ranging among 20 °C and 25 °C and surrounded by air channels. The average cooling load of the unit corresponds to approximately 1 kW over 8 h. It fulfils the peak ventilation cooling load during summer of an office building in Portugal. The study provides a techno-economic analysis and the environmental benefits of the LES technology compared to a traditional air conditioning (AC) unit for the cooling and ventilation of an office building. During daytime, the air-multiple PCM unit allows reducing the energy consumption by nearly 200 kWh. The full charging of the PMs during nighttime, requires significant energy consumption due to the high air flowrate demand for full solidification. The competitiveness of such units can be achieved by introducing fins into the panels, allowing double the energy savings. In an overall perspective, the unit presents several benefits such as lower initial cost and reduced maintenance requirements (non-use of refrigerants and batteries) that also allows better personal health issues when related to traditional ACs.

Keywords: phase change materials; free cooling ventilation; techno-economic analysis; case study

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1. Introduction

Nonresidential buildings in Europe encompass one fourth of the building stock, with office buildings accounting among the most significant contributors to demand growth [1]. Over the years, there has been a continuous increase in heating, cooling and ventilation (HVAC) systems, particularly in the developing countries, within offices and nonresidential buildings corresponding to the main energy consumption parcel [2]. Hence, developed countries are looking for renewable solutions to secure such needs. This figure is, however, still below the EU target of 20% energy being produced by renewable sources [3]. Latent energy storages (LES) are commonly used in buildings, jointly with HVAC systems, provided individually and incorporated into construction materials (e.g., construction wall, roof and ground) [4]. In particular, air-PCMs LES applications can provide the required cooling and ventilation demands or reduce the temperature swings within buildings. Such applications are commonly denominated as "free cooling". A differential temperature among the air and the melting of the PCM must range between 3 and 5 °C to assure enough heat transfer [5]. Therefore, the PCM melting temperature is a critical factor to enhance the buildings performance for different climatic conditions [6]. Several studies on active air- single PCM units applied to free cooling are presented in the literature. Iten et al. [4] present a comprehensive review on the air- PCM application for the air conditioning of buildings. Overall, for free cooling of buildings, such units require careful selection of the PCMs such that the melting and solidification points guarantee a complete charging and discharging process. This depends mostly on local climate conditions. Another important aspect to consider while applying PCMs, is its general low thermal conductivity, usually between 0.2 and 0.7 [W/m K] [7]; requiring heat transfer improvement techniques to enhance the charging and discharging rate of energy [8]. Lately, multiple PCMs are stated in the literature as a way to improve LES systems, presenting the following advantages: higher heat transfer rate, particularly during the change of phase [9]; keeping a higher transport temperature difference for the heat transfer process in charging and discharging processes [10]; quicker charging and discharging processes [11]; preserving a steady heat flux from the PCM and the heat carrier fluid [12]; and achieving a maximised storage capacity and melt fraction [13].

LES are mostly analysed on an experimental or numerical dimension, whereas commercial applications remain limited. In fact, it is noted that only in a few of these studies, has an economic analysis been included [14]. Moreover, regarding cooling applications considering PCMs, limited works considers such investigation. For instance, Chaiyat [15] developed a model to perform an economic analysis of an air conditioner assisted with a pack bed of PCM balls in order to improve its efficiency. It has been found that the electrical consumption of the modified air-conditioner could be decreased to around 3.09 kWh/d. The saving cost from the PCM bed could be 9.10% of 170.03 USD/y, and the payback period corresponded to around 4.15 years. Later, Boccardo et al. [16] investigated the economic performance of thermally active building systems (TABS), radiant ceiling panels with PCM and a traditional all-air system (e.g., variable air volume system) in an open-plan office. Different cooling loads have been studied and the global cost and the payback period of each system has been compared. It was observed that TABS corresponded to the cheapest option. The costs estimated for PCM ceiling scenarios were higher, however, they corresponded to a valid alternative when TABS were not viable (e.g., renovation projects). In addition, for high cooling loads, PCM ceiling panels were a good option as they were only marginally more expensive than the all-air system. Overall, the cooling energy corresponded to the lowest cost component of the global costs (over 30 years), suggesting that the economic focus must be mainly on initial costs, maintenance and replacement in order to obtain substantial economic savings. Recently, the effect of the integration of PCMs into buildings also employing natural or mechanical ventilation has been analysed by Mechouet et al. [17]. The application of a mechanical ventilation rate of 6 air change per hour (ACH) with a 6mm thick PCM panel allowed to reduce the cooling energy from 6 to 21% (depending on the climatic zone in Morocco) compared to the use of mineral wool insulation. For instance, in a building located in Marrakech, such a solution, for cooling purposes, corresponded into a dynamic payback period of 11 years.

Overall, there is still a lack of adequate information on real potentials and practical aspects of PCM application in buildings (e.g., techno-economic), namely on independent air-PCM systems to provide cooling of buildings. On this segment, this paper provides a contribution to knowledge by presenting the application of an air-multiple PCM unit for the free cooling ventilation of an office building located in Portugal. The paper focuses on a techno-economic analysis of such unit and a conventional air conditioning system also considering the environmental aspects. This analysis intends to bridge the LES application gap in buildings as other relevant applications. Such standalone analysis corresponds to an essential input for applied research, looking for a higher level of readiness and its market uptake.

2. Structure of the Work

The work is structured as displayed in Figure 1. Firstly, the required cooling ventilation, building occupancy and thermal comfort conditions for the case study building are specified (Section 3.1). This will allow sizing the two cooling units: air-multiple PCM (Section 4.1) and the air conditioning (Section 4.2). The sizing of the novel air-multiple PCM unit considers the works of the author as input data, namely: validity of the numerical model in Iten et al. [18], followed by its design in Liu et al. [19]. The presented approach enables the techno-economic analysis, i.e., the focus of this paper (Section 5). This analysis includes the running costs (e.g., energy consumption of required fans and systems) and the capital and maintenance costs of the proposed unit and a conventional AC for the cooling ventilation of a case study building. Moreover, the environmental benefits are identified for each unit.

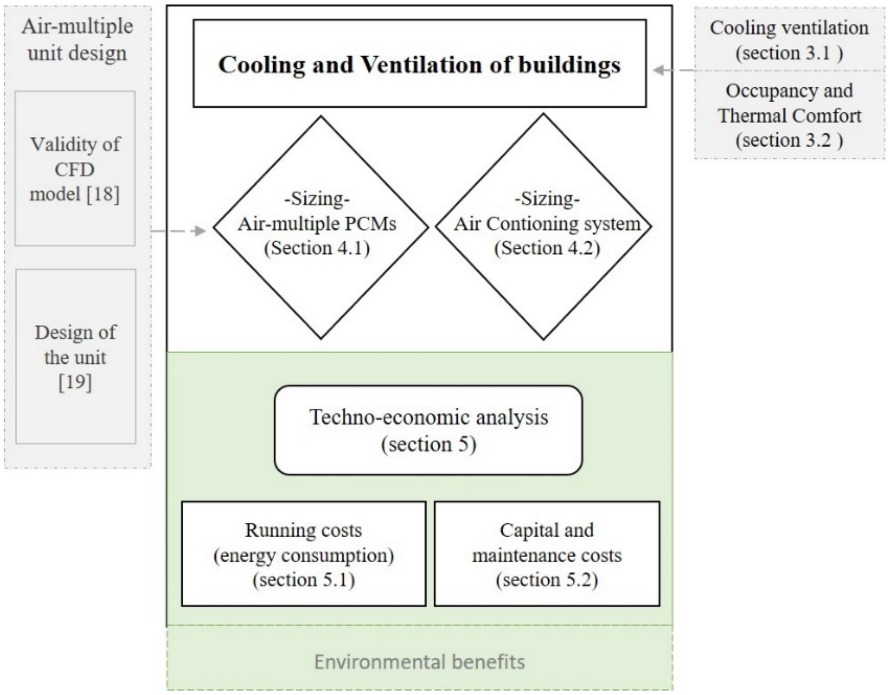

Figure 1. Structure of the work: techno-economic analysis and environmental benefits of air-multiple PCM unit and AC system.

3. Requirements

3.1. Cooling Ventilation Load

The current work presents a case study of an office building with 200 m^2 located in Castelo Branco, Portugal and accommodating 20 occupants. The cooling demand for the case study building is focused only on the occupants, excluding the other factors such as equipment, appliances and infiltrations, in order to provide a comfortable temperature of the fresh air supplied. The recommended air supply for office buildings corresponds to 35 m^3/ (h. occupant) according to the Portuguese Directive [20]. Therefore, the total cooling ventilation load required corresponds to 700 m^3/h. Such a flow rate needs to be provided by the fans of the air-multiple PCM unit as well as by the air conditioning system.

3.2. Occupancy and Thermal Comfort

The predominant occupancy profile for office buildings is commonly considered from 9:00 to 18:00 [16]. For the thermal comfort, for the adaptive thermal comfort temperatures, the external temperature and the occupant's perceptions have been considered. For conditioned buildings, the limit of comfort conditions corresponds to 30 °C for an external temperature of 30 °C [21]. For the sizing of the units, cooling takes place when the external temperature is higher than 30 °C, corresponding to overheating (i.e., discomfort conditions).

4. Sizing of the Cooling Ventilation Units

4.1. Sizing of the Air-Multiple PCM Unit

(i) Validity of the CFD model [18]

The design of the air-multiple PCM was performed by a computational fluid dynamics (CFD) model using FLUENT 15.0 software. The model has been previously validated by the author in Iten et al. [18] with the experimental data presented in Iten et al. [22,23]. The experimental apparatus included an exhaust fan, an air-PCM unit, a portable air conditioner, electrical coils, a data logger, a personal computer (PC) and measurement equipment (thermocouples and anemometer) (Figure 2). The experimental uncertainty has been determined in Iten el. [22] and is presented in Table 1.

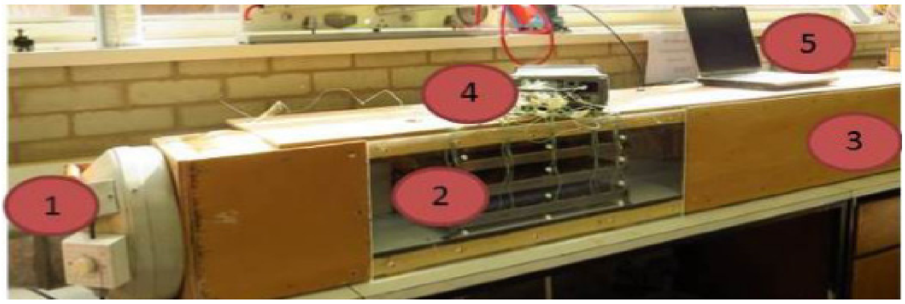

Figure 2. Testing rig (1. Exhaust fan; 2. Air-PCM unit; 3. Heating/Cooling unit; 4. Data logger; 5. Laptop) [23].

Table 1. Experimental uncertainty [23].

Parameter	Equipment	Uncertainty
PCM temperature	K-type thermocouples, Data logger	1.3%
Air temperature	K-type thermocouples, Data logger	1.6%
Air velocity	Anemometer	0.16%

In the experimental testing, the inlet air temperature has been setup constant at 38 °C (discharging process) and 12 °C (charging process), for a constant air inlet velocity of 2.5 m/s. Such temperatures correspond to extreme daytime temperature (noon to 4 p.m.) and nighttime temperature (midnight to 7 a.m.) in Mediterranean Countries [24]. The initial temperature of the PCM for each testing has been setup at 16 °C (discharging process) and 30 °C (charging process). The PCM temperatures have been measured by thermocouples along the panels and at the air outlet and recorded with a data logger until the phase change of the PCM panels were complete. The thermophysical properties of the materials applied into CFD modeling are presented in Table 2.

Table 2. Thermophysical properties of selected materials [22].

Material	Melting Temperature (°C)	Density (kg/m^3)		Thermal Conductivity (W/m. °C)	Specific Heat Capacity (kJ/kg. °C)
		Solid	Liquid		
PCM	23–25	880	760	0.20	2000
Steel	-	8030		16.27	0.502
Air	-	1.23		0.02	1006

Iten et al. [18], namely, Figures 3 and 4, present the experimental and numerical results for the PCM temperature (last point where phase change takes place) and air outlet temperature (exit of the air channel). Good agreements have been achieved between the experimental and numerical data with a max. error of 2.6% for the PCM temperature and 1.5 % for the outlet air temperature.

(ii) Design of the unit [19]

The design criteria of the unit considered the building occupancy and the thermal comfort (as described in Section 3.2). Matching these two criteria allowed to identify the required cooling demand and, more precisely, the required cooling period. Figure 3 displays a typical daily temperature profile during summer in Castelo Branco, Portugal [25] and considered for the design of the unit in Liu et al. [19]. This profile corresponds to average daily temperature observed in the Summer, namely between 21 June and 21 September. From Figure 3 it is observed that the PCM panels need to be fully charged (i.e., solidified) during nighttime: 21:00 to 07:00, when night temperature is below the melting temperature. While during daytime, between 11:00 and 18:00, the PCM panels need to be fully discharged (i.e., melted) to provide free cooling to the building. During this period, predominant occupancy is observed, and the external temperature reaches more than 30 °C (i.e., overheating period).

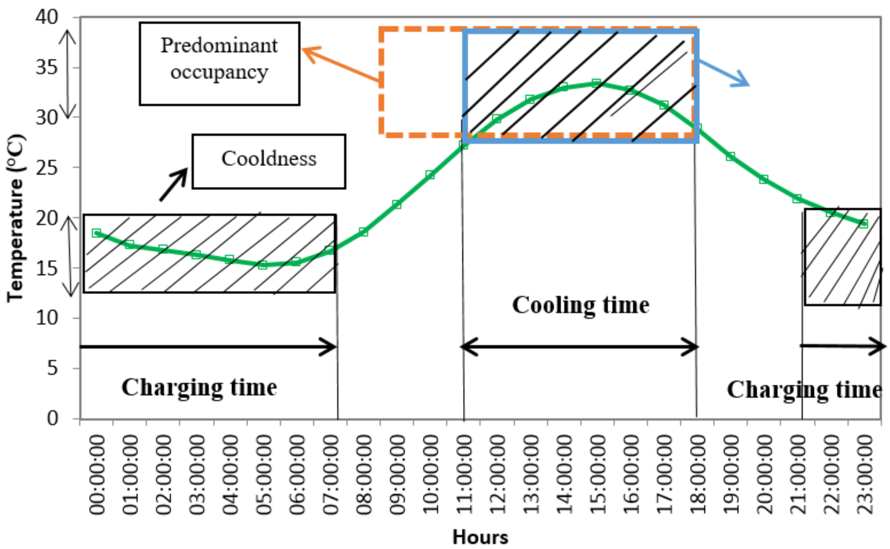

Figure 3. Typical daily temperature profiles for the summer in Castelo Branco, Portugal (Aguiar and Coelho [25]; Liu et al. [19]).

The validated model (transcribed in section *i* from Iten et al. [18]), has been further extended for the design and optimisation of the air-multiple PCMs unit in Liu et al. [19]. For the multiple PCM unit, in addition to the PCM included in the experimental testing and numerically validated (melting temperature between 23 °C and 25 °C), a PCM with a melting temperature between 18 and 20 °C was selected and accurately integrated in the model as it presents same structural and physical behavior. The addition of a PCM with inferior melting temperature permitted that a temperature difference sustained between the PCM and the air in the flow direction, enhancing the heat exchange rate. Furthermore, a PCM with a melting point at 20 °C fits with the occupant's comfort temperatures as well as with the local climatic conditions for charging and discharging. Each panel of the unit was filled halfway with one PCM and another half the other. The optimisation of the unit was studied by the author and reported in Liu et al. [19]. The optimisation focused on the dimensions of the panels and on the charging and discharging flowrates to assure that a full cycle was undertaken for the storage and release of coolness. The optimal dimensions and flowrates are listed in Table 3. For these optimised variables, the hourly delivered cooling load varies from 0.4 to 1.46 kW with an average load corresponding to 1.1 kW [19].

Table 3. Multiple PCM unit details and operating conditions [19].

Total PCM mass	102.6 kg
Mass per panel	34.2 kg (17.1 kg/ PCM type)
PCM panels height	0.03 m
PCM panels length	1.5 m
PCM panels width	1 m
Discharging air mass flow rate	734.7 m^3/h
Charging air mass flow rate	5877.6 m^3/h
Average cooling load	1.1 kW

Considering 20 occupants in the case study building, for a fresh air flowrate of 700 m^3/h (described in Section 3.1) and guaranteeing the comfort temperatures (below 30 °C—Section 3.2), the required cooling load and ventilation corresponds to 1 kW. As the required cooling load for the case study building is assured by the air-multiple PCM presented in Table 3, the techno-economic analysis has been carried out for this storage unit.

4.2. Sizing of the Air Conditioning System

A convectional cooling unit has been identified for this study aiming at the comparison with the PCMs unit, considering a cooling load of 1 kW. The AC unit corresponds to a ceiling cassette with a four-way blow system and a centrifugal fan, fulfilling the fresh air requirements (734.7 m^3/h). The energy consumption of the fan is determined by Equation (3), further detailed.

5. Techno-Economic Analysis

A techno-economic analysis has been undertaken by determining the running costs (i.e., energy consumption), capital and maintenance costs of the storage unit and the conventional AC unit followed by the payback time.

5.1. Running Costs (Energy Consumption)

A fan has been selected, considering the flow rate the air duct provided by the air multiple PCM unit: 734.7 m^3/h and 5877.5 m^3/h for the daytime (e.g., discharging) and nighttime (e.g., charging), respectively. The total pressure drop, related to the frictional pressure loss, corresponded to 30 Pa (e.g., discharging) and 484.38 Pa (e.g., charging) [19]. In order to fulfil such requirements, a fan ranging from 0.036 kW (e.g., discharging) to 0.853 kW (e.g., charging) has been selected.

(i) Air-multiple PCM

The total energy consumption of the air-multiple unit is associated with the operation of a fan (W_{fan}) at the two flow rates (charging and discharging) and consequently to the two powers ($P_{fan,1}$ and $P_{fan,2}$). Hence, its consumption corresponds to the sum of the fan operating at lower power (*fan*,1) over 8 h (daytime) and at a higher power (*fan*,2) over 9 h (nighttime) for 65 days (June–September) as follows:

$$W_{fan} = \left(P_{fan,1} \times t\right)_{charging} + \left(P_{fan,2} \times t\right)_{discharging} \tag{1}$$

(ii) Air conditioning system (AC)

The energy consumption of the AC unit (W_{AC}) and the fan (W_{fan}), running 8 h a day over 65 days (June–September), are determined by Equations (2) and (3) as follows:

$$W_{AC} = P_{AC} \times t \tag{2}$$

$$W_{fan} = P_{fan} \times t \tag{3}$$

5.2. Capital and Maintenance Costs

The proposed air-multiple PCM unit comprises commercially available PCMs (e.g., paraffins) fairly inexpensive (7 GBP/kg) [26]. Paraffins present good combability with most materials, namely with metallic container. Hence, the cost of its encapsulation is highly competitive. Such PCMs also suffer from insignificant supercooling or phase segregation, presenting a longstanding stability. This ensures that the PCM performs in good conditions after many solidification and melting series. Overall, the PCMs unit requires no significant maintenance, ensuring substantial cost reduction. The two commercial paraffins encapsulated into rectangular panels make up a total volume of 0.045 m^3 and weight of 102.6 kg. Apart from the paraffins, the proposed unit includes its encapsulation, fan and pipework. The encapsulation comprises rectangular containers of steel and introduced into a rectangular ducting. The space and labor of installation are considered to be similar for both systems and therefore are not included in the analysis (e.g., interconnection with building, external unit).

The air multiple PCMs unit and the AC present yearly energy consumption of 517.67 kWh and 219.02 kWh, respectively. Table 4 shows that the PCM unit presents a considerable inferior energy consumption (18.67 kWh) than the traditional AC (219.02 kWh) throughout the day. This enables a saving of 200.35 kWh per year relating to the AC unit. The proposed unit, however, presents a predominant energy consumption owing to the fan operation during the period. Nevertheless, the PCM unit involves a lower capital cost than the AC system. It also presents a lower maintenance cost as it requires mostly the cleanness of the air filters. In Portugal, considering a bi-hourly electricity package (0.1890 GBP/kWh: daytime; 0.0978 GBP/kWh: nighttime [27]), the yearly cost corresponds to GBP 52.3 and GBP 41.4 for the PCM unit and AC, respectively. To promote the competitiveness of the unit, the charging process of the PCMs requires further improvement during night-time. For instance, improving the heat transfer inside the PCM panels will require less air flow rate for its full charging and so to reduce the fan size and running costs. The insertion of fins in similar PCM panels, following Stritih's study [28], has revealed reduced natural convection (e.g., dominant phenomena during melting), however, a better heat transfer over solidification, enabling to decrease the solidification period by 40%. Considering such figures, three air-multiple PCM scenarios have been analysed: (i) current unit, (ii) improved unit (including fins and considering 40% solidification time reduction according Stritih [28]) and (iii) ideal unit (solidification time is similar with the melting time). The analysis has been performed for the common 20 year lifetime of ACs. Figure 4 presents the total cost (investment, running and maintenance) of each unit over the lifetime and the savings achieved by the three units in comparison to the traditional AC system.

It is observed that the energy savings for each air-multiple PCM unit increases over the years. For instance, for the improved unit—including fins—after 20 years, it presents the double of savings compared to the current (proposed) unit. Regarding the ideal unit (melting time same as solidification time), the savings can be greater than 11 times compared to a traditional AC system. Such ideal solutions are, however, complex to achieve, because while high conductive elements are introduced within the PCMs panels (such as fins) to reduce solidification time, they compromise the natural convection during melting. Given that the viability of such technology relies mostly on the running costs (Table 4), such analysis and respective results highlight how such measures can have impact throughout its lifetime. Overall, this analysis shows that such units can become economically competitive with the inclusion of fins by significantly improving the charging process. Moreover, they benefit from the maintenance point of view as during their lifetime this is related mostly the cleanness of air filters.

In addition, any air-multiple PCM unit for free cooling presents several environmental benefits such as no need of refrigerants (e.g., CFCs, HFCs and HCFCs) that are significant responsible for the ozone depletion and applied into AC. Such refrigerants also involve cautious management for the AC pull to pieces for recycling or deposited in landfills. The US Environmental Protection Agency such as further environmental agencies are lawful to execute fines up to GBP 16000 for failing to conform with the present legislation. Commonly, dedicated businesses are responsible for handling the discarding of AC units. Indeed, AC can also guarantee individual health issues, however, failing with satisfactory maintenance, they can be a health threat. Muddy components can permit allergens, insecticides such as other elements to enter from the outside atmosphere, compromising the indoor air environment. In addition, the extended contact to such contaminants can affect health difficulties, counting allergies, asthma and eye, nose and throat irritation.

Table 4. Equipment capital and running cost.

	Air-Multiple PCM Unite		Traditional AC System
	Daytime	**Night-Time**	
Capital cost	PCMs: GBP 718.2 Steel encapsulation: GBP 313 Air duct: GBP 107 Fans: GBP 1100.5		Ceiling cassette system: GBP 2099 Fan: GBP 254.2
Maintenance cost	GBP 15 (yearly: cleanliness of air-filters)		GBP 70 (yearly: hygiene of the coils, air-filters and leaks detection/remediation)
Average cooling load	1 kW		1 kW
Motor Power (fans/air-conditioning)	0.036 kW (daytime) 0.853 kW (night-time)		0.059 kW/0.362 kW
Yearly running hours	Daytime: 8 h per day (520 h) Nighttime: 9 h per day (585 h)		8 h per day (520 h)
Yearly energy consumption (daytime)	18.67 kWh		219.02 kWh
Total yearly energy consumption (daytime and night-time)	517.67 kWh		
Electricity cost [27]	Day tariff (8 h–24 h): GBP 0.189 /kWh Night tariff (24 h–8 h): GBP 0.098 /kWh		
Yearly running cost (daytime)	GBP 3.53		GBP 41.4
Total yearly running cost (daytime and night-time)	GBP 52.3		GBP 41.4

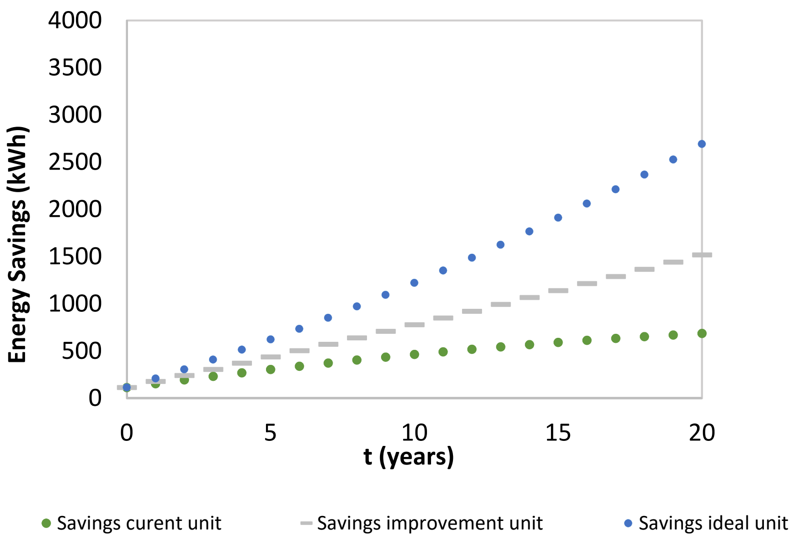

Figure 4. Energy savings for current air-multiple unit, improved unit and ideal unit.

6. Conclusions

The scope of this research was to perform a techno-economic analysis and environmental benefits of a low-carbon technology (e.g., air-multiple PCM unit, previously studied and designed by the author) and a traditional air-conditioning (AC) unit for cooling and ventilating application. There is a lack of such analysis, specifically on the economic side of such upcoming technology, being crucial for industrial applications and for its uptake in the market.

The analysis has been performed to a case study, involving the space cooling of an office building in Portugal. Considering the occupancy of 20 occupants, for a fresh air flowrate of 700 m^3/h and guaranteeing the comfort temperatures, the required cooling load and ventilation corresponded to 1 kW. The capital, maintenance and running costs have been estimated for such cooling capacity of both systems. The labour costs and space requirements have not been considered, as similar costs were expected for both units. Regarding the capital costs, both present a similar cost, however, for the maintenance, the AC system presents a 4.5 times higher cost than the air-multiple PCM unit (mostly related with cleanliness of air filters) during their lifetime. Concerning the running costs (most impact on the overall costs), the study showed that air-multiple PCMs unit, during daytime, enabled a reduction in energy consumption (greater than 5,5 times) comparing to a conventional AC system. The proposed PCM unit, however, turns out compromised when considering the energy consumption linked to the charging of the PCMs during the night period. An analysis has been performed considering the whole lifetime of such units to evaluate the impact of a heat transfer improvement method (e.g., insertion of fins in PCM panels) on the running costs—the major costs of such units. Such method enables a greater heat transfer during solidification time and, consequently, a lesser air flowrate is required for its charging. The results show that such method can duplicate the energy savings of the current air-multiple PCM unit during its lifetime.

Looking at the environmental benefits, the air-multiple PCM units present several environmental benefits such as the non-use of refrigerants and disposal requirements, as well as the benefit of a better individual health conditions when compared to traditional ACs.

This study also showed that air-PCM units require, for any application, a combined analysis of charging (e.g., solidification) and discharging (e.g., melting) processes. In addition, if for instance, the charging period is achieved “passively” without energy consumption, then, consequently, the discharging (cooling) load will be more efficient or cheaper.

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