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Decarbonisation pathways of 100 % electrified building facilities: An experimental and simulation case study in a Mediterranean area☆

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ABSTRACT

Decarbonising the built environment is crucial for the European Union to achieve its 2030 and 2050 climate targets, as outlined in the European Green Deal. Heating and cooling account for nearly 80 % of the total final energy consumption in buildings. Typically, the decarbonisation of a building's heating and cooling facility involves replacing the fuel-based heating system with an alternative energy source. However, these solutions do not apply to all buildings in the EU. There are areas of the EU in which heating and cooling can be 100 % electrified, without any connection to a district heating or cooling grid, nor to other energy carrier grid like gas. These scenarios are seen, for example, in some service buildings located in Mediterranean areas of the EU. This paper shows a practical pathway for the decarbonisation of an office building by improving its energy facilities. The building is located in a Mediterranean area, and it is 100 % electrified. The heating and cooling demand of the building, along with its entire electricity consumption, are measured as a starting point. This data enables the calibration of an energy model of the building carried out in EnergyPlus. The energy efficiency measures proposed to decarbonise the building are analysed using the calibrated energy model of the building, enabling more realistic calculations about the impact of these measures. Some results indicate that the use of variable speed pumps can reduce the electricity consumption for pumping water by almost 8 %, that a dimming controller of the lighting facility could reduce the lighting consumption by 25 % and that a photovoltaic facility, which occupies all available roof space, could produce 20 % of the building's total annual electricity consumption. The novelty of this work is to create a pathway to decarbonise 100 % electrified buildings located in Mediterranean areas and to understand their decarbonisation possibilities, thereby providing practical insights to help the decision-making process to reduce the carbon footprint of this type of buildings.

1. Introduction

The decarbonisation of buildings will play a key role in reaching the European Green Deal objectives for 2050 [1]. Under the Fit for 55 package, the European Green Deal also seeks to reduce greenhouse gases (GHG) by 55 % compared to 1990 levels by 2030. The *Renovation Wave* strategy [2] is linked to the European Green Deal. Its objective is to accelerate building renovations, improve energy efficiency, and reduce carbon emissions.

The energy consumption in buildings located in the European Union (EU) accounts for approximately 40 % of final energy consumption in Europe and is responsible for around 36 % of its GHG emissions [3]. The reduction of GHG emissions is linked to the use of more efficient systems. In 2012, the Energy Efficiency Directive was released, emphasizing the importance of innovative solutions to increase energy efficiency, particularly in buildings [4]. This directive was reviewed in 2023, demonstrating the EU's ambition for energy efficiency and building renovations and its importance in reaching climate neutrality by 2050 [5]. In the latest version of the directive, the principle "energy efficiency first" was included, which is linked not only to reducing fossil fuel use, but also to reduce the overall energy consumption by improving energy efficiency.

The Energy Performance of Buildings Directive (EPBD) [6], launched in 2002, is the most important directive that deals with decarbonising the building stock. It introduced the concept of nearly zero-energy building (NZEB). The EPBD established that, from January 2021, all new buildings must comply with NZEB standards [7]. The 2024 recast of the EPBD introduces a definition for Zero-Emission Buildings (ZEB), which is a building with a very high energy performance, requiring

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Nomenclature

GHG
EU
EPBD
NZEB
ZEB
MS
JRC
REHVA
EEM
PV
DHW
AC
BEM

$\dot{Q}$
$\dot{m}_{water}$
T_{IW}
T_{RW}
P_{elec}
COP
EIR
$EIRfTEMP$
$CAPfTEMP$
PLR
$EIRFfPLR$
P_{nom}
$P_{Heat\ pump}$

almost no energy and generating insignificant on-site CO_2 emissions. A study conducted in 2025 reviews how the Member States (MS) of the EU define these concepts of NZEB and ZEB [8], concluding that the definitions of energy thresholds should be stricter.

All these policies have helped to reduce GHG emissions in buildings. They had an impact on, for example, the building code of Spain.[1] It started in 2006 and has been modified several times since then, becoming more restrictive on energy demand and consumption thresholds in its last modification in 2019. In 2020, a study carried out by authors of the European Commission's Joint Research Centre (JRC) reviewed the last 50 years of EU energy efficiency policies in buildings [9]. Furthermore, the Federation of European Heating, Ventilation, and Air Conditioning Associations (REHVA) Task Force wrote a guidebook in 2022 about the fundamentals of energy efficiency measures in existing buildings [10].

There are several ways to decarbonise the building stock. One is the reduction of the energy demand. Usually, the reduction of energy demand is linked to the improvement of the building envelope (see [11,12] for detailed reviews on this). In addition to studies evaluating the building envelope, several authors have studied the quantification of thermal bridging: [13,14,15]. Other authors have proposed specific designs of building envelopes to reduce the thermal bridges in residential buildings, and they estimated that it can lead to a reduction of the heating demand between 16–22 % [16].

Improving the energy efficiency of the facilities is another way to decarbonise buildings. The energy savings achieved by the application of a range of energy efficiency measures (EEM) can be estimated. For example, in Austria, from 2000 to 2017, 23 million MWh of heating was saved, and almost 27 million MWh in Switzerland [17]. Intermittent heating is able to reduce energy consumption by 14 % [18]. The replacement of gas boilers with heat pumps for space heating can lead to CO_2 emission reductions of about 40–70 % in different residential buildings [19,20]. A report made by the JRC, following the REPowerEU plan,[2] estimated that replacing 30 million fossil fuel individual boilers in residential dwellings with heat pumps could lead to a reduction of 36 % of the gas and oil consumption in the affected residential dwellings [21]. A recent study conducted in 2025 demonstrated that R290 heat pumps can lead to a non-renewable primary energy reduction of 20 % when compared with condensing boilers [22].

The use of energy storage systems can contribute to the improvement of the performance of heating and cooling systems. They can increase the water volume in the hydronic system, which enables the facility to maintain a high level of inertia when heating or cooling demand varies, thereby reducing the start/stop of the generator. Several studies propose different energy storage approaches to improve the facilities' energy efficiency or make them more cost-effective [23,24].

Another type of measure that can be implemented in buildings is the renewable energy production, for example, renewable electricity from a photovoltaic facility (PV). The use of PV for self-consumption could save 300 tCO_2/ year per GWh of household PV consumed [25]. In another study, the authors estimated that the rooftops in the residential sector have the potential to produce 1.5 times more electricity than the current electricity demand [26]. The installation of 3 MW of PV in the University College Dublin campus can reduce CO_2 emissions by 26 % [27]. The connection of PV facilities with Air Conditioning systems could reduce CO_2 gas emissions by 60 % [28]. In another study, the authors demonstrated that a PV facility connected to a heat pump that produces Domestic Hot Water (DHW) can reduce CO_2 gas emissions by 82 % [29]. PV facilities cannot only contribute to renewable energy production but also enhance the efficiency of heating and cooling systems. A study that analyses a water/water heat pump connected to a PV facility, demonstrated that the PV electricity production efficiency and the performance of the heat pump could be improved, making the system able to reduce its energy use by 10 % [30]. A similar study, conducted in this case with an Air Conditioning (AC) split system, demonstrated an increase of 18 % in the energy efficiency [31].

To measure the impact of EEMs, the different types of measures need to be compared with the current energy consumption of the building. Building Energy Modelling (BEM) is a tool to estimate the impact of different EEMs and provide help in the decision-making process. There are several BEM tools available, including TRNSYS [32], DeST [33], DOE-2 [34], and EnergyPlus [35]. One of the issues with these types of tools is the accuracy. Usually, the results of these simulations are not close to the real energy consumption of the building, as they are based on theoretical assumptions and calculations. For this reason, experimental data are crucial to calibrate these simulations. Once the simulation is calibrated, the different EEMs can be compared with the initial consumption and their impact can be estimated.

In terms of Mediterranean-focused decarbonisation studies, some authors explore these buildings. For example, a study carried out at the Polytechnic University of Valencia analysed the possibilities to disconnect some buildings from the central boiler system and use waste heat with a heat pump from a data centre to provide the heating demand. One of the scenarios proposed by the author could lead to a reduction in GHG emissions of 207 tons [36]. Another study studied the decarbonisation opportunities in the heating facility of a school located in Palermo (Italy). The authors proposed a system based on Road thermal collectors, borehole thermal energy storage, and water/water heat pumps to

[1] https://www.codigotecnico.org/DocumentosCTE/AhorroEnergia.html.

[2] https://commission.europa.eu/strategy-and-policy/priorities-2019–2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en.

replace its current gas boiler, demonstrating a potential CO_2 emission reduction by 40 % [37].

Following the Mediterranean buildings line of research, a case study developed in the city of Valencia (Spain) analysed the Valencia building stock with an urban building energy model. The authors outlined that retrofitting the 17 % most energy-demanding buildings could lead to a decrease in the thermal demand by 50 % [38]. Other authors highlighted the singular cases of Mediterranean islands in the energy transition, showing how their distance to land, geographical location, population, or protected areas can affect the renewable energy contribution [39]. Furthermore, the work carried out by [40] shows the importance of façades retrofitting to improve thermal comfort in Mediterranean buildings. In addition to this, other authors investigated the potential use of PV to satisfy the NZEB standard in Mediterranean buildings with a case study, showing how essential PV is to reach that standard in Italy [41].

In most of the general literature consulted or the literature that focuses more on Mediterranean climate, the decarbonisation of a building heating facility usually refers to the removal of the current fossil fuel system and installation, for example, of a heat pump. It can also refer to the improvement of the building envelope by adding, for example, more layers of isolation and reducing the energy demand. On the other hand, there are buildings that, for economic reasons, cannot improve the building envelope, do not consume fossil fuels directly, and are 100 % electrified. There is no room in these buildings for these types of decarbonisation strategies. For instance, office buildings in Mediterranean areas often require a cooling system. In such cases, an air/water heat pump is utilized not only for cooling but also for heating throughout the year, replacing the traditional system that relies on a chiller for cooling and a boiler for heating.

For this type of buildings that are 100 % electrified, what can still be done to decarbonise them and meet the 2050 European Green Deal targets? This is the research question that this manuscript aims to answer. Furthermore, the decrease in electricity consumption of these buildings can help de-stress the power grid, allowing other buildings to electrify their heating facilities.

The novelty of the paper lies in creating a pathway to decarbonise 100 % electrified buildings located in Mediterranean areas, and determining whether there is room and if it is worth investing efforts in decarbonising them. This question remains unanswered in the literature reviewed since it is an underexplored niche. The decarbonisation of the building is understood as a reduction of the CO_2 emissions; it does not refer to completely reducing the CO_2 emissions.

A case study has been developed in an office building located in a Mediterranean area of the EU to answer this research question and to create this pathway. It includes the use of experimental data that has been used to calibrate the BEM developed. The definition of the heating and cooling systems has been done using the real performance curves of the heat pump, which have been obtained using experimental data. This work enabled the creation of an energy model that accurately represents the real building. Therefore, any EEMs that are simulated can provide a more accurate result of their impact. This case study can serve as an example of EEMs that could be carried out in similar buildings located in Mediterranean areas. Case studies can help the introduction of sustainability strategies, like the case study carried out by [42].

The objective of the work is to provide a decarbonisation strategy for 100 % electrified buildings located in Mediterranean areas. Considering the results obtained, the role of renewable energy is the most promising contribution to decarbonising these buildings. Other measures, such as the use of natural light or improvements to the HVAC facility, lead to a reduction in the facility's electricity consumption, but with a lower impact. All these insights can provide a wide range of possibilities that can feed the decision-making process of the end users in their building decarbonisation strategy.

The manuscript starts with the description of the methodology followed, in which it is explained how the experimental data has been measured and processed, how the building has been modelled, how the performance curves of the heat pump were obtained and finally how the BEM was calibrated. Once the methodology is described, the results are presented. The energy efficiency measures are proposed based on the building energy balance, trying to reduce the highest electricity consumption sources. Following the presentation of results, a discussion section is conducted to assess their potential impact on the building. This section includes the decarbonisation strategy proposed. The final chapter includes the conclusions of the work carried out.

2. Methodology

The methodology followed includes field measurements and the virtual modelling of the building. First, an energy model of the building was created, taking into account the construction documents of the building, the schedules of use, weather conditions, and HVAC systems installed. Then, the electricity consumption of the HVAC system and the total electricity consumption of the building were measured. With the experimental data, the results of the simulations were calibrated. Once the BEM is considered calibrated, then EEMs are proposed.

Fig. 1 shows the approach followed in the paper, highlighting the order of the steps considered to obtain the final results of the study. Moreover, this figure helps to understand the steps followed, specifying in which subchapter the specific information can be found.

2.1. Information about the building studied

The building selected to carry out the study is an office building located in the city of Elche (Alicante, Spain), of about 8,000 m2. Elche belongs to the Mediterranean area of Spain, being part of the climatic area B4, according to the Spanish building code.[3] Most of the building envelope is oriented to the south, and almost all the envelope of the north part is composed of windows. The building has four floors with different types of enclosures, including a canteen, kitchen, hall, shared offices, individual offices, and storage. Figs. 2 and 3 show the shape of the building.

The construction documents of the building include the U-values of the walls, roof, and windows. Other information, such as the U-value of the floor, was obtained by using the edification standard followed during the construction period of the building, as there was no specific information available. The standard used for this construction was NBE-79.[4] The U-values allowed in NBE-79 could be, depending on the climatic area of Spain, between 1.2 $W/m^2{\cdot}K$ for the roofs and 1.03 $W/m^2{\cdot}K$ for the walls in contact with the exterior air.

One of the most characteristic parts of the building is its semi-circular conference hall. The ground floor is the most varied in terms of uses; these include a hall, shared offices, coffee break rooms, a canteen, and a kitchen. From floors 1 to 4, the enclosures are offices; 50 % of the offices on the first floor are open plan, and the rest of the building is composed of individual offices.

The building is in use from 8 h–9 h, depending on the enclosures, and is usually empty after 19 h–20 h. It is closed on Sundays and in August. Enclosures such as shared offices are assumed to start at 8 am, and individual offices usually start at 9 am. The information about occupation is important for the modelling of the internal load of the building, but the HVAC systems start around 7 h and they usually finish around 21 h.

2.2. Description of the HVAC facilities

Heating and cooling generator. The heating and cooling generator is an air/water heat pump that uses fan coils as indoor units. Table 1 shows the properties of the heat pump model. The brand is

[3] https://www.codigotecnico.org/.

[4] https://www.boe.es/buscar/doc.php?id=BOE-A-1979–24866.

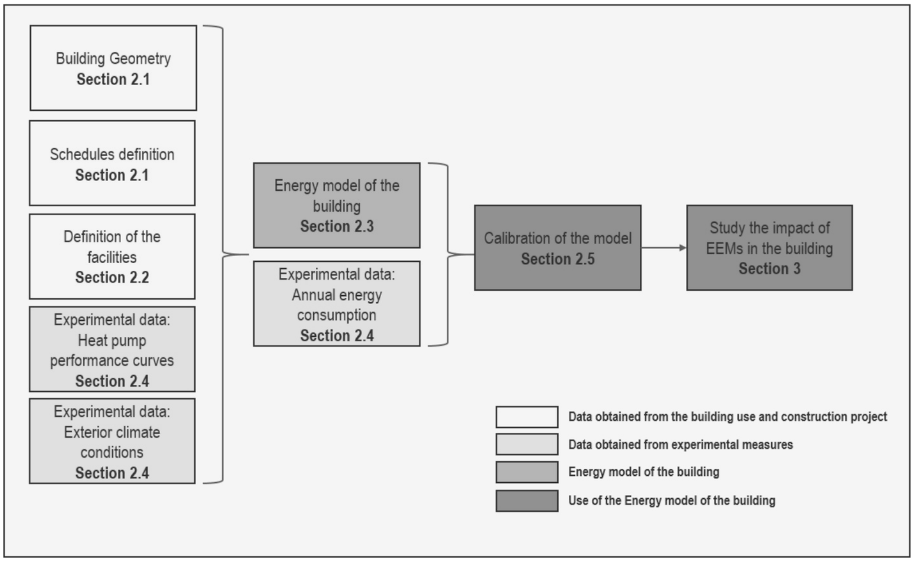

Fig. 1. Methodology of the study.

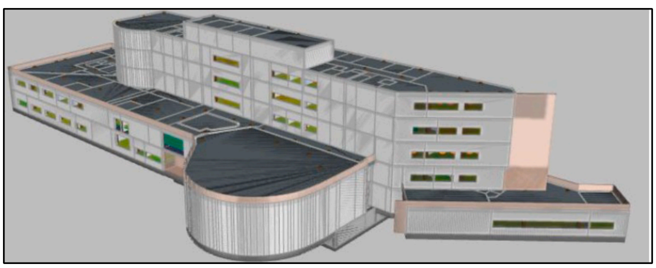

Fig. 2. Building geometry view (South part).

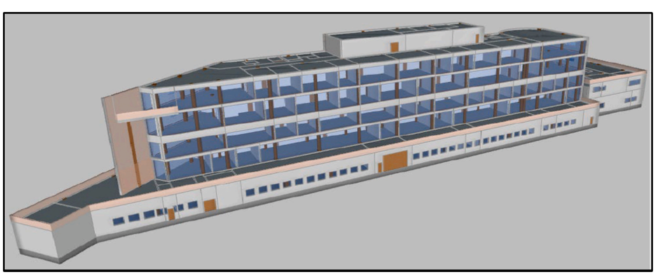

Fig. 3. Building geometry view (North part).

CLIMAVENETA, and the specific model is ERACS-R 1962 L. It has two compressors, which allow the heat pump to modulate the heating or cooling production depending on the energy demand of the building. Fig. 4 shows the heat pump on the rooftop of the building and the current circulation pump systems. The heat pump is connected to the manifold. The circulation system is connected to the manifold as well, and it moves the water through the piping system to the fan coils located in every thermal zone. In heating mode, the heat pump works at 45/40 °C (supply/return) and 7/12 °C (supply/return) in cooling mode. The indoor temperature was set at 21 °C for heating and at 24 °C for cooling, according to the Spanish HVAC legislation.[5]

Ventilation system. The building has mechanical admission of exterior air through fans connected to a duct facility, which has a grill in all the enclosures. The rated capacity of these fans is 1.3 kW. The

Table 1
Heat pump properties.

Cooling capacity [kW]	399
Nominal Cooling COP [–]	2.69
Heating capacity [kW]	438
Nominal Heating COP [–]	3
Number of fans [–]	10
Water flow [m^3/h]	69
Number of compressors [–]	2
Refrigerant [–]	134a

ventilation system only provides exterior air, without any heat recovery. One enclosure of the building, the conference hall, has an independent air treatment unit (ATU). Nevertheless, this ATU is only used for 2 days per year, so it does not have an impact on the annual energy consumption of the building.

Lighting facility. The lighting facility of the building uses LED technology. The installed capacity varies depending on the enclosure, from 5 to 10 W/m^2. The total installed capacity reaches approximately 50 kW, with specific schedules during the morning and afternoon. Most of the luminaries are located on the west side of the ground floor, where the shared offices are. The luminaries in enclosures such as storage and technical rooms use sodium vapour technology.

Indoor units and pumps. The heating and cooling facility uses more than 100 fan coil units. Most of them are cassette fan coils, while some of them have a duct distribution. These fan coils work with a water temperature of 45 °C-40 °C during the heating season and of 7 °C-12 °C during the cooling season. The hydronic facility that connects these fan coils to the heat pump is a 2-pipe facility, which means that every fan coil receives two pipes (inlet and outlet) from the same loop. This means that they can only work with either warm or cold water, i.e., the building can only receive heat or cold from the facility. The heat pump provides heating in the seasons January-April and November-December, and cooling during the rest of the year. The hydronic facility operates at a pressure level between 2 and 2.5 bars, with a maximum of 3 bars. The pumps connected to the hydronic facility have a rated power capacity of 11 kW and work at a fixed speed.

Other elements. Elements such as computers, appliances, and photocopying machines are included in the model. The total capacity installed is estimated to be more than 35–40 kW for these elements. There are different appliances installed depending on the use of the office. For example, shared offices have more elements installed than individual offices, as there are more desks/computers per square meter,

[5] https://www.boe.es/eli/es/rd/2007/07/20/1027/con

Fig. 4. Heat pump (left) and circulation pumps (right) of the facility.

and that is where the photocopying machines are located.

2.3. Energy model of the building

The tool selected to define the building geometry is IFC Builder of CYPE Ingenieros.[6] This graphic design tool enables the creation of a virtual 3D model of the building, as shown in Fig. 5. All the data presented in the previous subchapters and the virtual 3D model of the building were defined in EnergyPlus. In order to consider the thermal load of the interior elements, lighting, and occupation, the assumptions made in [43] were used. Below, it is explained how the HVAC systems have been modelled in EnergyPlus.

Heating and cooling generator. The heat pump installed in the building has been modelled taking into account the rated characteristics shown in Table 1 and its performance curves. These curves consider the effect of the exterior conditions, the water production temperature, and the load at which the heat pump is working. Usually, BEM software includes default performance curves that define generic systems. However, to achieve more precision, the performance curves of the current heat pump have been calculated by using experimental data (see subchapter 2.4). There is a total of 6 curves defined: CAPfText, EIRfText, and EIRfPLR for both heating and cooling.

Ventilation system. The electricity consumption of the ventilation facility has been modelled using the nominal consumption of the unit and the hours it is working.

Lighting facility. The lighting facility is defined using the IES files[7] of every specific model and brand of each building luminaire. All these IES files were defined in the building model by using CYPELUX CTE.[8] Most of the office enclosures use LED luminaires, but other enclosures such as storage and bathrooms use incandescent luminaries that have 2–3 times more electricity consumption. Fig. 6 shows how the lighting facility has been modelled.

Fan coils and pumps. Circulation pumps and fan coils are defined using manufacturers' data. This information includes the rated flow of fluid (water or air) and the pressure drop that the fan/pump provides. These data, with the mechanical efficiency of the elements (around 0.85–0.9), provide enough information to estimate the electricity consumption of these elements.

Thermal zones. Enclosures included in the building envelope need to be classified into thermal zones. Every enclosure that has a different thermostat is considered an independent thermal zone, as the indoor conditions in it could be different from those of other enclosures with a separate thermostat. One helpful step is identifying the fan coil units in the building. Usually, every indoor unit has a thermostat, which sets the thermal parameters of the enclosure. For example, if there are three individual offices with three different fan coil units (one each), they could be considered as three different thermal zones. On the other hand, if one fan coil unit is connected to these three offices by using a duct facility, then these three offices could be considered the same thermal zone, as the set points of the indoor thermal conditions are the same. Considering all these concepts, the building has a total of 103 thermal zones. Enclosures that are not thermally conditioned should be excluded from the building envelope. These enclosures will act as an air mass inside the building that will affect the energy demand of those included in the building envelope.

2.4. Experimental data

As mentioned above, experimental data was used to calibrate the BEM created. The experimental data can be classified into two types: the first is the electricity consumption of the building and the heat pump during a year. The second is that of two specific measurements campaigns focused only on the heat pump. Two campaigns were conducted to calculate the performance curves of the heat pump in cooling mode and heating mode, respectively. The first type of experimental data was used to calibrate the BEM, and the second to calculate performance curves that enabled the definition of the heat pump in the BEM.

In the first type of experimental data, the electricity consumption of the HVAC systems and the building itself was measured over the course of a year. To achieve this, a power meter connected to the Building Management System (BMS) tool, known as "ELECGY-UP", was utilized. The exterior air temperature of that year was obtained from the closest weather station to the building [44].

Fig. 7 shows the experimental data obtained from the BMS, where the heat pump electricity consumption is classified per month. Fig. 7 also shows the average exterior temperature of that month. It is worth highlighting that from May to October, the electricity consumed is used to supply cooling, and the rest of the year, the electricity data shows the electricity consumed to provide heating. There is no experimental electricity consumption data for August due to the closure of the building.

The second type of experimental data, as mentioned above, is intended to enable the calculation of the performance curves of the heat pump. These measures were carried out for 2 weeks in June to analyse the behaviour of the heat pump in cooling mode. During these days, exterior air temperature, cooling production, and electricity consumption were measured. This allowed to link these three variables. To acquire the same information in heating mode, the same activity was carried out for 2 weeks in January. These months were selected due to the availability of the equipment to measure the data.

Figs. 8 and 9 show the results of heating/cooling production, electricity consumption, and exterior temperature for the weeks when the experimental measures were carried out. Moreover, only measurements when the heat pump was working at a steady state were taken into account for the analysis. Transient states of the heat pump were excluded from the measures because, in some hours, for example, there was no measurement of electricity consumed, but there was a measurement of heating production. This is because the water loop still has the level of temperature required to provide some heating or cooling due to the inertia of the facility, so the production cannot be linked to any data on electricity consumption.

To measure the thermal data, multiple sensors were installed in the facility. A water flow meter (measuring $\dot{m}_{water}$) and two type K thermocouples (measuring T_{IW} and T_{RW}) were used. With these variables measured, it was possible to estimate the heating or cooling demand ($\dot{Q}$). Additionally, an electricity consumption meter, Chauvin Arnoux C. A. 8334, connected to the heat pump was employed (measuring P_{elec}). It

[6] https://info.cype.com/en/software/ifc-builder/.

[7] IES files contain specific information about the model of a luminaire that is simulated in a calculation software like, for example, CYPELUX XTE or DIALux.

[8] https://info.cype.com/es/software/cypelux-cte/.

Fig. 5. Real and modelled Building Geometry.

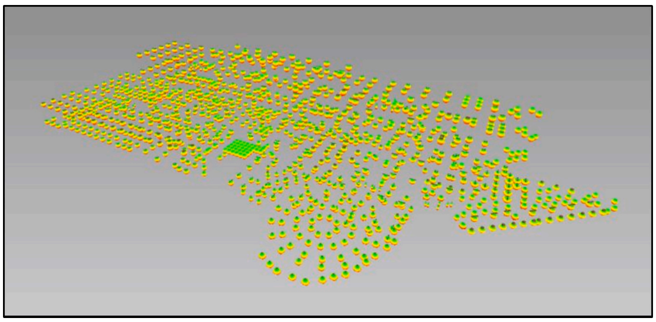

Fig. 6. Model of the lighting facility.

can be seen in Fig. 10 (left part). This element was connected to the electrical panel of the heat pump, where the electrical protections are located. Fig. 10 (right part) shows where the water flow meter was connected. That pipe is the one that connects the heat pump with the manifold, meaning that all the water flow of the facility passes through this pipe. In the exact figure mentioned above, one of the thermocouples can be seen, which is in the upper part of the flow meter. This data enables the computation of the heating and cooling production and the coefficient of performance (COP) of the heat pump. The parameter that indicates the efficiency of a heat pump in EnergyPlus is the Energy Input Ratio (EIR), which is the inverse of the COP. Eqs. (1), 2, and 3 show how these parameters can be calculated. In cooling mode, the COP is referred to as the Energy Efficiency Ratio (EER).

$$\dot{Q} = \dot{m}_{water} \cdot C_p \cdot (T_{IW} - T_{RW}) \tag{1}$$

$$COP = \frac{\dot{Q}}{P_{elec}} \tag{2}$$

$$EIR = \frac{1}{COP} \tag{3}$$

where $\dot{Q}$: Heating production (kW). $\dot{m}_{water}$: Mass flow of water (kg/s). C_p: Specific heat of the water (kJ/kg·K).

Experimental uncertainties were estimated according to [45]. In order to measure the power consumption, voltage and current were taken into account. These measures presented uncertainties lower than 1 % at a 95 % confidence level. These uncertainties yield uncertainties in the power measures lower than 1.5 %. The type K thermocouples presented an accuracy of ±1.5 °C.

These specific measurements allowed to calculate the performance curves of the heat pump. The performance curves of a heat pump can have a biquadratic shape, and they depend on the water supply temperature and the exterior air temperature. These types of curves can represent the efficiency of the heat pump in function of the exterior temperature (EIRfTEMP) or the maximum capacity that a heat pump can provide in function of the exterior air temperature (CAPfTEMP). Whereas EIRfTEMP was obtained by using experimental data, CAPfTEMP was obtained directly from the manufactureŕs databook. Equations (4) and (5) show these curves.

$$EIRfTEMP = a + b \cdot T_{water} + c \cdot T_{water}{}^2 + d \cdot T_{air} + e \cdot T_{air}{}^2 + f \cdot T_{water} \cdot T_{air} \tag{4}$$

$$CAPfTEMP = a + b \cdot T_{water} + c \cdot T_{water}{}^2 + d \cdot T_{air} + e \cdot T_{air}{}^2 + f \cdot T_{water} \cdot T_{air} \tag{5}$$

where T_{air}: Dry bulb exterior temperature [°C]. T_{water}: Water production temperature [°C].

The final performance curve calculated was the one that links the efficiency of the heat pump and the part load ratio conditions. This is represented by a polynomial curve of degree 2 in equation (6).

$$EIRFfPLR = a + b \cdot \text{PLR} + c \cdot \text{PLR}^2 \tag{6}$$

where PLR: Part Load Ratio (Heat pump production / Maximum heat pump production at specific conditions).

All the coefficients calculated with these performance curves are values between 0 and 1.5, and they have an impact on the nominal electricity consumption of the heat pump (Calculated at the specific

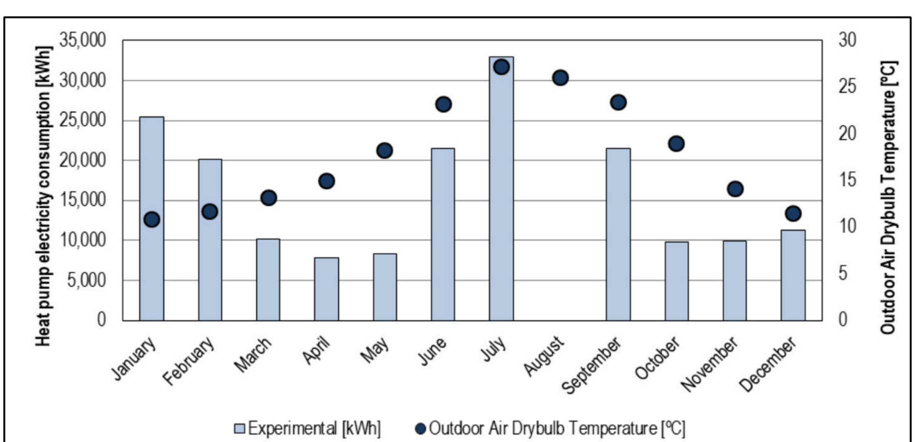

Fig. 7. Experimental data of electricity consumption and exterior dry bulb temperature.

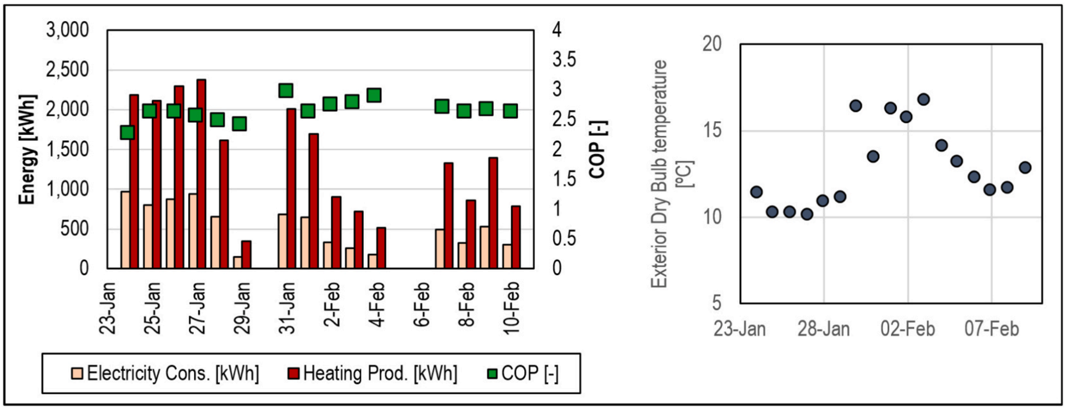

Fig. 8. Experimental data during 2 weeks of the heating season.

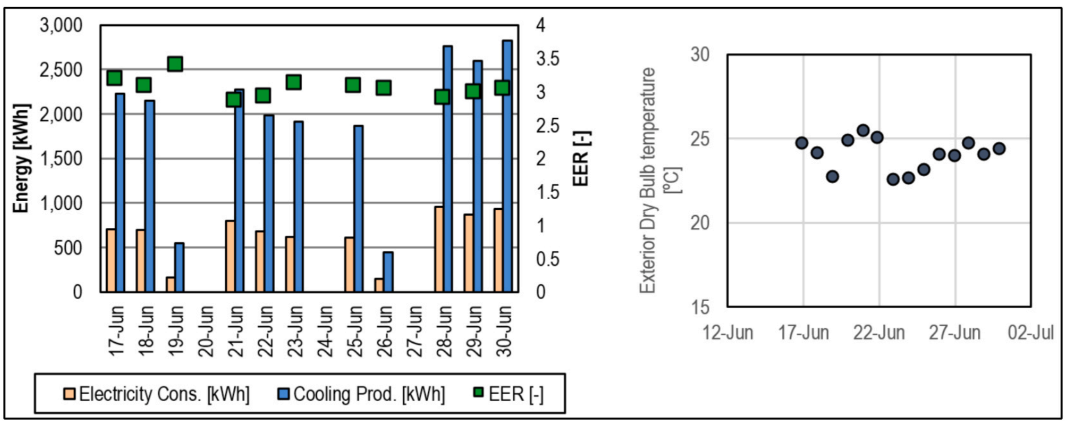

Fig. 9. Experimental data during 2 weeks of the cooling season.

conditions ofT_{air} = 7°C andT_{water} = 35 °C). The way to calculate the electricity consumed by a heat pump at specific conditions considers the consumption at rated conditions and the coefficients calculated by equations (4), 5, and 6. These coefficients take into account the effect of water production temperature, exterior air conditions, and the part load ratio of the heat pump at different conditions than the nominal conditions. Eq. (7) shows this approach.

$$P_{Heatpump} = P_{nom} \cdot EIRfTEMP \cdot CAPfTEMP \cdot EIRFfPLR \quad (7)$$

The performance curves are calculated by applying linear regression with two variables to the data measured. This procedure is similar to the one followed by [46]. Figs. 11 and 12 show the results obtained. It can be seen how the capacity and the efficiency of the heat pump in cooling mode are lower when the exterior temperature is higher. This is what happens in reality; if the exterior temperature is high, it is difficult for an air/water heat pump that is working in cooling mode to condense the refrigerant. In heating mode, the situation is completely opposite: if the exterior temperature is higher, the efficiency increases because it is easier for an air/water heat pump to evaporate the refrigerant and extract heat from the exterior air. Note that in Figs. 11 and 12, the efficiency plotted is the coefficient EIR, which is the inverse of the COP (EER for cooling). For this reason, the effect explained above is the opposite of the one shown in Figs. 11 and 12. Table 2 shows all the coefficients obtained with the linear regression and the errors obtained.

Fig. 10. Sensors installed in the facility. Power meter (left) and flow meter (right).

2.5. Calibration of the simulation

The methodology followed to calibrate the BEM relies on the variation of different parameters that affect the energy demand. As the energy efficiency measures focus on system efficiency and energy consumption, there is no issue modifying inputs such as ventilation or infiltration rate, envelope resistance, etc., as they contribute only to the energy demand.

The objective of the calibration is to match the monthly electricity consumption of the heat pump to the measured electricity consumption and then propose energy efficiency measures. The ventilation rate has been assumed to have a value based on the Spanish building HVAC systems legislation, which establishes that the ventilation rate for offices should be around 12.5 l/s/person. To calibrate the model, the building's infiltration rate was used as the key parameter. This parameter was chosen due to the higher level of uncertainty surrounding its value. In contrast, there is more reliable data for other factors such as the U-values

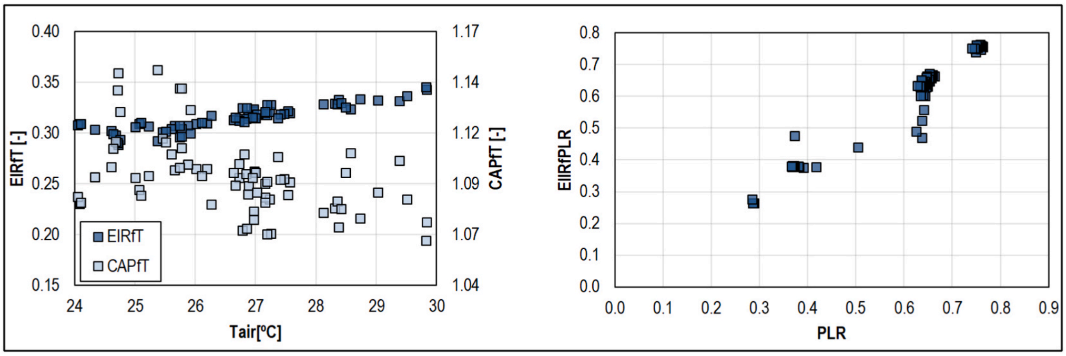

Fig. 11. Performance curves in cooling mode. [].
Source: 47

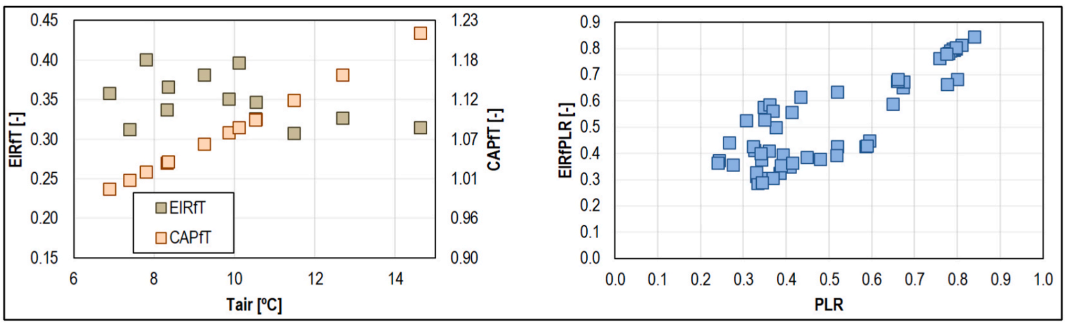

Fig. 12. Performance curves in heating mode. [].
Source: 48

Table 2
Performance curves of the heat pump.

	a	b	c	d	e	f	R^2
CAPfText Heating	0.870	−0.002	0.000	0.022	0.0004	−0.0001	0.999
EIRfText Heating	0.913	−0.028	0.001	0.028	0.001	−0.002	0.996
EIRfPLR Heating	0.551	−1.087	1.722	–	–	–	0.787
CAPfText Cooling	0.916	0.039	0.00004	0.001	−0.0001	−0.0003	0.9999
EIRfText Cooling	1.810	−0.151	0.006	−0.042	0.001	0.001	0.938
EIRfPLR Cooling	0.090	0.604	0.361	–	–	–	0.947

Source: [47,48].

of the building or the schedules of use. The infiltration rate has been defined with equation (8) [43] as follows:

$$Infiltrationrate = F_{schedule}\cdot\sqrt{(c\cdot C_s\cdot \Delta T^n)^2 + \left(c\cdot C_w\cdot (s\cdot W_{speed})^{2n}\right)^2} \quad (8)$$

where $F_{schedule}$: Value defined depending on the schedule. c: Flow coefficient [$m^3/(s\cdot Pa^n)$]. The default value is 0.0039 $m^3/(s\cdot Pa^n)$. C_s: Coefficient for stack-induced infiltration [$(Pa/K)^n$]. The default value is 0.078 $(Pa/K)^n$. ΔT: Temperature difference between the exterior and interior air [K]. n: Pressure exponent [–]. The default value is 0.67. C_w: Coefficient for wind-induced infiltration [$(Pa\cdot s^2/m^2)$]. The default value is 0.142 $(Pa\cdot s^2/m^2)$. s: Shelter factor [–]. The default value is 0.5. W_{speed}: Wind speed [m/s].

To consider a simulation calibrated, some error thresholds between simulated and experimental results must be met. Different sources provide instructions on the statistical errors to be used and the error thresholds to validate the model. For instance, AHSRAE Guideline 14 [49], the Federal Energy Management Program (FEMP) [50], and the International Performance Measurement and Verification Protocol (IPMVP) [51] bring orders of magnitude of error thresholds to be taken into account before considering a model calibrated. The errors recommended by these sources are the Normalized Mean Bias Error (NMBE) and/or the Coefficient of Variation of the Root Mean Square Error CV (RMSE). A summary of the errors taken from the references mentioned before is shown in Table 3.

The NMBE represents the average of errors of all the measurements. This error is normalized using the average value of the measurements and considers the number of measurements as well. NMBE could be used with seasonal data, as singular errors could be compensated during the measurement period. Eq. (9) shows how NMBE is defined:

$$MBE = \frac{1}{\overline{m}}\cdot\frac{\sum_{i=1}^{n}(m_i - s_i)}{(n-p)}\cdot 100(\%) \quad (9)$$

where m_i: Measured data. s_i: Result of the simulation. $\overline{m}$: Average value of the measured data. n: Number of measurements. p: Number of adjustment model parameters. Considered zero for the calibration.

On the other hand, the CV (RMSE) considers the difference between measured and simulated data hour by hour. Furthermore, positive and negative differences are not compensated in this parameter, which makes it more focused on obtaining precision on an hourly basis, rather than in a seasonal result. Eq. (10) shows this approach:

$$CV(RMSE) = \frac{1}{\overline{m}} \cdot \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{(n-p)}} \cdot 100(\%) \tag{10}$$

Considering the different sources and the need for calibrating seasonal results, the monthly criteria selected was the one from IPMVP [51], with an error of 20 % in the NMBE.

The calibration process consisted of the modification of the infiltration rate by multiplying it by different factors. After some attempts, the factor that gave results that aligned with the IPMVP [51] criteria was 1.5. Fig 13. shows the results of the calibrated model and Table 4 the final NMBE obtained.

The BEM has been calibrated considering the electricity consumption. With the model calibrated, the final thermal energy delivered to the building, the electricity consumed by the heat pump and the average coefficient of performance per month are shown in Fig. 14.

Once the model is considered calibrated, energy efficiency measures are proposed to estimate how much the building can be decarbonised. The efficiency measures proposed, and their results are shown in the following section.

3. Results

To identify areas for energy efficiency measures, a breakdown of the building's energy consumption is necessary, detailing its consumption in heating, cooling, lighting, circulation pumps, fan coils, and other equipment. Fig. 15 shows this approach, in which the heat pump of the building has the highest energy consumption, followed by the lighting facility. The total electricity consumption of the building is about 460,000 kWh per year, only taking into account elements that can be modelled in EnergyPlus. Exterior lighting or water supply systems are not taken into account in this balance. According to the energy invoices, the building could consume approximately 550,000 kWh of electricity, considering all its energy consumption.

EEMs for interior equipment, such as computers, coffee machines, and photocopying machines, and other types of office appliances are beyond the scope of this study.

The highest electricity consumption in the building is attributed to heating, cooling, and lighting, followed by the interior equipment. To optimize energy efficiency, the heating and cooling systems can be improved by replacing the heat pump, which would allow for an assessment of potential efficiency gains from installing a new one.

About lighting, it was found that the building mainly uses LED luminaries, except for those in bathrooms and storage areas, which account for a small share of the lighting facility and have a low usage frequency. Improving these non-LED lights would have minimal impact on overall energy consumption. However, there is an opportunity for improvement. Currently, the lighting system operates on a fixed schedule, without considering the availability of natural light, which is typically abundant in Mediterranean regions. Installing a dimming controller would enable the lighting to activate only when natural light levels fall below a certain threshold. This would ensure that the lighting is used only when necessary, reducing energy consumption when daylight is sufficient. Given that lighting is the second-largest energy consumer in the building, this measure could lead to significant electricity savings.

Table 3
Calibration criteria from different sources.

Data type	Index	FEMP [50]	ASHRAE Guideline 14 [49]	IPMVP [51]
Monthly criteria (%)	NMBE	+-5	+-5	+-20
	CV (RMSE)	15	15	–
Hourly criteria (%)	NMBE	+-10	+-10	+-5
	CV (RMSE)	30	30	20

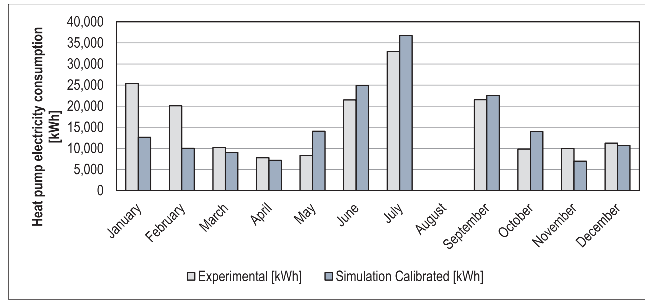

Fig. 13. Results of the calibrated model. [].
Source: 52

Table 4
Simulation errors.

Index	Simulation	IPMVP
NMBE	5.16 %	+-20 %

Another area for improvement lies in the circulation pumps, which operate at constant speeds and could be optimized for better performance. After implementing the energy efficiency measures, renewable electricity production will be introduced to reduce the building's energy footprint further. Below, a detailed account of each EEM is provided.

The results are presented depending on the type of facility improved: HVAC facility, lighting facility, or PV facility integration. Each type of EEM has its own subchapter.

3.1. HVAC facility

Improvement of the hydronic facility. The circulation pumps work at a constant speed. This means that they move the same amount of fluid every time the hydronic facility is working, consuming the same amount of electricity without taking into account the energy demand of the building. However, if the water flow varies in function of the energy demand, the amount of water that would be moved would decrease if the energy demand decreases. This means that there would be less electricity consumption in pumping the water through the loop.

Fig. 16 shows a comparison between constant and variable speed circulation pumps. The electricity consumption decreases when a variable speed pump system is installed. It is worth mentioning that the savings with variable speed pumps are linked to the time the system works at part load ratio conditions. For instance, if the heating and cooling demand is always close to the nominal load of the building, the difference between constant and variable speed pumps is minimal, as the water flow to be moved would be the same.

According to the results obtained, the savings in heating mode are about 7 % and in cooling mode about 2 %. This percentage refers to the initial consumption of the current constant-speed pumps. In heating mode, the savings are higher as the heat pump works most of the time at part load ratio conditions, reducing the water flow in the loop.

Replacing the heat pump. To assess the potential improvement of current heat pump performance, its replacement is studied with a new model. Table 5 shows the properties of the new heat pump proposed.

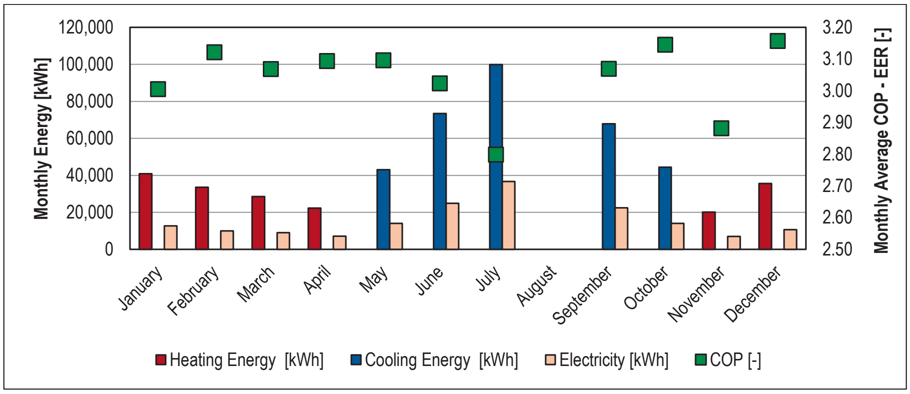

Fig. 14. Energy balance of the heat pump.

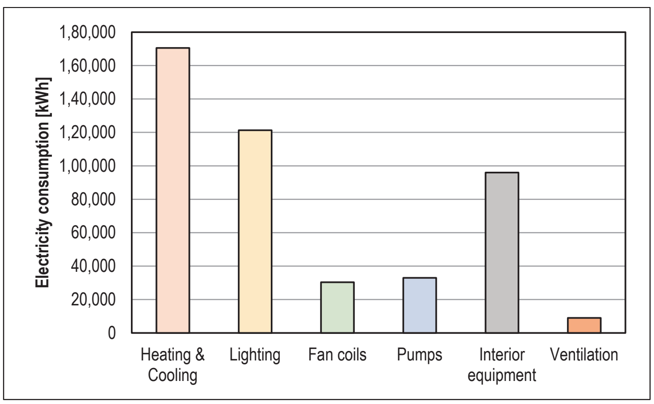

Fig. 15. Building energy balance.

The new performance curves have been implemented in EnergyPlus. Due to the lack of data, the part load ratio curves of the current model have been maintained. For this reason, the efficiency of the heat pump would only be influenced by the exterior temperature and the water production temperature, as the effect of part load ratio conditions would be the same for both models. Fig. 17 shows the results obtained with the new heat pump.

The results of this measure indicate that the current heat pump still offers good performance, and there is no need to change it. Installing a new heat pump with similar characteristics would only reduce the electricity consumption in cooling by 2 % and in heating by 4 %. Given the insufficient data to consider the part load ratio effect, the new model proposed, with its additional three compressors, may offer more room for savings by allowing for a higher level of energy modulation. Nevertheless, this would not make a significant impact on the results for cooling, as the heat pump is most of the time at full load in cooling mode. During the heating season, this effect could have improved the results by 5–6 % as an estimation, taking into account that the COP could improve by 30–40 % in most of the working hours. Despite considering this effect, the savings are not dramatic enough to justify replacing the current heat pump.

3.2. Lighting facility

The current lighting system does not account for natural daylight. By integrating daylight-responsive controls, the system can adjust its intensity based on the available natural light, making it more flexible and energy-efficient. Using a dimming controller that monitors the average illumination levels in each room is proposed. For office spaces, it is recommended to maintain a minimum of 500 lx. This system would adjust the lighting to meet this threshold, considering both natural light and the lighting facility's output. Fig. 18 illustrates the impact of this energy efficiency measure. It shows a 25 % reduction in electricity consumption by implementing the dimming controller. This system ensures a minimum illumination of 500 lx, utilizing natural light as much as possible while supplementing with artificial light when needed. As a result, annual electricity consumption would be reduced to 30,000 kWh.

Table 5
New heat pump characteristics.

Cooling capacity [kW]	401
Nominal Cooling COP [–]	2.46
Heating capacity [kW]	525
Nominal Heating COP [–]	4
Number of fans [–]	8
Water flow [m^3/h]	69
Number of compressors [–]	5
Refrigerant [–]	410a

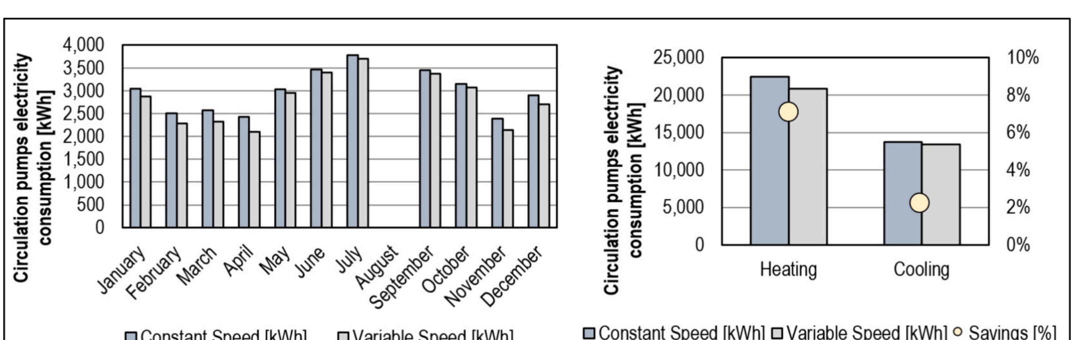

Fig. 16. Comparison between constant and variable speed pump system.

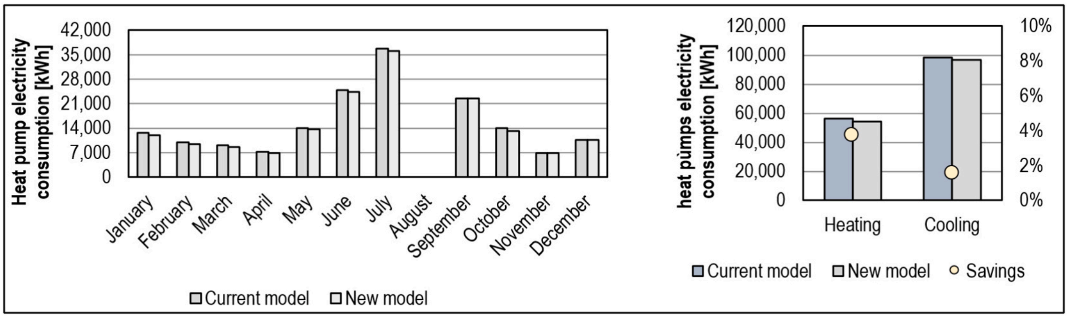

Fig. 17. Comparison of the electricity consumption of different heat pumps.

3.3. PV facility integration

Once the energy efficiency of the system has been increased, the next step would be the analysis of the integration of renewable energy in the building. As the only energy carrier of the building is electricity, one option would be the installation of a photovoltaic (PV) facility. This facility consists of 204 modules of 340 Wp each, resulting in a total capacity of 69 kWp. These modules are organised into 12 different strings of 17 modules per string. This division has been made taking into account the number of modules, but also the input parameters of the inverters. These strings are connected to 3 inverters, each with a 20 kW capacity. All the elements have been modelled by using the software ARCHELIOS PRO.[9] Fig. 19 shows the layout of the facility, showing the part of the roof where the modules have been installed.

According to the global simulation results, the PV facility can produce 110,206 kWh per year. It is significant to note that, with almost all the available surface for PV being occupied, it can only produce 20 % of the total energy consumption of the building. Another issue is not only the quantity of energy generated, but also when this energy is generated. Since there is no battery system to store the generated electricity, it must be consumed immediately or be lost. For this reason, the hourly energy consumption of the building needs to be checked to see if the electricity consumption occurs at the same time that the PV facility generates electricity.

Figs. 20 and 21 show this approach for different days of the heating and cooling season, respectively. The lighting consumption is also shown alongside the heating and cooling consumption for these days, allowing for comparison with the PV generation.

According to Fig. 20, the PV facility can cover a maximum consumption of 40 kWh around midday. The generation curve aligns with the lighting consumption, allowing the generated electricity to be utilised effectively. On the other hand, the electricity consumed in heating mode by the heat pump has a different shape, with a peak of energy consumption early in the morning. For this reason, in heating mode, it is not easy to use electricity produced by the PV for the heat pump. During the cooling season, the shape of the electricity consumed by the heat pump is completely different. This is because the maximum energy demand is at midday when the cooling demand is at its maximum. Fig. 21 shows this approach.

The shape of the PV production during the cooling season indicates that the facility can produce electricity for more hours, as this season is during spring and summer when there are more hours of sun. Depending on the day's type, the shape typically falls under the electricity consumption for cooling, although it is not as high as the cooling electricity consumption, which can exceed 100 kW. Nevertheless, PV production is more useful for cooling than for heating due to the similarities between the hourly production of PV and the hourly electricity consumption of the building.

[9] https://www.trace-software.com/es/nuestras-soluciones/archelios-pro/.

3.4. Summary and combined potential of the EEMs proposed

In this subchapter, a summary of the results obtained is presented in Table 6. This table shows the electricity and CO_2 emissions saved from the different EEMs proposed. The decarbonisation potential has been measured by using the emission factor of electricity. This value measures the CO_2 emissions produced to generate 1 kWh of electricity; therefore, it is an indicator of the cleanliness of the electricity grid. The value used for electricity coming from the grid in mainland Spain[10] is 0.331 $kgCO_2$/kWh.

The total potential CO_2 emission reduction that this building could achieve with the EEMs proposed is 48.42 CO_2 tonnes per year, with PV integration being the most interesting measure. In Chapter 4, there is an in-depth discussion about the EEMs proposed.

3.5. Economic analysis

In this type of studies, the economic aspects of the EEMs proposed should also be taken into account. The economic parameters considered in the study are the Net Present Value (NPV) and the payback. They are calculated as shown in Eqs. (11) and (12):

$$\mathrm{NPV} = \sum_{j=1}^{n} \frac{\mathrm{CS_j} - \mathrm{O\&M_j}}{(1+\mathrm{i})^{j}} - \mathrm{C_0} \tag{11}$$

$$\mathrm{Payback} = \frac{\mathrm{C_0}}{\left(\frac{\sum_{j=1}^{n} \mathrm{CS_j} - \mathrm{O\&M_j}}{n}\right)} \tag{12}$$

where n: years (technical lifetime of technology). j: Specific year. CS_j: Energy cost savings (annual benefits) in year j. $O\&M_j$: Operation and maintenance costs in j (OPEX). i: Discount rate. C_0: investment costs (CAPEX).

The annual economic savings can be estimated by multiplying the electricity saved, as presented in Table 6, by an average electricity price of 0.116 €/kWh.[11] The discount rate is assumed to be 3 %. The lifetime estimated for the EEMs is 25 years. The investments and the operation and maintenance costs are presented in Table 7, with the economic results of NPV and payback. The investment costs have been estimated using data from a construction database of CYPE Ingenieros called "Generador de precios".[12] In the hydronic facility EEM, four pumps are needed. Taking into account this database, a base price of 7.5 k€ per pump has been considered. Replacing the heat pump alone, according to

[10] https://www.miteco.gob.es/content/dam/miteco/es/energia/files-1/Eficiencia/RITE/documentosreconocidosrite/Otros%20documentos/Factores_emision_CO2.pdf.

[11] This Price has been obtained as an average of the electric periods, which take place at different hours and their electricity consumption. This information comes directly from the university.

[12] https://generadordeprecios.info/obra_nueva/Actuaciones_previas.html.

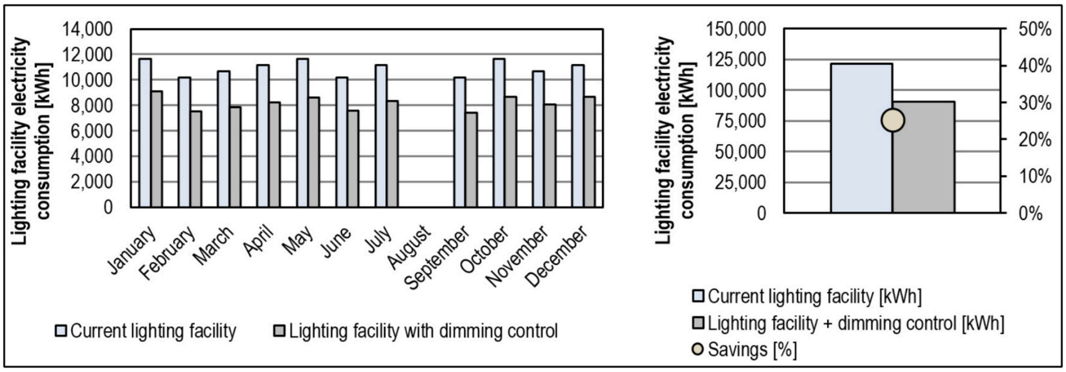

Fig. 18. Comparison of electricity consumption of the lighting facility with and without dimming control.

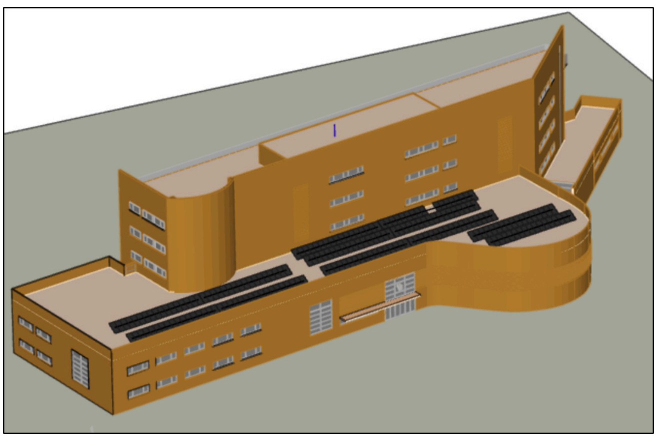

Fig. 19. Photovoltaic facility of the building.

the database used, could cost around 70 k€. Regarding the lighting facility EEM, it would be applied to 100 enclosures. The investment cost of this EEM is calculated assuming one dimming controller per enclosure and a cost of 420€ per dimming controller. The Operation and Maintenance costs (O&M) have been estimated with the collaboration of the facility management service of the building. The O&M costs of the PV facility are higher than those of the others. It has been estimated that the facility would need at least two cleanings per year plus the preventive and corrective maintenance.

The results show that the PV facility is the most valuable investment in 25 years, showing the highest NPV. The EEM linked to the lighting facility shows that it is an interesting investment as well. The renovation of the heat pump is the only EEM that is not worth it in economic terms. As mentioned earlier in the manuscript, the difference in electricity consumption between the current heat pump and the new model proposed is very little. Given the high upfront costs of this EEM relative to the savings, it is not a viable option for decarbonising this building.

4. Discussion

Considering the results obtained, the most interesting EEM in economic terms and regarding CO_2 emissions is the installation of a PV facility. On the other hand, it does not mean that it should be done before the other measures take place. Prior to the installation of a PV facility in a building, all the electricity consumption should have been reduced to its maximum. In this way, the PV facility will not be oversized. In the case of this building, the proposed PV facility would occupy the entire available roof space. Even if it occupies all the roof, its maximum electricity production would be 20 % of the electricity demand. If the other measures are done before this one, around 10 % of the electricity consumption would be reduced. This means that the electricity consumption must be reduced by an additional 70 % before it can be discussed whether the installed PV capacity should be reduced. This means that, considering the amount of electricity consumed in the building and potential reduction strategies, prioritizing the installation of a PV over other EEMs should not be an issue.

The results obtained with the installation of a PV facility are in line with the ones obtained in [27,53], but not directly comparable due to the type of facilities and the different locations. Nevertheless, the order of magnitude is similar. The other studies estimate between 10 % and 19 % of CO_2 emission reduction with PV in university campuses. Considering the studies were conducted in Ireland, it is reasonable to expect a lower PV contribution due to climatic reasons. It remains challenging to compare results from different studies, as external factors such as shadows, facility orientation and inclination, radiation level, etc., can vary significantly among all the studies.

The second most impactful EEM measure is the one that includes

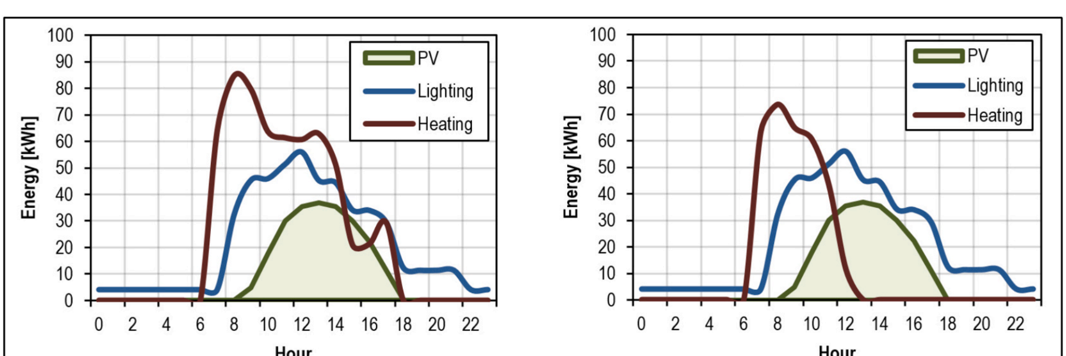

Fig. 20. Heating season days hourly profile.

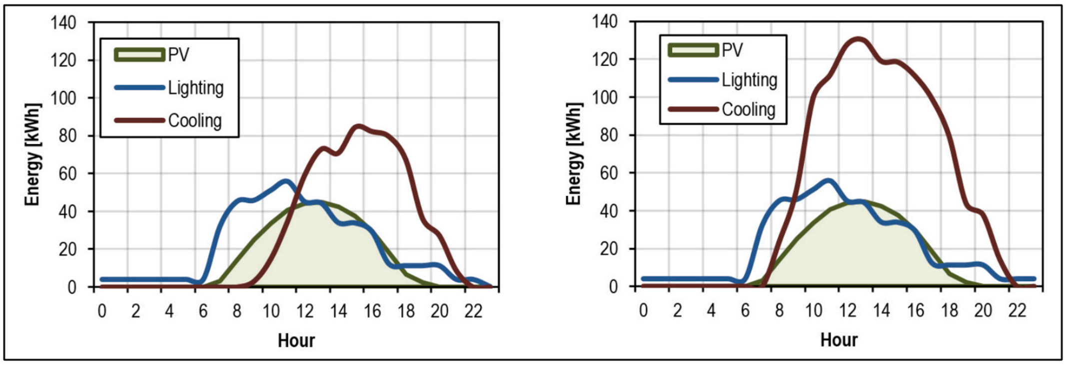

Fig. 21. Cooling season days hourly profile.

Table 6
Summary of the different EEMs.

EEM	Electricity saved [kWh]	Electricity saved [% of total building electricity consumption]	CO_2 emission reduction [tonnes/year]
Improvement of the hydronic facility	1,878	0.40	0.62
Replacing the heat pump	3,628	0.79	1.2
Lighting facility with dimming controller	30,566	6.65	10.12
Photovoltaic facility	110,206	23.96	36.48

Table 7
Economic analysis of the different EEMs.

EEM	Initial investment [€]	O&M [€]	Annual cost savings [€]	NPV [€]	Payback [years]
Improvement of the hydronic facility	30,000	150	219	26,986	13.2
Replacing the heat pump	70,000	500	423	−13,160	30.8
Lighting facility with dimming controller	42,000	300	3,562	14,891	18.5
Photovoltaic facility	75,000	1,000	12,842	131,544	9.1

dimming controllers in the lighting facility. In the case of this building, they could reduce the lighting electricity consumption by 25 %. In economic terms, it is also interesting, as the payback is lower than the estimated lifetime of these facilities, which could be around 20–25 years. On the other hand, it can be considered technically and economically viable; however, installing dimming controllers in more than 100 enclosures necessitates a BMS capable of handling all the information in an existing and operational lighting facility. This requires an extra workload from the maintenance team, which is not always easy to handle.

In terms of results, these dimming controllers are in line with other studies in which the authors estimated 20 % of savings in the New York Times headquarters [54]. Another study done in an office building in Seoul estimated that the application of daylight-linked controls can reduce the lighting electricity consumption by 30 % [55]. In a more recent work, the authors propose different control options of daylight dimming systems [56]. In that study, energy savings range from 27 % to almost 80 % depending on the zone. It covers a specific open-plan office that has several windows facing the south and the southeast. This is an indicator of how challenging it is to compare the results of dimming systems in different buildings, due to the building's geometry and landscape, and the radiation levels. The building studied in this work is located in a Mediterranean area, which has one of the highest radiation levels in the EU. On the other hand, most of the windows are in the north façade, limiting the penetration of direct radiation in the building during sun peak hours.

The replacement of the heat pump should not be considered until the current one stops working. The results show that the current system still has high energy efficiency levels, making investments in a new heat pump unnecessary. When the current heat pump stops working, this EEM should be considered straightforward, since the hydronic facility is prepared to work at the water temperature production level of heat pumps, and the building is electrified enough to feed it.

The adaptation of the hydronic facility by substituting the current fixed speed pump system with variable speed pumps is a good option. On the other hand, it should not be considered a priority, since the other measures can reduce the CO_2 emissions more effectively. The measure is cost-effective, but it should be considered as a last step for this building.

After comparing all the results obtained in the previous chapter, discussing their meaning, and comparing them with other sources, a building decarbonisation strategy for this building can be provided. Fig. 22 shows this strategy.

The results of the paper show that there is room for energy savings in 100 % electrified buildings located in Mediterranean areas. Investing in PV generation shows to be more competitive than improving HVAC system efficiency. These results support key policy frameworks like the RED and the EPBD, both of which incentivise building electrification and the adoption of solar PV technology to reduce carbon emissions in the building sector. By emphasising renewable generation over HVAC upgrades, this study reinforces the priority of clean energy investments outlined in these policies, with special emphasis on PV generation to achieve ambitious climate goals in Mediterranean climates.

5. Conclusions

This paper proposed a decarbonisation strategy for a 100 % electrified building located in a Mediterranean area by using experimental data and a building energy model. Experimental data were processed for use in the calibration of the energy model. Once the model was calibrated, different energy efficiency measures were proposed.

The analysis of the energy balance shows that the electricity consumed by heating and cooling represents the primary consumption of the building. This is followed by lighting consumption, which is high even though the luminaires in most of the building are LED. Interior appliances that contribute to the energy balance, such as computers and other electronic devices common in office buildings, represent a considerable percentage of the energy balance, with almost the same consumption as the lighting facility. This consumption is followed by the

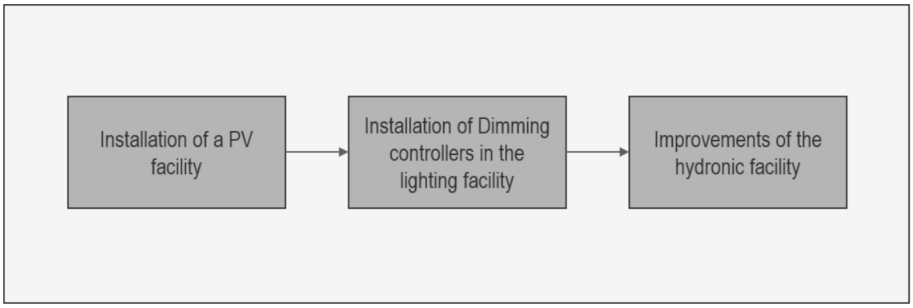

Fig. 22. Decarbonisation strategy proposed.

electricity consumed in fan coils and water circulation pumps. The lowest consumption in the energy balance relates to the ventilation.

The water circulation pump system has been studied as an energy efficiency measure. The current system is composed of a constant speed system. If variable speed pumps substitute the current system, there would be less water circulating in the loops at part load ratio conditions, which means a reduction in the pumps' electricity consumption. The more the heat pump operates at part load ratio conditions, the higher the chances of increasing the efficiency in pumping water through the loop. In heating mode, this consumption could be reduced by 7 %, and in cooling mode by about 2 % compared to the electricity consumption of the current pump systems. However, this measure would only save around 1 kW of electricity.

The substitution of the heat pump would lead to a reduction of 4 % in the electricity consumption during the heating season. This means that the current heat pump still performs well, providing almost the same level of performance as a more modern model. It would therefore not deliver significant benefits to change the heating and cooling generator.

Installing a dimming controller in the lighting facility can reduce 25 % of the electricity consumed by this facility. The addition of this type of control can lead to a 6 % reduction of the total electricity consumed in the building, making it an interesting energy efficiency measure for this type of buildings.

Installing a PV facility could help to decarbonise the building by supplying renewable energy directly. The results show that the occupation of almost all the surfaces available on the roof could produce 20 % of the building's yearly electricity consumption. This energy could be used more effectively during the cooling season, as the curves of PV production and electricity consumption more closely overlap.

This study affirms the centrality of clean energy investments advocated by policies like RED or EPBD, placing particular emphasis on photovoltaic generation to achieve ambitious climate objectives in 100 % electrified buildings located in Mediterranean regions, while de-emphasising HVAC upgrades.

6. Disclaimer

The information and views set out are those of the authors and do not necessarily reflect the official opinion of the authors' employers.

CRediT authorship contribution statement

Juan Carlos Roca Reina: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Conceptualization. **Francisco Javier Aguilar Valero:** Writing – review & editing, Supervision, Methodology, Data curation. **Pedro Ginés Vicente Quiles:** Writing – review & editing, Supervision, Methodology.

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

The data that has been used is confidential.

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