Programa de Doctorado en Tecnologías Industriales y de Telecomunicación

Contributions to the decarbonisation of the EU building stock by the upgrade of its heating & cooling facilities

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La presente Tesis Doctoral, titulada "Contributions to the decarbonisation of the EU building stock by the upgrade of its heating & cooling facilities", se presenta bajo la modalidad de **tesis convencional,** con las siguientes publicaciones como **índices de calidad**:

- Roca Reina, J.C, Aguilar Valero, F.J and Vicente Quiles, P.G, "Energy model development of an office," in XII National and y III International Conference on Engineering Thermodynamics, Madrid, 2022.
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Además de las publicaciones citadas previamente, se han realizado otras publicaciones que no forman parte de los índices de calidad de la tesis doctoral, no obstante, parte del contenido de la tesis proviene de las mismas. Dichas publicaciones son:

- Roca Reina, J. C., Toleikyte, A., Volt, J., & Carlsson, J. (2024). Alternatives for upgrading from high-temperature to low-temperature heating systems in existing buildings: Challenges and opportunities. Energy And Buildings, 114798. https://doi.org/10.1016/j.enbuild.2024.114798
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El Dr. D. Pedro Ginés Vicente Quiles, director, y el Dr. D. Francisco Javier Aguilar Valero, codirector de la tesis doctoral titulada **“Contributions to the decarbonisation of the EU building stock by the upgrade of its heating & cooling facilities”.**

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Que D. Juan Carlos Roca Reina ha realizado bajo la supervisión de nuestro Programa de Doctorado el trabajo titulado **"Contributions to the decarbonisation of the EU building stock by the upgrade of its heating & cooling facilities"** conforme a los términos y condiciones definidos en su Plan de Investigación y de acuerdo al Código de Buenas Prácticas de la Universidad Miguel Hernández de Elche, cumpliendo los objetivos previstos de forma satisfactoria para su defensa pública como tesis doctoral.

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Abbreviations and symbols

RED	Renewable Energy Directive
EPBD	Energy Performance of Buildings Directive
nZEB	Nearly-zero energy buildings
ETS 2	Emission Trading System 2
EEM	Energy efficiency measures
GHG	Greenhouse Gas
PCM	Phase-change materials
TES	Thermal energy storage
PV	Photovoltaic
MPC	Model predictive control
TMY	Typical meteorological year
BMS	Building Management System
COP	Coefficient of performance
EER	Energy Efficiency ratio
EIR	Energy Input Ratio
NMBE	Normalized Mean Bias Error
RMSE	Root Mean Square Error
ϕ_{gains}	Thermal gains of the building
ϕ_{solar}	Solar gains
ϕ_{int}	Internal gains
F_{sh}	Factor of external shading
F_F	Fraction of the frame in the window
F_W	Reduction factor
$g_{gl,n}$	Solar factor
$A_{w,j}$	Area of windows with orientation j
F_{ob}	Form factor between the buildings and the sky
α_{op}	Absorption coefficient of the opaque envelope
R_{se}	External thermal surface resistance
U_i	U-value of the of the building envelope element i
$A_{i,j}$	Area of the opaque element i with orientation j
I_j	Average global irradiation on surfaces with orientation j
φ_{int}	Internal heat gain due to occupation and internal appliances
A_c	Heated floor area of the building
$Q_{heating}$	Heating demand of the building
ϕ_{losses}	Thermal losses of the building
C_b	Building inertia coefficient
T_b	Interior temperature of the building
EIRfTEMP	Energy Input Ratio in function of the exterior temperature
CAPfTEMP	Capacity in function of the exterior temperature
EIRfPLR	Energy Input Ratio in function of the Part Load Ratio Conditions

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Summary

The decarbonisation of buildings has become key to meet the targets of several energy related policies, being the main one the Green Deal, which has stablished that the EU should be carbon neutral by 2050. The aim of this work is to provide insights that can help the decision making in the decarbonisation of the EU building stock, making emphasis in its heating and cooling facilities.

The electrification of the heating demand through the use of heat pumps is a common solution adopted in the building sector to substitute fuel-based heating systems, like boilers. In the last few years, the installation of heat pumps to substitute gas boilers has increased. The main issue, that most of the end users do not take into account, are the different working conditions of heat pumps and boilers. If a facility has been calculated and sized to provide the heating demand at specific water production temperatures, it won't work if these temperatures are lower, unless some conditions are meet.

One line of research explores the barriers that the downgrade of the water temperatures in the facility could make and how to overcome them. Issues with the current indoor units' surface, due to the lower temperatures, or the higher water pressure drop, due to the higher water flow, can be the key to understand if the installation of heat pumps is feasible. In most of the cases, a previous building retrofit is essential to make the building "low-temperature" ready.

If building retrofits cannot be performed, then the installation of heat pumps that work at 45/50°C is challenging. In the second line of research, we explore the possibilities of installing low-carbon technologies without downgrading the water supply temperature. The technologies covered are hybrid and high-temperature heat pumps.

The procedure followed to decarbonise buildings is usually seen as changing a boiler with a heat pump. Having a boiler is not the case in buildings located in Mediterranean areas that have a much higher cooling than heating demand. The third line of research explores the possibilities to decarbonise 100% electrified buildings that are located in Mediterranean areas. In this line of research, we explore what type of solutions can be applied this type of buildings with a case study.

The work done in this doctoral thesis covers different types of buildings located in specific areas of the EU. This means that it covers a wide range of decarbonisation strategies, which depend on the location of buildings and the heating and cooling systems used.

Resumen

La descarbonización de los edificios se ha convertido en la clave para cumplir los objetivos de varias políticas relacionadas con la energía, siendo la principal el Green Deal, que ha establecido que la UE debe ser neutra en carbono para 2050. El objetivo de este trabajo es proporcionar información que pueda ayudar a la toma de decisiones en la descarbonización de los edificios de la UE, haciendo hincapié en sus instalaciones de calefacción y refrigeración.

La electrificación de la demanda de calefacción mediante el uso de bombas de calor es una solución comúnmente adoptada en el sector de los edificios para sustituir los sistemas de calefacción basados en combustibles, como las calderas. En los últimos años ha aumentado la instalación de bombas de calor para sustituir a las calderas de gas. El principal problema, que la mayoría de los usuarios finales no tiene en cuenta, son las diferentes condiciones de funcionamiento de las bombas de calor y las calderas. Si una instalación se ha calculado y dimensionado para proporcionar la demanda de calefacción a unas temperaturas de producción de agua determinadas, no funcionará si estas temperaturas son inferiores, a menos que se cumplan algunas condiciones específicas.

Una línea de investigación explora las barreras que podría suponer el descenso de las temperaturas del agua en la instalación y cómo solucionarlas. Los problemas con la superficie de las unidades interiores actuales, debidos a las temperaturas más bajas, o la mayor caída de presión del agua, debida al mayor caudal de agua, tienen una gran importancia para entender si la instalación de bombas de calor es viable. En la mayoría de los casos, para que el edificio sea declarado “Apto para bajas temperaturas” es esencial que se haya realizado previamente una reforma del edificio.

Si no es posible renovar el edificio, la instalación de bombas de calor que funcionen a 45/50 °C puede llegar a ser casi imposible en muchos casos. En la segunda línea de investigación, exploramos las posibilidades de instalar tecnologías de baja emisión de carbono que trabajen en el mismo nivel de temperatura que los sistemas de calefacción a reformar. Las tecnologías contempladas son las bombas de calor híbridas y de alta temperatura.

El procedimiento seguido para descarbonizar los edificios suele consistir en cambiar una caldera por una bomba de calor. No es el caso de los edificios situados en zonas mediterráneas, cuya demanda de refrigeración es mucho mayor que la de calefacción. La tercera línea de investigación explora las posibilidades de descarbonizar edificios 100% electrificados que estén situados en zonas mediterráneas. En esta línea de investigación, exploramos qué tipo de soluciones pueden aplicarse a este tipo de edificios con un estudio de un caso.

El trabajo realizado en esta tesis doctoral abarca diferentes tipos de edificios situados en varias zonas de la UE. Además, abarca una gama variada de estrategias de descarbonización, que dependen de la ubicación de los edificios y de los sistemas de calefacción y refrigeración utilizados.

1. Introduction

The emissions of CO2 into the atmosphere have been a highly relevant problem since the beginning of the 20th century. In 1896, a Swedish scientist called Svante Arrhenius highlighted that burning fossil fuels could increase the overall temperature of the planet[1]. Several policies, conferences, research works, or projects have been developed to fight against this effect. For example, 20 years ago, the Kyoto Protocol[2] was adopted, which is the main convention involving many different countries that fights against the greenhouse effect.

The European Union has fought against greenhouse emissions (GHG), developing different policies with different climate goals. For instance, Horizon 2020 had, among other objectives, the goal of decreasing CO2 emissions by 20% compared to the levels of the 1990s. Regarding this goal, the EU was able to reduce its emissions by over 30%. In 2019, the EU launched an ambitious plan called the Green Deal[3]. One of the goals of this plan is to reduce CO2 emissions by 55% by 2030 and to become carbon neutral by 2050.

Buildings account for 40% of the EU's energy consumption and 36% of its GHG emissions [1]. For this reason, how energy is consumed and the energy carriers used in buildings will play a key role in reaching all the targets mentioned above.

The need to reduce GHG emissions in buildings has led to the release of several policies, such as the Energy Efficiency Directive, which emphasizes the importance of innovative solutions to enhance energy efficiency, for instance, in buildings [2]. The directive was updated in 2023, expressing the importance of creative solutions to increase energy efficiency, for example, in buildings [3].

Moreover, the Renewable Energy Directive [4] (RED) highlights the use of renewable energy, including the building stock. One of the targets of this directive mentions at least 42.5% of renewable energy by 2030.

Regarding buildings, the Energy Performance of Buildings Directive (EPBD) can be considered a pillar in reaching a carbon-neutral building stock. It started in 2002 with energy efficiency requirements for new construction buildings. It introduced the concept of Energy Performance Certificates, as well as the definition of nearly-zero energy buildings (nZEB) and zero-emission buildings. Member states are asked to design policies that remove the use of fossil fuels in buildings by 2040. The EPBD established that new buildings must comply with NZEB standards from January 2021 [5]. The 2024 recast of the EPBD introduces the concept of Zero-Emission Buildings (ZEB). The buildings included in this definition require almost no energy, and their CO2 emissions are practically null. It is the responsibility of all Member States (MS) to introduce their own definition of nZEBs and ZEBS. In 2025, Scientists from the Joint Research Centre of the European Commission (JRC) reviewed how the MS have defined these concepts of NZEB and ZEB [6]. In 2020, a work done by the JRC analysed the last 50 years of energy efficiency policies in buildings of the EU [7].

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[1] https://courses.seas.harvard.edu/climate/eli/Courses/EPS281r/Sources/Greenhouse-effect/Arrhenius/3-optional-Crawford-1997.pdf

[2] https://unfccc.int/resource/docs/convkp/kpspan.pdf

[3] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_es

In addition, the European Commission started in 2022 with the REPowerEU plan [8]. The main goal of this plan is to make the EU independent of Russian fossil fuels before 2030.

Following the need to reduce the carbon footprint of different appliances, the Ecodesign Directive was released in 2009. Directive 2009/125/EC served as the starting point for various appliances to increase their energy efficiency and reduce their energy consumption. For example, following the ecodesign requirements, the Commission Regulation 813/2013 implemented the ecodesign directive for space heaters. The energy consumption obtained by different products had to be compared easily by the end-user of these types of appliances. For this reason, Directive 2010/30/EU was released, describing how products should be classified with different energy labels.

In 2027, the new Emission Trading System (EU ETS 2) will work as a cap-trade scheme and will cover the emissions coming from fossil fuels in buildings, increasing the bill of the end-users who use gas or oil boilers for space heating or domestic hot water.

The work developed during these years has focused on providing insights into how to reduce the carbon footprint of buildings by improving their heating and cooling facilities. The proposed solutions encompass the energy efficiency of current facilities, the energy carriers utilised, and the feasibility of renewable energy production.

The proposal of EEMs lies in the impact they can have on the building. The energy consumption of the buildings covered has been analysed before the implementation of EEMs. The current energy consumption is crucial for understanding the order of magnitude of buildings' energy consumption, and most likely when it comes to heating in buildings located in central Europe.

These energy efficiency measures (EEMs) proposed take into account the type of climate, current heating systems installed in buildings, and the building typologies. The research area spans from residential building typologies built in the 1970s in cold climates to an office building constructed in 2003 in a Mediterranean region. For this reason, the work carried out can provide valuable insights into the strategies to be considered for reducing the carbon footprint of buildings.

Part of this thesis has been the case study of an office building located in the Mediterranean area of Spain. This building is 100% electrified, not consuming any fossil fuel inside the building. This is a particular case that has been studied, and it employs a very different type of decarbonisation approach than residential buildings located in central Europe, which consume fossil fuels for heating.

It is essential to mention how the term "decarbonisation" is used. This term refers to a partial reduction in carbon footprint. It needs to be specified because this term is used in some literature as the total reduction of the carbon footprint of a building.

2. State of the art

For so many years, the decarbonisation of buildings has become a common topic of research. The policies mentioned in the previous chapter have boosted study in this field, allowing different authors to explore various aspects of the buildings.

There are three different research topics to analyse the potential decarbonisation of buildings: the first is the reduction of energy demand, the second is the improvement of system efficiency, and the third is the integration of renewable energy. Energy demand reduction measures focus on improving the quality of the building envelope by adding more insulation, enhancing the windows installed, and implementing passive solutions, among others. This should be the first step in a building decarbonisation strategy, as the best energy is the one that we do not consume. Once the energy has been reduced to its minimum, we must cover that energy demand with efficient systems that provide low energy consumption, thereby meeting the heating or cooling demand. Finally, once we have reduced energy demand and implemented efficient systems, we must evaluate the integration of renewable energy sources, such as photovoltaics. This type of strategy is frequently presented as a pyramid, like the one shown in Figure 1.

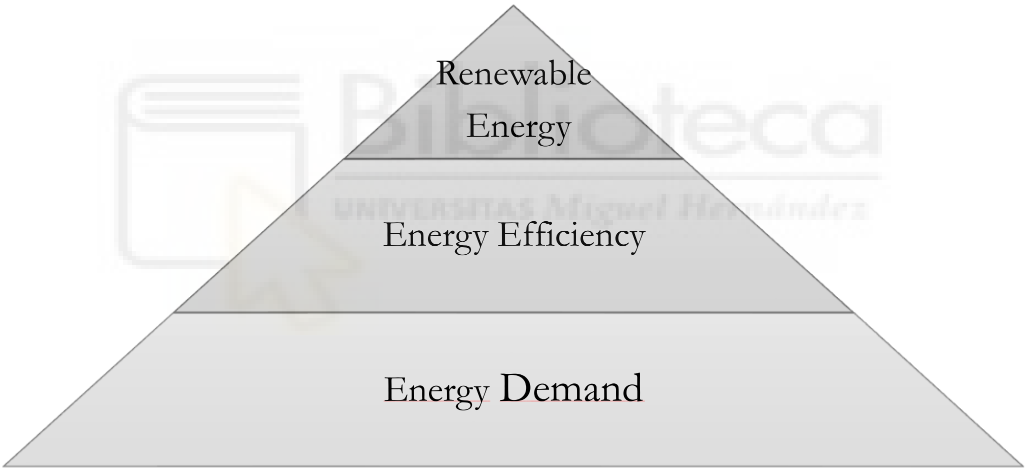

Figure 1. *Energy efficiency measures pyramid*

The work carried out in this thesis is mainly focused on the second type of measure, the efficiency of the systems. In one specific case, we also provide an estimation of how renewable energy integration can contribute to decarbonising a building.

Energy demand. Different works in the literature try to find a cost-effective solution to the improvement of the building envelope of buildings, and therefore contribute to their decarbonisation. Considering the materials used, approximately 40% of the heating demand can be reduced, in accordance with Spanish regulatory standards [9].

Adaptive envelope technologies like cool roofs or switchable insulation systems can achieve up to 51% savings in space cooling and 109% in the total energy demand of office buildings [10].

Thermal bridging is another aspect to consider when improving the building envelope. Different authors have worked on the definition of thermal bridging [11, 12, 13]. In addition to these studies, other authors estimated different façade designs to improve the quality of the building envelope and reduce the effects of thermal bridging [14].

Phase-change materials (PCM) have become an option to optimise the heat transfer in building envelopes. PSM can improve thermal comfort and minimise energy demand by up to 24.2% [15]. The origin of these materials should also be considered; bio-based PCMs are an effective option to add in building envelopes, improving the heat transfer and the thermal energy storage rates [16].

Building envelopes are strongly linked to the indoor thermal comfort of the end users. A case study in Mediterranean buildings shows that the improvement of the building envelope can reduce the discomfort hours by 80% [17].

The effectiveness of building retrofits is dependent on future climate change. If exterior conditions change, it can be challenging to judge how effective an energy demand reduction measure is. The development of integrated modeling considering climate effects, the development of optimization methods that mitigate climate uncertainty, and the implementation of policy frameworks can play a key role in building retrofits [18].

The improvement of the building envelope is key to reducing the water supply temperature in hydronic heating facilities. A study carried out by [19] concluded how important it is to add more insulation to the building envelope to enable the introduction of low-temperature heating.

Energy efficiency. The European Commission Joint Research Centre carried out a Science for Policy report in which they discussed how the deployment of 30 million heat pumps (following the REPowerEU targets) could affect the EU. They concluded that the replacement of 1/3 of the current boilers installed in buildings with heat pumps could lead to a reduction of 36% of fossil fuel consumption and a reduction of 28% of CO_2 emissions [20].

Changing gas boilers with heat pumps for space heating could achieve CO_2 emission reductions of around 60-70% in houses located in Germany or Spain [21]. In this study, the authors decided to compare boilers with air/water heat pumps, which work at lower temperature levels than boilers. They discussed what needs to be done to make the building low-temperature ready.

Another study analysed this comparison of heat pumps and gas boilers in residential buildings. The results show that heat pumps can consume between 1.15 and 2.34 times less energy than gas boilers to meet the same energy demand of the building [22].

Heat pumps can also contribute to energy savings in ventilation systems. A study reviewed this type of technology and its status of the art. It talked about the adoption of heat exchangers located in the different air currents or the use of passive energy recovery units [23].

The optimization of the water supply temperature can be done with heat pumps. A study analysed this type of energy efficiency measure, aiming to achieve thermal comfort inside the building. The results achieved indicated that automatic water supply temperatures in function of the thermal load can be implemented in the heat pump [24].

Hybrid heat pumps and high-temperature heat pumps can be considered an option as well [25]. This study assumed that the building envelope could not be refurbished; therefore, the level of water temperature in the hydronic facility should not be reduced. The results of using this type of system allowed for achieving around 60% of CO_2 emission reductions.

Following the same topic of high-temperature heat pumps, other authors investigated how R290 heat pumps could be integrated into buildings [26], achieving a 20% reduction in non-renewable primary energy consumption. In terms of costs, a study reveals that high-temperature heat pumps can be considered a cost-effective solution for substituting natural gas boilers, with payback years lower than four [27].

The exterior unit situation of an air-source heat pump can be a bottleneck in the installation work, due to the need for air to evaporate the refrigerant, noise, and visual impact. A study carried out in Germany had a look into this, mentioning that the use of sound insulation hoods could achieve reductions up to 15 dB(A) [28].

The combination of hydronic heat pumps with thermal energy storage systems (TES) is also a matter of study. The way these systems work is by connecting the hydronic heat pump directly with the water tank. Then, this water tank would be associated with the indoor units, such as radiators. This type of configuration enables more stable performance of the heat pump, preventing unnecessary starts and stops that can reduce the system's efficiency during periods of low heating or cooling demand. Different studies have proposed strategies to enhance system performance or decrease costs [29, 30].

Variable Refrigerant Flow (VRF) systems in buildings are also a matter of study. Some authors estimated that the use of heat recovery in these systems can lead to coefficients of performance from 3 to 7.5 [31]. The efficiency measurements of these types of systems are not always straightforward. Some authors proposed two techniques to improve this type of measurement [32]. The energy efficiency of this type of system is sometimes eclipsed by the amount of refrigerant to be used. The inaccuracies in the amount of refrigerant used in the VRF systems can lead to charge faults. Some authors have investigated this topic, proposing fault diagnosis strategies or developing experimental analyses [33, 34, 35, 36, 37].

Different authors have also evaluated energy efficiency measures in the lighting facility. In a study conducted at the New York Times headquarters, the authors estimated that the use of dimming control systems can lead to a 20% reduction in electricity consumption in the lighting facility [38]. In addition to this study, other authors estimated this reduction in 30% in a building located in Seoul [39]. Another study analysed in depth a specific part of a building with two façades oriented to the South and East. They concluded that energy savings in lighting facilities using dimming controllers are about 27-80% depending on the area [40].

Renewable energy. Once the consumption of the energy carrier has been reduced to its minimum, we have to care about the origin of this energy carrier. If we cannot reduce the amount of energy carriers, but the amount we consume to meet the energy demand comes from a renewable energy source, then the building would be fully decarbonised.

One solution that is widely used is the photovoltaic (PV) energy production for self-consumption in buildings. According to [41], the use of PV for self-consumption could reduce 300 tCO_2/ year per GWh of PV consumption.

Some authors have studied the possibility of integrating PV in green envelopes, achieving good levels of performance and enhancing the aesthetic value of the building [42].

In a study where the authors estimated the potential of adding 3 MW of PV at University College Dublin, they were able to assess a 26% reduction in GHG emissions. Other authors in similar conditions estimated between 10% and 19% of GHG emissions [43, 44].

The integration of PV with heat pumps or air conditioning systems can play a key role in the decarbonisation of buildings. In one study, the authors demonstrated that a heat pump producing domestic hot water connected to a PV facility can reduce non-renewable primary energy consumption by 79% and CO_2 emissions by 82% [45]. In terms of air conditioning systems, the connection of a PV facility can save more than 60% of CO_2 emissions [46]. Another similar study concluded that model predictive control (MPC) is crucial for the optimal operation of this type of PV system combined with heat pump systems [47]. In line with these studies, some authors studied the optimization possibilities of dimensioning PV and heat pump systems. The study focused on the optimisation of the system size [48]. Following this line of work, other authors analysed the refurbishment with PV and heat pumps of 128 buildings in the north of Spain [49]. Different authors have examined the decarbonisation possibilities of a multi-apartment building by utilising heat pumps, district heating, and photovoltaic electricity production, concluding that the use of heat pumps is the most promising solution, not only in terms of usage, but also in terms of its environmental impact [50]. In line with these studies, other authors identified the technical feasibility of retrofitting existing buildings with PV and heat pumps, achieving 60-86% emission savings due to the installation of the heat pump and between 13-39% due to the PV facility self-consumption [51].

Over the last few years, a new system that utilises PV and heat pumps has emerged as a promising technology. This is the case of the direct expansion photovoltaic heat pump (PVT-HP). It uses the sun as a heat source to warm up the refrigerant and then uses this energy to heat the building. Some authors have reviewed these systems, enhancing their capacity to increase heating energy efficiency and reduce the carbon footprint of buildings [52, 53, 54, 55, 56].

This state-of-the-art analysis has allowed us to understand where there is room for more studies that can contribute added value to the research line of decarbonising buildings. One line of research is the analysis of technical barriers that may arise when considering the decision to change a boiler to a heat pump. The different working conditions make these types of measures challenging in some buildings; therefore, some steps should be carried out on a case-by-case basis before declaring a building "low-temperature ready" by using a low-temperature heating system as a heat pump. In addition to this, the decarbonisation options of different EU residential buildings without decreasing the water temperature level are a good approach to look into as well, since not all the buildings in the EU can reach low-temperature levels in winter. Furthermore, there is not much in the literature that talks about the decarbonisation of buildings that do not consume fossil fuels like gas or oil. Considering the decarbonisation options of buildings 100% electrified can be very important in mediterranean areas, in which several buildings are 100% electrified due to the cooling demand.

3. Objectives

The work developed over the past few years has focused on the decarbonisation of the EU building stock. The buildings considered and the strategies are quite different. These buildings belong to other sectors, like residential or services (offices).

One of the objectives is to understand the **feasibility of upgrading the heating facilities of existing buildings from high-temperature to low-temperature heating systems**. Most of the literature review analyses decarbonisation options using heat pumps, but does not focus on what needs to be done before this type of upgrade. Heat pumps and boilers operate at different temperature levels and water flows. For this reason, adjustments to the hydronic facility need to be made, or a preliminary analysis of the facility's needs must be conducted before deciding to use heat pumps in the current EU building stock.

The second objective is to analyse what **would happen with buildings that cannot work at lower water temperatures** and use boilers for heating. Usual air/water heat pumps cannot be used in these types of buildings, since they cannot meet the water temperature of boilers. Other solutions will be proposed, like the use of hybrid heat pumps or high-temperature heat pumps. These systems allow for the reduction of the use of fossil fuels without decreasing the water temperature level of the hydronic facility. A detailed analysis of the minimum temperature of the water required to meet the heating demand will be conducted. This will help to understand how many moments the boiler will need to act as a booster in hybrid systems.

These two objectives to be analysed in this thesis will be carried out in residential buildings of the EU. The building typologies are selected from the TABULA project [57]. They are mainly single-family houses built in the 1970s. The exterior conditions for this part of the work were taken from the PVGIS database [58]. These exterior conditions did not represent a specific year. We used the typical meteorological year (TMY) available in PVGIS, which is a fictitious year that contains the average climate conditions of a particular region.

To carry out the energy balance of these buildings, a bottom-up model has been created. This model is a simplified hourly energy model based on ISO 52016-1:2017. It considers the building geometry, its envelope characteristics, exterior conditions, and the use of the building, including schedules of heating systems, ventilation rates, interior loads, etc.

The third objective is to see if there is room to **decarbonise buildings that are 100% electrified**. Since they do not use fossil fuels directly for heating, the standard techniques of just changing the heating system do not apply. In addition to this, if the building envelope cannot be upgraded, what can still be done in these buildings? This is the last objective of the thesis: to propose a decarbonisation pathway of 100% electrified buildings and understand the feasibility of proposing energy efficiency measures in this type of building. To do this, a case study has been conducted in a Mediterranean area. In this case study, an experimental building energy balance was performed and used to calibrate a simulation energy model, enabling the assessment of the actual impact of the proposed measures. The measures are presented not only in terms of their decarbonisation potential, but also using economic parameters to assess whether they can be considered cost-effective and therefore applicable to the building.

4. Contributions of the thesis

The thesis provides insights into how to decarbonise the current EU building stock. The solutions provided not only depend on the type of current system installed in the building, but also on the climate where he building is located.

The three objectives highlighted above lead to the following research questions:

1. **Is it possible to decarbonise buildings that use high-temperature heating systems by using low-temperature heating systems like heat pumps?**

   The answer to this question is shown in Chapter 5.1. A heating system is not always easy to adapt when the heating generator is changed. Usually, one thinks that if I have a boiler and I want to install a heat pump, it is just a matter of disconnecting one and connecting the other. This is equivalent to telling an electrical engineer that if a distribution grid operates at 1kV, it will now provide power directly to consumers at 400/230V without the use of transformation centers. Heat pumps work at lower temperatures than boilers; this means that they need, as explained in chapter 5.1, some specific requirements to be used in the same heating facilities as boilers. Renovations of the building envelope or adapting the hydronic facility can help the heating system to work at lower temperatures.

2. **If it is not feasible to downgrade the water temperature in the hydronic facility, is it still possible to install heat pumps?**

   There are specific cases in which the envelope of buildings or the hydronic facility cannot be upgraded. This means that the temperature level cannot be lower than the one already being used by the current heating system installed. To remove boilers without lowering the heating production temperature, other types of systems need to be installed to produce heating at the same temperature. These systems could be high-temperature heat pumps or hybrid heat pumps. In Chapter 5.2, insights into how these systems work and how they can help decarbonise these types of buildings are provided.

3. **If a building does not use fossil fuels and is 100% electrified, is it feasible to continue proposing energy efficiency measures?**

   There are several buildings 100% electrified. As decarbonisation of heating systems is commonly seen as removing boilers and installing heat pumps, what happens in cases that do not include boilers? The answer to this research question is in chapter 5.3, in which an experimental case study has been conducted to analyse what the best options for this type of building are.

5. Results and discussion

In this chapter, the outcomes of the different works carried out are shown. All the publications linked to the thesis are linked to one of the subchapters. In each subchapter, the methodology followed, and the discussion of the results obtained are presented for each type of work. Subchapter 5.1 is linked to the analysis of the possibilities of downgrading the working temperature of hydronic facilities, 5.2 includes how to maintain the level of water temperature but changing the heat generator, and 5.3 shows the outcomes of a case study of a building located in Mediterranean area 100% electrified.

5.1. Upgrading from high-temperature to low-temperature heating systems

This part of the work is focus on how to address the challenges that appear when a heating systems using a boiler as heat generator is substituted by an air/water heat pump. As a first step, it can be seen that just changing it can be enough, but in these types of facilities the hydronic parts play a key role. Therefore, several preliminary analyses need to be done to see if upgrading from one system to another is feasible.

5.1.1. Barriers and opportunities

Water temperature. This parameter is essential to understand what we are doing when we substitute a boiler with an air/water heat pump. Usually, non-condensing boilers could work producing water at 80ºC with a ΔT of 20ºC. This water moves through a pipe facility using circulation pumps and reach the indoor units, which usually are radiators. The average temperature of the facility is 70ºC. This average water temperature is very important when one needs to select the radiators needed. The capacity of the radiators depends one main factor: The ΔT between the facility and the room. Usually, the room is maintained at 20ºC, so if we use a facility that works with an average temperature of 70ºC, this ΔT would be 50ºC. If an air/water heat pump is used, when they work with radiators, they usually produce the water at 45ºC with a ΔT of 5ºC. This means that the average temperature of the facility is 42,5ºC, therefore the ΔT between the facility and the room would be 22,5ºC. They also can work producing water at 55ºC, which would make a ΔT of 32,5ºC. Condensing boilers can also produce water at 65ºC with a return water temperature of 55ºC, which makes an average hydronic facility temperature of 60ºC and a ΔT with the room about 40ºC. With these parameters, one can calculate the capacity of the radiators, and therefore the surface needed. Equation 1 shows how to calculate the capacity of a radiator with these parameters presented.

$$\mathrm{Rad.\,Capacity} = \mathrm{K} \cdot \ \Delta \mathrm{T_{room}}^{\mathrm{n}} \qquad (1)$$

Where:
$\mathrm{Rad.\,Capacity}$: Capacity of the radiator at specific conditions [kW].
K: Radiator constant. Its value could be around 0.3-0.6. The value taken is 0.4 [-].

ΔT_{room}: Difference between the average temperature of the facility and the room [K].
n: Radiator exponent. Its value is assumed to be 1.3 [-].

Figure 2 shows a comparison of how the capacity of the radiators changes when the average temperature of the facility decreases. The reference heating system taken into account for this figure is a non-condensing boiler working at 80/60ºC. If this non-condensing boiler is changed and a condensing boiler producing the water at 65 ºC is installed, the energy demand should decrease in a 25% to be able to use the current hydronic facility as the capacity of the radiators will decrease in a 25% due to the decrease in the water temperature production. For heat pumps producing the water at 55 ºC or 45 ºC this is even more radical, as the capacity of the radiators will decrease in a 50% or in a 65%. This means that if a heating system working at 80/60ºC is changed and a heating system working at 45/40ºC is used, the capacity of the radiators will decrease in a 65%. For this reason, to still be able to use the current hydronic facility, the heating demand should also decrease in the same proportion by upgrading the building envelope.

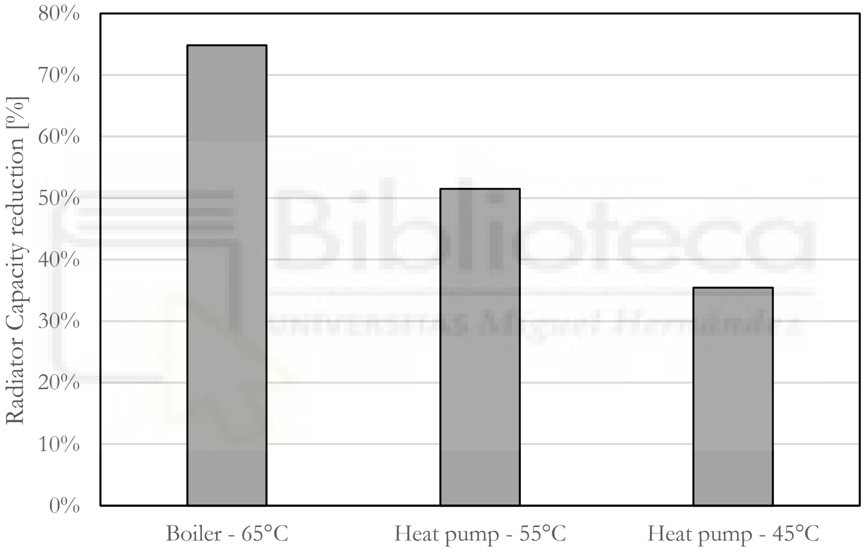

Figure 2. *Radiators capacity comparison – Current heating system working at 80/60ºC*

The situation when the current heating facility installed is a condensing boiler working at 65/55ºC is less dramatic, as the water temperature does not need to decrease to half of its current value to still use the hydronic facility. The results are shown in Figure 3.

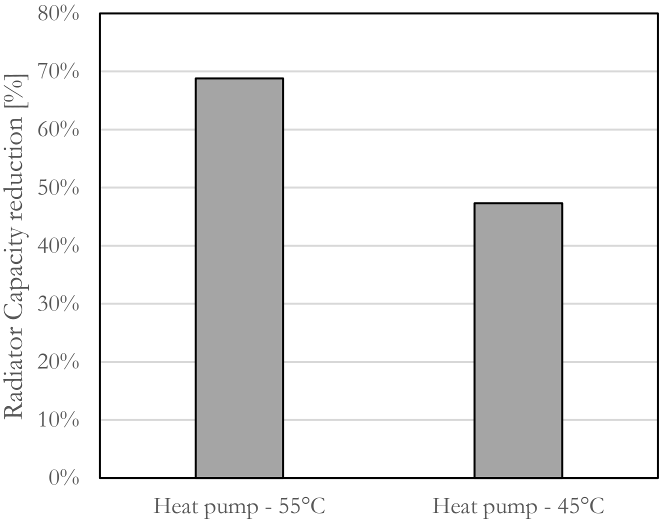

Figure 3. *Radiators capacity comparison – Current heating system working at 65/55ºC*

In this new case, the capacity of the radiators decreases in 30% if the average temperature of the facility decreases in around 10ºC and in 50% if the average temperature of the facility decreases in 20ºC. These levels of capacity reduction of the radiators or, in the same way, reduction of the heating demand is doable by implementing partial or deep renovations in the building.

This usually appears when radiators have been calculated exactly to deliver the maximum heating demand, without any type of margin. Sometimes radiators could be oversized, therefore some decrease in the working temperature of the system could be allowed. According to one study, around 80% of heating systems are oversized, and could be considered 92% taking into account energy renovations towards 2050 [59]. On the other hand, when there is a lack of information to calculate the heat load, heating facilities need to be calculated with conservative assumptions [60]. A study carried out in the Netherlands determined that water supply temperatures could be lowered to 55ºC in 60% of the dwellings analysed [61]. The approach followed in this work is based on a reference heating demand. It is considered that if the heating demand is higher than 150 kWh/m^2, the radiators should be changed.

Power system. One of the main questions that arise when the electrification of the heating is proposed is if the current power grid can afford it. A study carried out by the Joint Research Centre of the European Commission in 2023 [20] analysed the impacts of the deployment of 30 million heat pumps in the power system. The authors obtained the result shown in figure 4. The study found out that the power grid, in terms of global capacity, could afford an increase of 20-40%. However, specific regions should be analysed as a case by case.

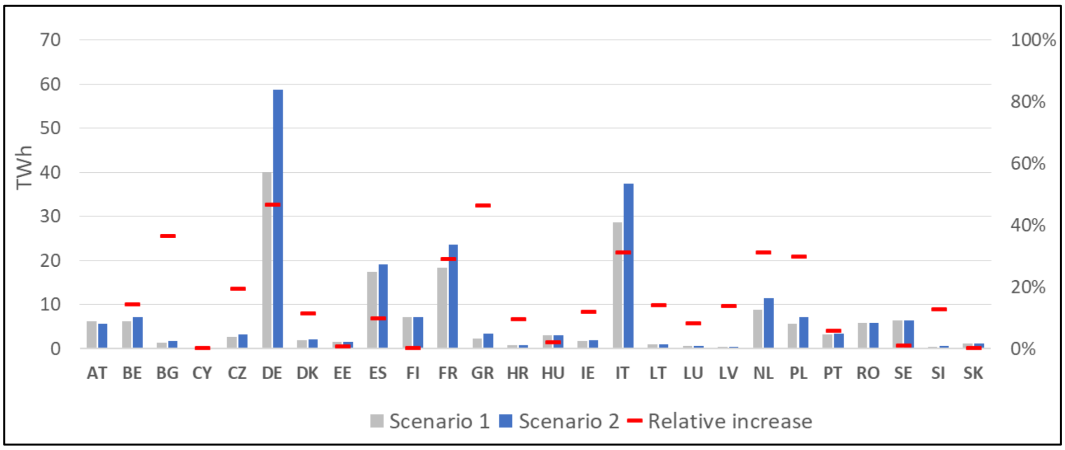

Figure 4. *Impact on the power system of the deployment of 30 million heat pumps following REPowerEU targets*

A different study [62] studied the deployment of heat pumps in Yverdon-lesBains (Switzerland). The authors realised that, on the coldest winter days, under-voltages and line overloading on the power grid could arise. They proposed strategies to reinforce the cables and using cogeneration or photovoltaic units to mitigate the voltage reduction. In addition to this, a different study [63] made a similar study but in the British Columbia (Canada). The authors calculated that an increase of the peak demand of 37% could appear with a full electrification of the gas used for space and water heating.

Hydronic facility. In addition to the other aspects to take into account, the size of the hrdronic facility is crucial to understand if a new system can still use the same pipes. Usually, a boiler is connected to the radiators through a piping facility. These pipes have a specific size calculated in the nominal working conditions. For the same capacity, a boiler usually works with lower levels of water flow than heat pumps since the ΔT of boilers is much higher. The water flow of the system and the ΔT are linked following equation 2:

$$\dot{Q} = \dot{m} \cdot C_p \cdot \Delta T \tag{2}$$

Where:

$\dot{Q}$: Thermal energy [kW]
$\dot{m}$: Water mass flow [kg/s]
C_p: Specific heat [kJ/kg·K]
ΔT: Fluid thermal drop [ºC]

If a heat pump works with lower difference of temperature (around 2-4 times of the one of the boilers) then they will need more water flow to exchange the same amount of heating. For this reason, it is difficult that the current pipes installed can work with heat pumps if before they were working with boilers. As an example, table 1 shows how much the pressure drop in the system can change depending on the water flow for the same water pipes size.

Table 1. *Pressure drop comparison for different heating systems*

Heating system	ΔT [$°C$]	Water flow [l/s]	Di [mm]	Speed [m/s]	Press drop [mmwc/m]	Long [m]	Press drop [bar]
Boiler	20	0.287	20	0.9	49	10	0.064
Heat pump	5	1.148	20	3.6	593	10	0.77
Heat pump	5	1.148	22	3	374	10	0.48
Heat pump	5	1.148	33	1.3	53	10	0.068

As can be seen in table 1, a boiler connected to a Di20 copper pipe will have the same amount of pressure drop than a heat pump working with a Di 33. This means that the size of the pipes should increase in a 60% so ensure the same amount of pressure drop in the hydronic facility. This supposes a low-risk challenge, since most of the pipes are hidden in the walls and cannot be replaced.

In order to avoid this issue, one can think about a hydraulic separation with an inertia water tank. This solution will add a secondary circulation pump between the water tank and the radiators. The heat pump will be in charge of warming up the water tank with almost 0 pressure drop. Figure 5 shows this approach. The inefficiency of this solution is that we are adding an extra electricity consumption to the system due to the new circulation pump that will take care of the drop of pressure through the current piping system.

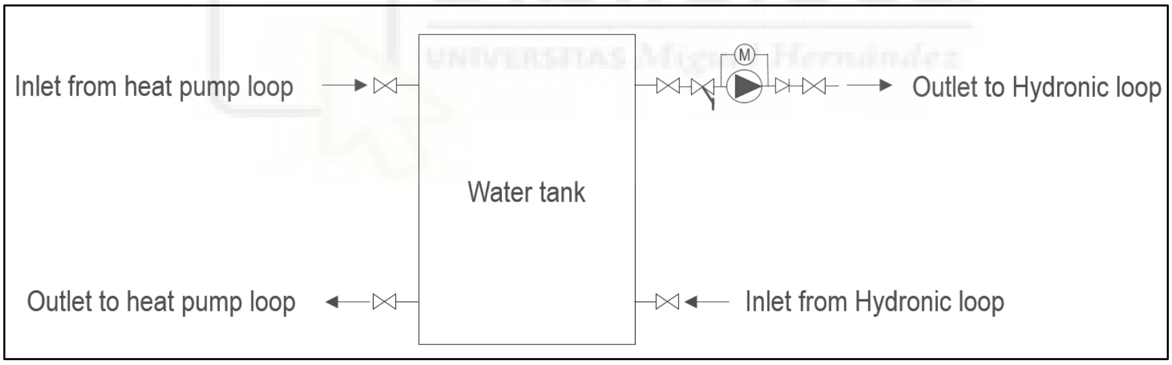

Figure 5. *Hydraulic separation solution*

In the following subchapters, the analysis of substituting from high-temperature to low-temperature heating systems is carried out. The heating demand of all the buildings covered is calculated following a methodology presented in the following chapter. Then the decarbonisation and economic results are compared.

5.1.2. Heating demand methodology

To understand if these types of renovations are feasible or not in buildings an energy balance has been implemented in different EU single family houses. The energy balance used is a simplified energy model based on ISO 52016-1:2017. The geometry of the buildings is taken from the TABULA database and the climate conditions from PVGIS, as mentioned in chapter 3.

The first step in the energy balance is to calculate the energy losses, which are calculated as follows:

$$\phi_{losses} = \phi_{cond} + \phi_{vent} + \phi_{rad} \tag{3}$$

$$\phi_{losses} = \left[\left(\sum A_i \cdot U_i \cdot b_i \right) \cdot (T_b - T_{ext}) \right] + \left[n_{air} \cdot V \cdot C_p \cdot (T_b - T_{ext}) \right] + F_{sky} \cdot h_{re} \cdot \Delta T_{sky} \tag{4}$$

Where:
ϕ_{losses} : Total losses of the building in kWh
ϕ_{cond}: Conduction losses in kWh.
ϕ_{vent}: Ventilation losses in kWh.
ϕ_{rad}: Radiation losses in kWh.
A_i: is the area of the building envelope element i in m^2
U_i: is the U-value of the of the building envelope element i in W/m^2·K
b_i: is the factor soil of the building envelope element i, without units.
T_b: is the interior the building in ºC.
T_{ext} : Is the exterior air temperature in ºC.
n_{air}: is the renovation rate of air in the building in 1/h.
V and C_p are the volume of air conditioned and the air specific heat coefficient in m^3 and W/m^3·K, respectively.
F_{sky}: is the sky factor, the value is 1 for the horizontal envelope and 0.5 for the vertical envelope. h_{re}: Radiative heat transfer coefficient in W/K
ΔT_{sky} is the difference in temperature between the building envelope and the sky. 11 K is used as a suggestion of ISO 52016-2017.

In the energy balance, energy gains are also included. The way they are taken into account is as follows:

$$\phi_{gains} = \phi_{solar} + \phi_{int} \tag{5}$$

$$\phi_{solar} = F_{sh} \cdot (1 - F_F) \cdot F_W \cdot g_{gl,n} \cdot \left(\sum A_{w,j} \cdot I_j \right) + F_{ob} \cdot \alpha_{op} \cdot R_{se} \cdot \left(\sum U_{i,j} \cdot A_{i,j} \cdot I_j \right) \tag{6}$$

$$\phi_{int} = \varphi_{int} \cdot A_c \tag{7}$$

Where:

ϕ_{gains}: Total gains [kWh].
ϕ_{solar}: Solar gains (Opaque and transparent elements) [kWh].
ϕ_{int}: Interior gains in the building [kWh].
F_{sh}: Factor of external shading [-].
F_F: Fraction of the frame in the window [-].
F_W: Reduction factor which takes into account the effect of on-perpendicular radiation on the glazing [-].
$g_{gl,n}$: Total solar energy transmittance, commonly named "solar factor" of the glass [-].
$A_{w,j}$: Area of windows with orientation j [m^2].
F_{ob}: Form factor between the buildings and the sky [-].
α_{op}: Absorption coefficient of the opaque envelope, assumed to equal 0.6 as it represents the average colours of buildings [-].
R_{se}: External thermal surface resistance, assumed to be 0.04 m^2·K/W according to ISO 6946.
U_i is the is the U-value of the of the building envelope element i [W/m^2·K] with orientation j.
$A_{i,j}$: Area of the opaque element i with orientation j [m^2].
I_j: Average global irradiation on surfaces with orientation j [W/m^2].
φ_{int}: Internal heat gain due to occupation and internal appliances [W/m^2].
A_c : Heated floor area of the building [m^2].
Finally, in order to be able to calculate the heating that needs to be delivered by the heating systems to maintain the indoor conditions, the following equation is applied:

$$Q_{heating} = \phi_{losses} - \phi_{gains} + C_b \cdot \frac{dT_b}{dt} \tag{8}$$

Where:

$Q_{heating}$: Heating demand of the building [kWh].
ϕ_{losses}: Thermal losses of the building [kWh].
ϕ_{gains}: Thermal gains of the building [kWh].
C_b: Effective heat capacity of the building, which is the energy needed to increase or decrease in one unit the temperature of the building. This value is obtained from TABULA database. This database establishes this value in 45 Wh/m2.
T_b: Internal temperature of the building [ºC].

The heating demand calculated is taken into account to estimate how much gas is needed by the boiler or electricity by the heat pump to provide the hating demand. This term is commonly known as energy use, and it is described in the following equation:

$$\phi_{use} = \frac{1}{\eta} \cdot Q_{heating} \tag{9}$$

Where:

ϕ_{use} : Energy use of the heating system [kWh]. It could be electricity or gas.

η: Efficiency of the heating system [-]. It can represent the efficiency of a boiler or the COP of a heat pump.
$Q_{heating}$: Theoretical heating demand [kWh].

The efficiency can be calculated in different ways depending on the heating system selected. Two different equations are used:

- COPText: Biquadratic curve that links the performance of an air/water heat pump with the exterior temperature and with the water production temperature.

$$\text{COPfText} = a + b \cdot T_{water} + c \cdot {T_{water}}^2 + d \cdot T_{air} + e \cdot {T_{air}}^2 + f \cdot T_{water} \cdot T_{air} \qquad (10)$$

Where:

a, b, c, d, e, f: Coefficients of the curve calculated by linear regression.
T_{water}: Water supply temperature [°C].
T_{air}: Exterior air temperature [°C].

- EffPLR: Polynomic curve that can represent the performance of a heating system depending on the heat load that it is delivering and the maximum heat load it could deliver at the same conditions.

$$\text{EfffPLR} = a + b \cdot PLR + c \cdot PLR^2 \qquad (11)$$

Where:

PLR: Part Load Ratio coefficient.

The results obtained with these equations lead to theoretical results. Following the TABULA methodology approach, the results can be adapted to a more realistic heating demand. In order to scale this theoretical heating demand a factor called "utilization factor" is applied. Equation 13 shows how to calculate it. The utilization factor is shown in figure 6.

$$U_f = 1.07262 - 0.0013 \cdot \phi_{use} \qquad (12)$$

$$Q_{heating,real} = U_f \cdot Q_{heating} \qquad (13)$$

Where:

$Q_{heating,real}$: Real heating demand [kWh].
U_f: Utilization factor [-].
$Q_{heating}$: Theoretical heating demand [kWh].

ϕ_{use}: Energy use of the building, obtained using the heating demand and the efficiency curves of the heating system installed [kWh/m^2].

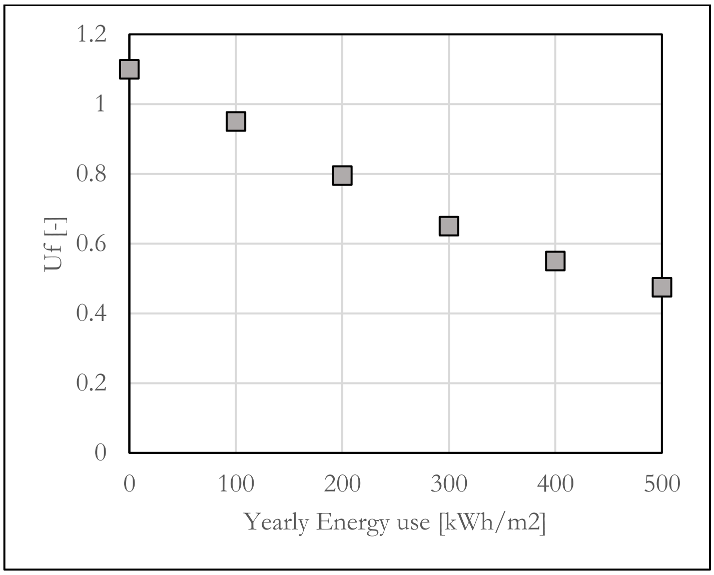

Figure 6. *Utilisation factor taken from TABULA project*

This energy balance has been implemented in three different residential buildings located in three different climate areas. These buildings are single-family houses (SFH) built in the 1970s, and are located in Sweden, Spain and Germany. The initial building characteristic are the ones called "NR", which means "non-renovated". Then some renovations levels are proposed: Partial "PR" (walls and windows) and deep "DR" (PR + floor and roof) renovation. This building information is taken, as mentioned above, from the TABULA project. Table 2 collects all this information.

Table 2. *Building geometry characteristics*

	SE	NR	R1	R2	**DE**	NR	R1	R2	**ES**	NR	R1	R2
	Surf	**U**	**U**	**U**	**Surf**	**U**	**U**	**U**	**Surf**	**U**	**U**	**U**
	m2	**W/m2·K**	**W/m2·K**	**W/m2·K**	**m2**	**W/m2·K**	**W/m2·K**	**W/m2·K**	**m2**	**W/m2·K**	**W/m2·K**	**W/m2·K**
Walls	200	0.31	0.21	0.21	178	1	0.22	0.22	312	1.33	0.64	0.5
Roof	125	0.21	0.21	0.1	183	0.5	0.5	0.19	63	4.17	4.17	0.8
Floor	125	0.32	0.32	0.24	152	0.86	0.86	0.3	90	0.85	0.85	0.85
Windows	22	2.3	0.9	0.9	34	2.8	1.3	1.3	12.6	4.59	1.84	1.84
Heated floor area	106	-	-	-	173	-	-	-	170	-	-	-

The climate considered are the ones of the capital cities of each MS. These exterior conditions, as mentioned in chapter 3, come from the TMY generated by PVGIS. In order to estimate the CO_2 emissions from the energy carriers, an emission coefficient for electricity has been taken into account. It is shown in table 3 at MS level. The factors used for gas and oil are the same for the three Member States, which are 202 gCO2/kWh for gas and 267 gCO2/kWh for oil [66].

Table 3. *CO_2 factors for electricity in different MSs [67]*

	Sweden	**Germany**	**Spain**
gCO_2/kWh	8	314	177

The model can estimate the cost-effectiveness of each heating solution as well. It is evaluated with economic parameters such as: Net Present Value (NPV) and payback. The NPV represents the value of an investment after the years assumed that the investment is worth it. Both parameters are shown in equations 14 and 15:

$$\mathrm{NPV} = \sum_{j=1}^{n} \frac{\mathrm{CS_j} - \mathrm{O\&M_j}}{(1+\mathrm{i})^{\mathrm{j}}} - \mathrm{C_0} \tag{14}$$

$$\mathrm{Payback} = \frac{\mathrm{C_0}}{\left(\frac{\sum_{j=1}^{n} \mathrm{CS_j} - \mathrm{O\&M_j}}{n}\right)} \tag{15}$$

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

5.1.3. Building decarbonisation improving the building envelope

In this part of the chapter, the decarbonisation possibilities by improving the building envelope is presented. Following the methodology described from equation 3 to 8 the yearly heating demand of each building is calculated for every building and each renovation level. The results of this calculation are in figure 7 and 8.

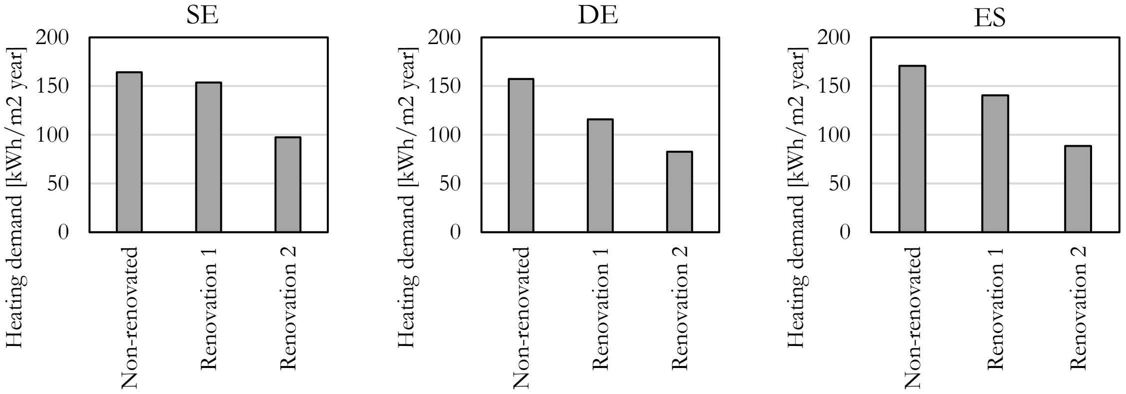

Figure 7. *Yearly heating demand estimation for different renovation levels*

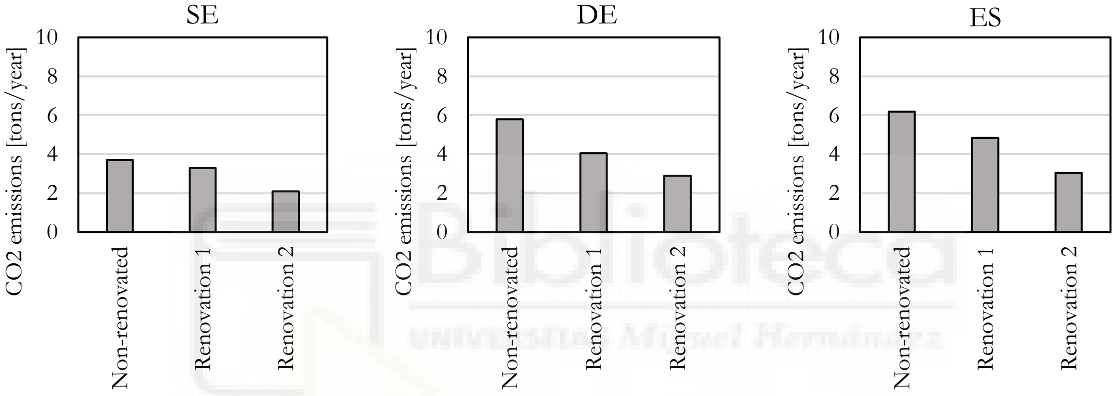

Figure 8. *Yearly CO2 emissions demand estimation for different renovation levels*

According to figure 3 results, if the current heating system is a non-condensing boiler working at 80/60°C, the heating demand should be reduced in 50% in order to be able to install an air/water heat pump working at 55/45°C. This can only be done with deep renovation in the house from Germany or Spain. If the current heating system is a condensing boiler working at 65/55°C, then only partial renovation is necessary in the Spanish and German house to install an air/water heat pump and be able to satisfy all the heating demand. In the Swedish house, it is challenging to improve the building envelope, as the initial quality of it is high already. Therefore, only deep renovations in the building envelope could be acceptable if the current heating system is a condensing boiler working at 65/55 °C.

5.1.4. Building decarbonisation changing the heating systems

In this subchapter, the decarbonisation results of changing the heating systems has been performed. The results are shown in figure 9.

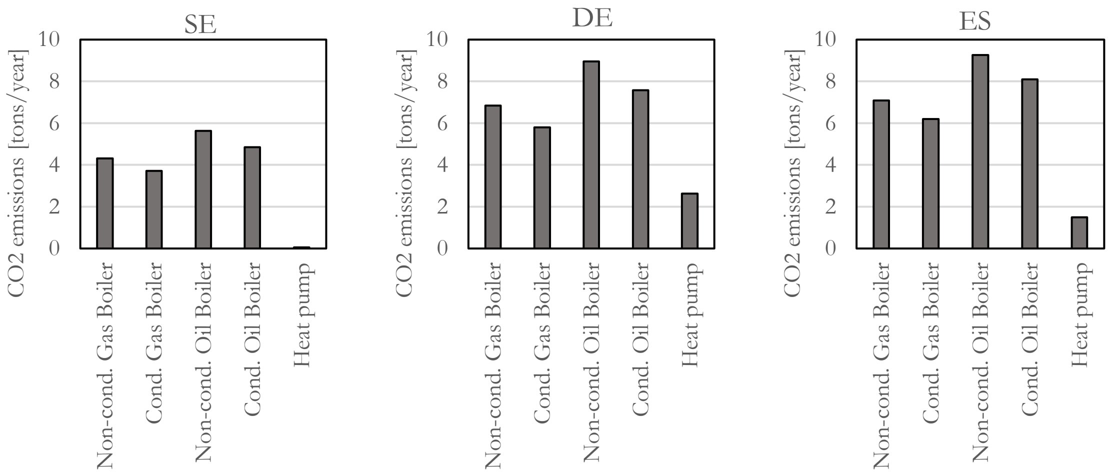

Figure 9. *Yearly CO_2 emissions of different heating systems*

The use of heat pumps as heating systems lead to the lowest CO_2 emissions in all the three residential buildings. The worst-case scenario is the use of non-condensing boilers, which have the lowest efficiency, leading the higher energy use in the building. In addition to this effect, oil also has the highest emission coefficient. This double effect makes oil the solution with the highest emissions.

In the case of Sweden, the use of heat pumps leads to almost the full decarbonisation of the heating system. This is due to how electricity is produced in Sweden. It is produced with renewable and nuclear energy, making the power grid almost decarbonised.

5.1.5. Yearly costs of the solutions proposed

In order to understand if building renovations or changing the heating systems are cost-effective measures, a cost evaluation needs to be carried out

Electricity and gas prices were taken from VaasaETT [64]. These prices are averages of the energy prices frcome have been obtained from the Weekly Oil Bulletin of the European Commission [65]. The data is called "*Gas oil de chauffage Heating gas oil Heizöl*", which was in €/100L. For this reason, an energy content of 10.6 kWh/l was assumed to obtain the same units as the other energy carriers.

Table 4. *Energy carriers costs [€/kWh]*

	Sweden	Germany	Spain
Electricity	0.24	0.40	0.27
Gas	0.25	0.13	0.12
Oil	0.12	0.08	0.08

Considering the prices shown in table 4 and using the energy use of each solution calculated above, an analysis of the yearly costs of using different heating systems can be developed. The results are shown in figure 10.

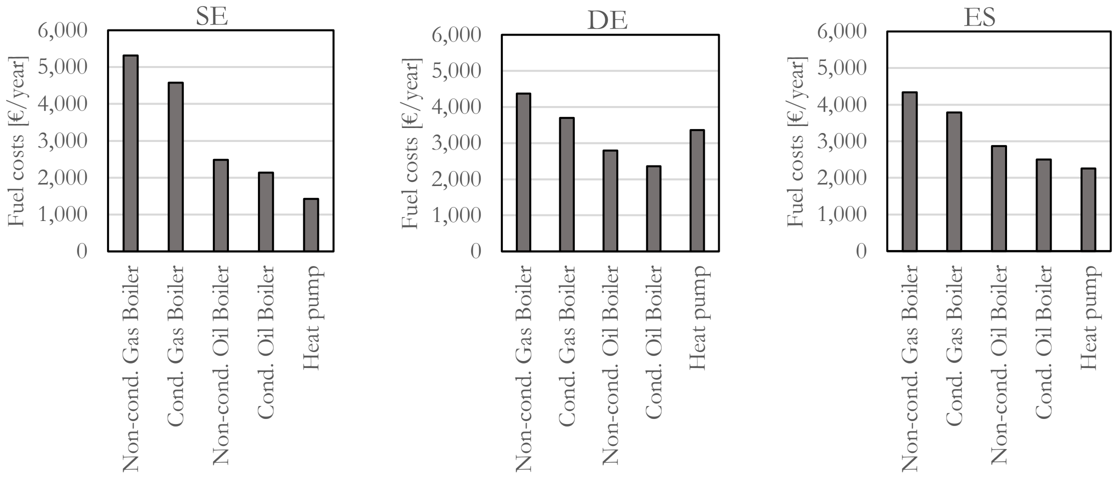

Figure 10. *Yearly costs comparison of different heating systems*

In the three buildings removing a boiler to install an air/water heat pump seems more challenging in Germany due to the comparison of costs between electricity and gas. In the one of Sweden and Spain the air/water heat pump is the cheapest solution in terms of yearly costs. These results provide insights of the cost-effectiveness of the electrification of the heating systems by using heat pumps.

The costs of the energy renovations are considered. Figure 11 shows the yearly fuel expenses of carrying out the renovation levels R1 and R2. The energy use considered in the buildings to evaluate the cost is gas, since it is assumed that the buildings have a condensing gas boiler when the energy renovations are done., so the only cost impact was due to renovation.

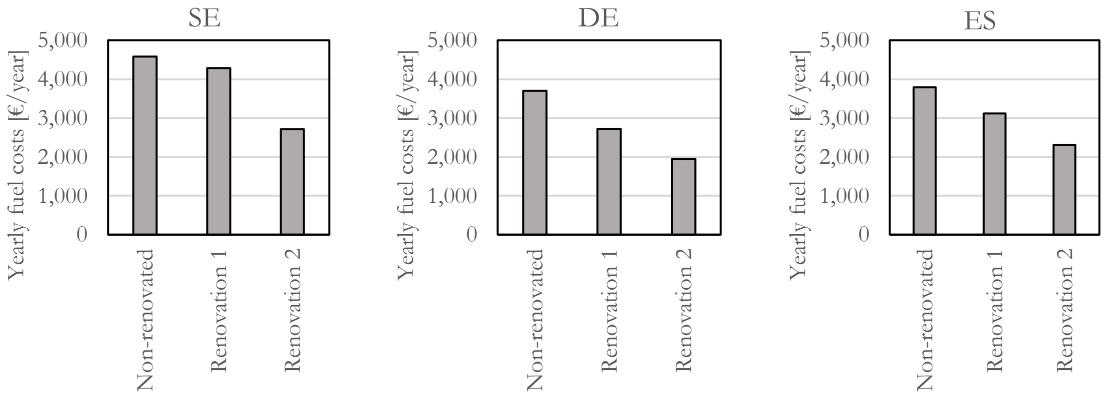

Figure 11. *Yearly costs comparison of different building renovations*

5.1.6. Decarbonisation strategy

Considering the analysis carried out above and the results obtained, some recommendations could be stablished. For the Swedish house, since the building envelope has a high quality already it does not make sense to implement energy renovations. Furthermore, as electricity CO_2 emission factor is almost 0 due to the contribution its production of renewable energy and nuclear energy, the heating is almost fully decarbonised only by electrifying it. The Spanish and German house need to carry out a building renovation before installing an air water heat pump to make the most efficient decarbonisation of the building. Figures 12 and 13 show the emission results and the yearly energy costs of the strategy proposed.

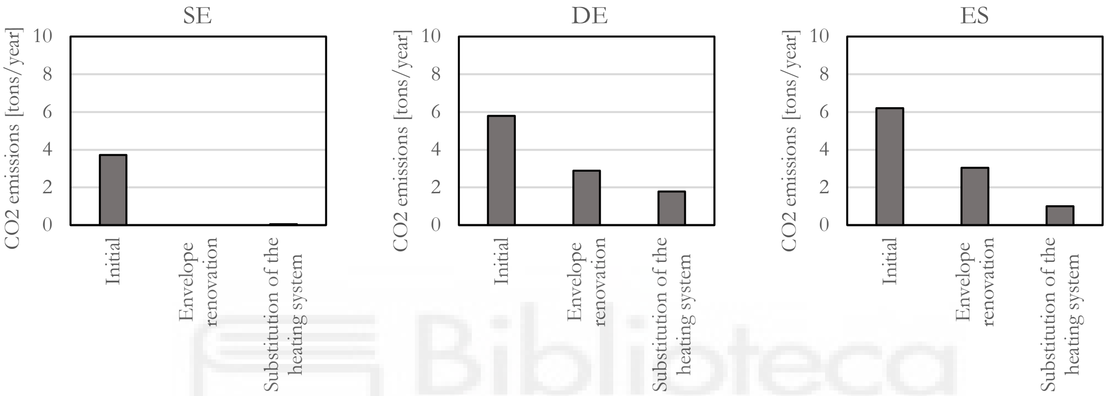

Figure 12. *CO2 emission level of the solutions proposed*

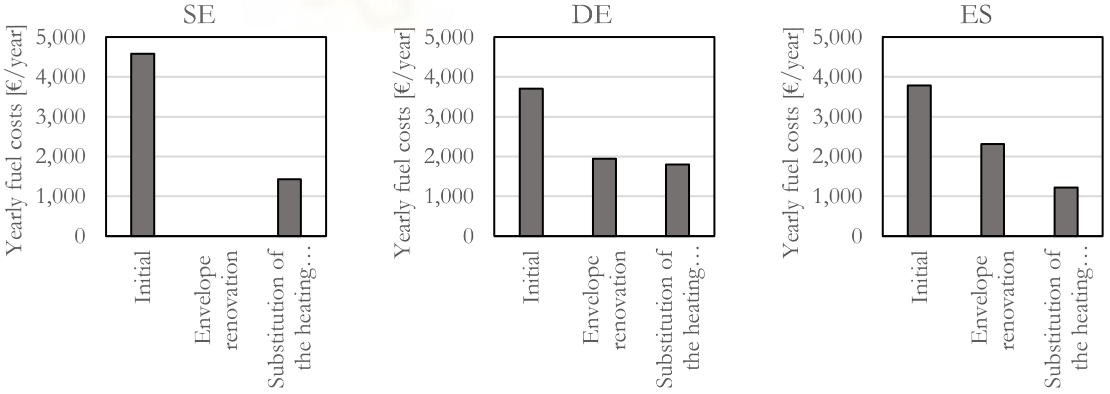

Figure 13. *Yearly energy costs of the solutions proposed*

The cost-effectiveness of the strategies proposed has been estimated according to the methodology proposed in 5.1.2. The investment in the Swedish house is calculated as an investment for 18 years. For the house in Germany or Spain, since they must carry out building renovations, the investment is calculated for 30 years. The discount rate assumed is 3%. Table 5 shows the results

Table 5. *Economic calculations of the strategies proposed*

	SE	DE	ES
Heated area [m2]	106	173	171
Heating demand [kWh/m2*year]	164	157	171
Capacity of the heat pump[kW]	11	11	12
Heating generator [€]	10,874	8,127	8,245
Installation cost [€]	5,105	4,897	2,801
Indoor unit adaptation [€]	7,083	-	-
Renovation costs [€]	-	96,366	52,386
Total investment [€]	**23,063**	**109,598**	**63,432**
NPV [€]	**44,463**	**-59,000**	**786**
Payback [years]	**4.0**	**59**	**28**

As an investment, the installation of an air/water heat pump in Sweden it is very interesting due to the low electricity prices when compared with gas prices. It is a different point of view when renovation costs have to be done prior the installation of a heat pump. According to the results obtained, the investment is worthwhile in the house of Spain. However, in the case of Germany, since the upfront cost are so high when compared with the savings of suing electricity for heating, it is not a good solution from an investment point of view. This type of situations shows the importance of subsidies for homeowners that want to renovate their houses.

The following chapter covers the second line of research, which is based on low-carbon heating systems that work at the same conditions than condensing boilers. Therefore, the bottlenecks of the indoor unit surfaces or the limitations in the drop of pressure do not apply to these systems.

5.2. Building decarbonisation using high-temperature hating systems

The level of the water temperature in hydronic heating facilities is key. The different working conditions between boilers and heat pumps make issues like the level of temperature and water flow appear. Adjustments in the hydronic facility can be done, as it was explained in the previous chapter. But there are some hydronic facilities that cannot be modified and need to continue working in the same conditions of temperature and water flow level.

In order to make the decarbonisation of these facilities feasible, high-temperature heating systems (apart from condensing boilers) have been taken into account. One of the systems considered are high-temperature heat pumps. These type of heat pumps have the same technology as regular heat pumps, but they are able to deliver the heating at higher levels of temperature, around (65°C -70°C). This can be done with two refrigerant-loops: Low pressure (R410a) and a high-pressure loop (R134a).

The other system is basically a hybrid heat pump, which is composed of a regular air/water heat pump and a condensing boiler. Figure 14 shows how this system works. If the exterior temperature is lower than a certain level (Toff), the only system working is the condensing boiler. For exterior temperatures higher than Toff, the heat pump is the one working until the heating demand is so high than it needs a booster to deliver the heating. The heat pump cannot work alone if the water needs to be at a temperature higher than 50°C.

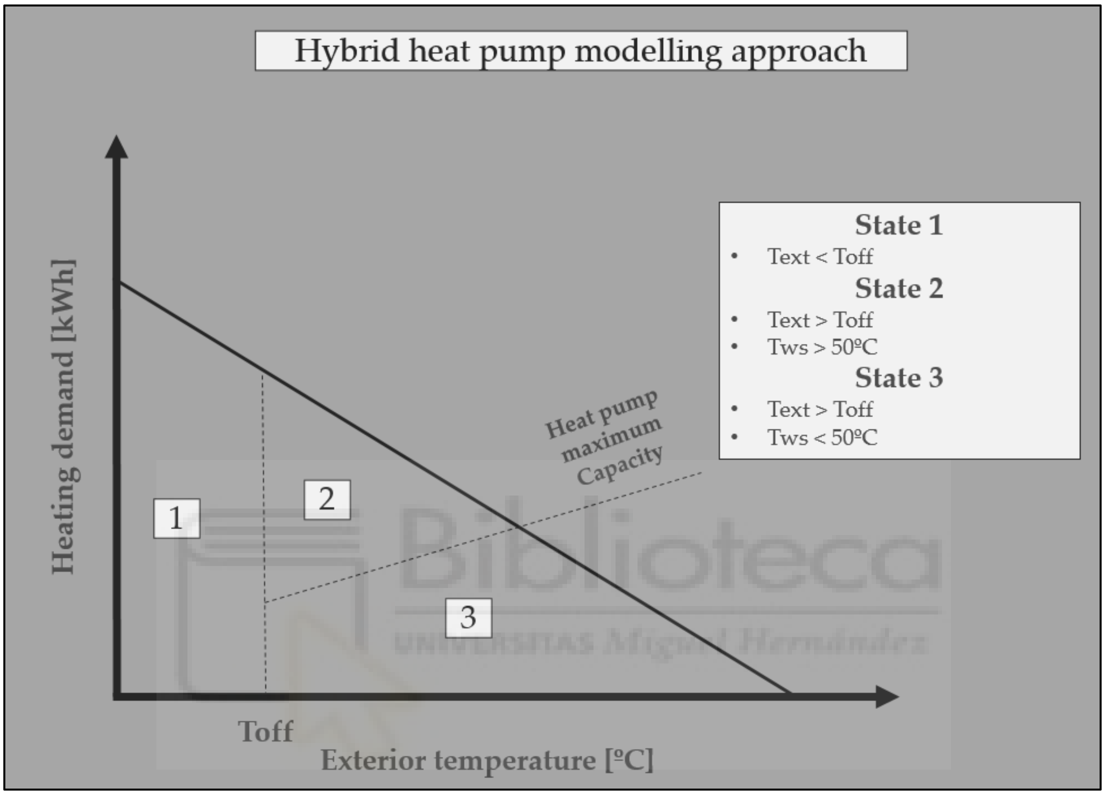

Figure 14. *Hybrid heat pump modelling*

In order to estimate the contribution of the heat pump or the boiler, assumptions need to be taken. The hydronic facility was calculated to the maximum capacity of the system at 65°C. The working temperatures of the condensing boiler are 65-55ºC. Therefore, the hydronic facility has a ΔT_{nom} of 10ºC when the heating demand is maximum.

The boiler works with the same water flow, producing the water at 65ºC. If the heating demand is lower than the maximum, the ΔT will be lower. The ΔT has to be calculated for every condition. This approach is explained in the following equations, assuming a constant mass flow and using equations from EN 442 standard [68].

$$\dot{Q} = K_m \cdot (T_{rad} - T_{room})^n \quad (16)$$

$$T_{rad} = \frac{T_{sup} + T_{ret}}{2} \quad (17)$$

Where:

$\dot{Q}$: Thermal energy delivered [kWh]
T_{sup}: Water supply temperature [ºC]
T_{ret}: Water return temperature [ºC]
T_{rad}: Water average temperature of the radiator [ºC]
K_m& n: Unit less factors that depend on the radiator [-]

Considering a constant water flow, $\Delta\mathrm{T}$ and T_{sup} will only depend on the heating demand. The fact that the heating demand is not the nominal one, makes the $\Delta\mathrm{T}$ lower and the water supply temperature lower as well. This fact makes a direct link between the heating demand and the minimum water supply temperature in the system that will be able to provide the heating demand. Equations 18 and 19 show how this link is made:

$$\Delta T = \frac{\dot{Q}}{\dot{Q}_{nom}} \cdot \Delta T_{nom} \tag{18}$$

$$T_{sup} = \frac{\Delta T}{2} + T_{room} + \frac{T_{sup,nom} - \frac{\Delta T_{nom}}{2} - T_{room}}{\sqrt[n]{\frac{\dot{Q}_{nom}}{\dot{Q}}}} \tag{19}$$

This exercise has been applied to 5 different single-family houses in the EU. It is assumed that all of them have a 20 kW condensing gas boiler with ΔT_{nom} 10°C. Knowing the nominal values, the heating demand is estimated hour by hour with the $\Delta\mathrm{T}$ and the minimum T_{sup} needed to exchange all this amount of heating without substituting the current hydronic facilities. This methodology is very useful to estimate when the condensing boiler booster of a hybrid heat pump should start working. The assumption is that, if following this methodology, the water supply temperature needed to exchange the heating is higher than 50°C, then the heat pump will work at full capacity and the boiler will provide the boost to reach the temperature needed.

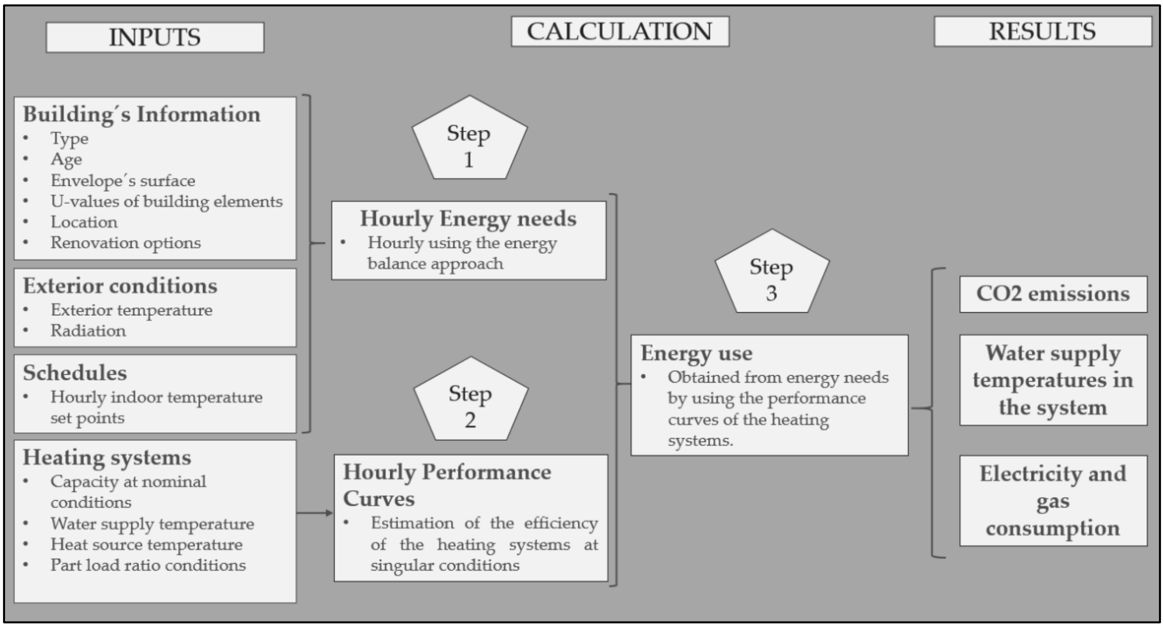

Figure 15. *Model scheme*

The first step would be to show the heating demand of the 5 single-family houses analysed. All of them come from TABULA database and were built in the 1970s. Applying the methodology explained in the previous chapter, the results of the five houses heating demand have been obtained. They can be seen in figure 16. These heating demand can be considered quite high for the residential sector, as they are around 150-200 kWh/m^2·year. These buildings are in different MS of the EU: Spain, Germany, Netherlands and Poland.

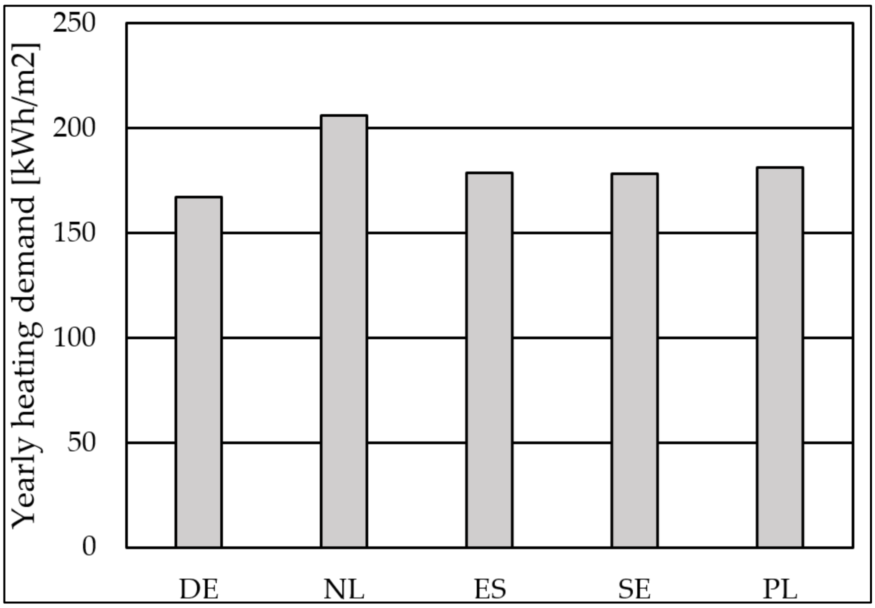

Figure 16. *Heating demand estimation*

The performances curves of the systems selected are exposed in figure 17. On the left side of this figure, we can see the comparison of the performance of normal an air/water heat pump and a high-temperature heat pump producing water at different levels of temperatures. On the right side, there is the efficiency of the condensing gas boiler used to boost the air/water heat pump in the hybrid system.

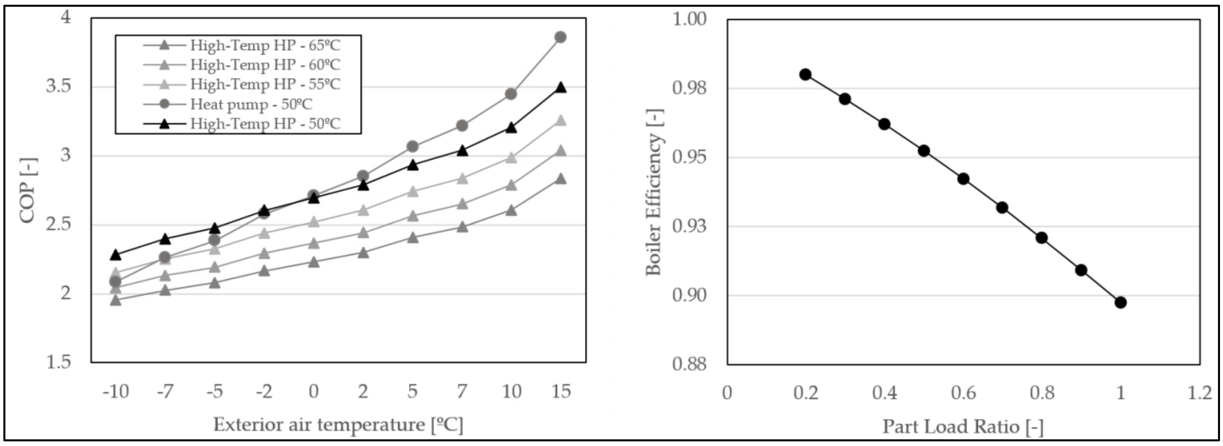

Figure 17. *Performance curves of the systems analysed*

The five different houses have been evaluated under a 1% of percentile to estimate the capacity that the heating systems should have to provide the heating demand under the worst potential exterior conditions. Table 6 shows these results.

Table 6. *Capacity of the heating systems proposed*

	High-Temperature heat pump	**Hybrid Heat pump**[4]
	kW	**kW**
DE	15	10
NL	12	8
ES	19	12
SE	10	7
PL	19	11

---

[4] Note that this capacity is boosted by a condensing boiler of 20kW

The results of the energy balance are shown in figure 18. When hybrid heat pumps are used, around 30% of the heating demand is provided by the condensing boiler and the rest by the air/water heat pump. This means that, by installing a smaller heat pump, the gas consumption can be reduced by 70%. In order to estimate if the solutions proposed are able to decarbonise the buildings, a similar approach as the one followed in the previous chapter has been followed. The conversion factors to tons of CO_2 equivalent used are in table 7. In figure 19, the comparison of CO_2 emissions from different heating systems is shown.

Table 7. *Co2 emission factors for the different MSs*

	Sweden	**Germany**	**Spain**	**Netherlands**	**Poland**
gCO_2/kWh	8	314	177	333	710

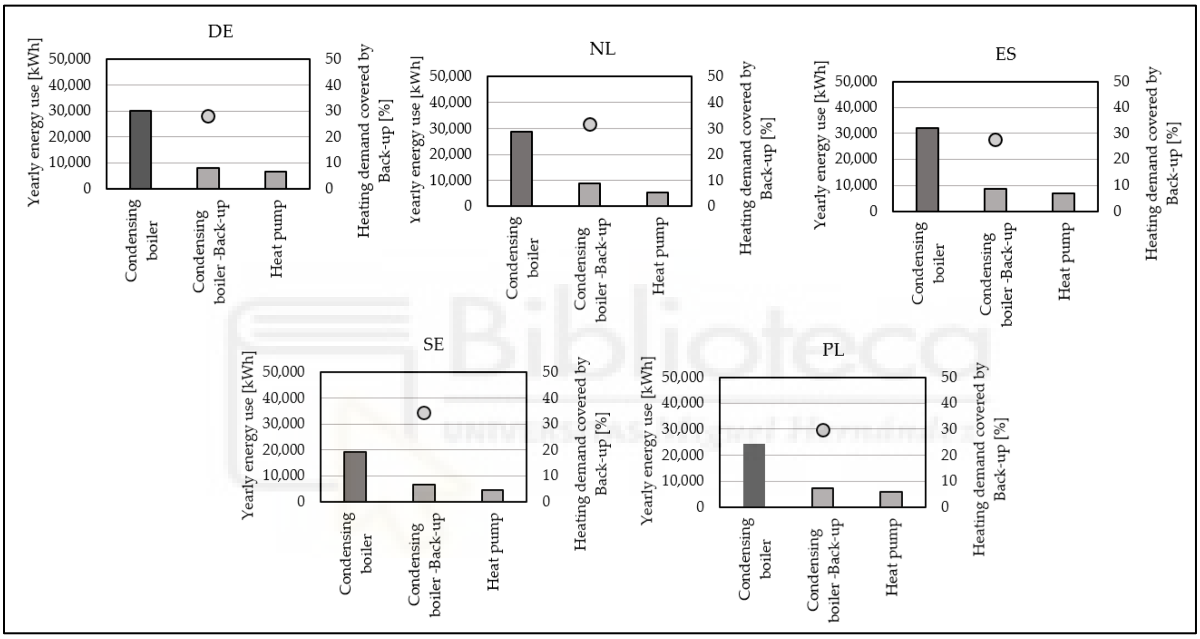

***Figure 18**. Energy use comparison*

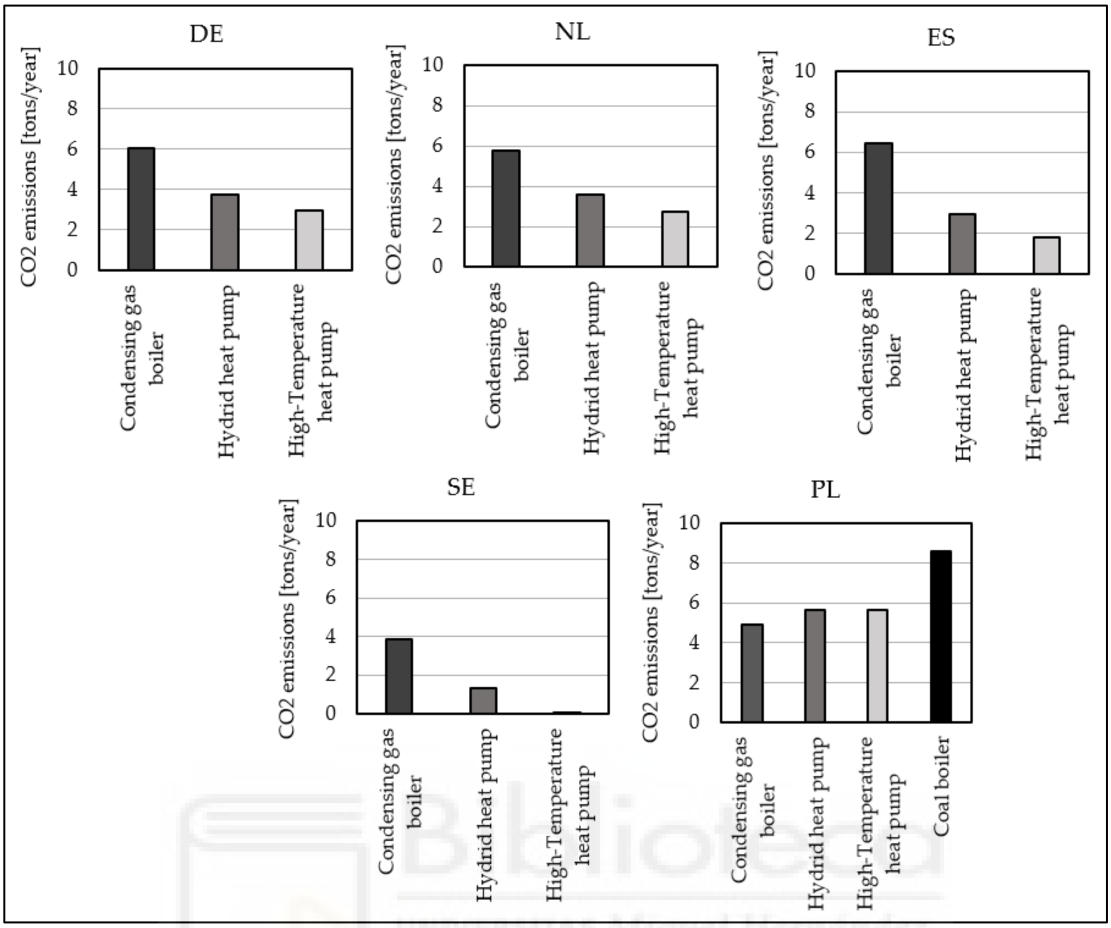

***Figure 19**. CO_2 emission comparison*

As can be seen in Figure 19, the use of high-temperature heat pumps is the solution that decarbonise the buildings the most. Moreover, in cases where a full electrification is not possible, the use of hybrid heat pumps can be considered as an efficient solution that allows the decarbonisation of the buildings heating facilities.

On the other hand, in the case of Poland, the electrification of the heating is not a feasible solution if the objective is to decarbonise the building when compared with the use of a condensing gas boiler. This is due the fact that the way electricity is produced in Poland, since Coal it is one of the main energy sources to produce electricity. This is an example that shows that the electrification of heating does not have an impact if the electricity grid is not decarbonised. For this specific case, since coal boilers is highly widespread in the country, the comparison of the systems proposed, and a coal boiler has been considered as well. The emission factor considered for Coal is 354 g CO_2/kWh. Even if the electricity grid has a high emission factor, still better to use air/water heat pumps than coal boilers in terms of decarbonisation of the building.

The selection of electricity as energy carrier must be evaluated beforehand. This depends on how electricity is produced in a country. One of the issues to analyse should be the conversion factor that equalises the emission level of condensing gas boilers and heat pumps. This can allow to understand the feasibility of the electrification of the heating demand to reduce the GHG emissions from a building.

First is to estimate how much, as an average, a building consumes electricity when using a heat pump for heating than the gas consumed with a condensing boiler. Figure 20 shows the result of the buildings selected for the study. As an average, the electricity use with a heat pump is 0.317 times lower than the gas consumed by a condensing boiler.

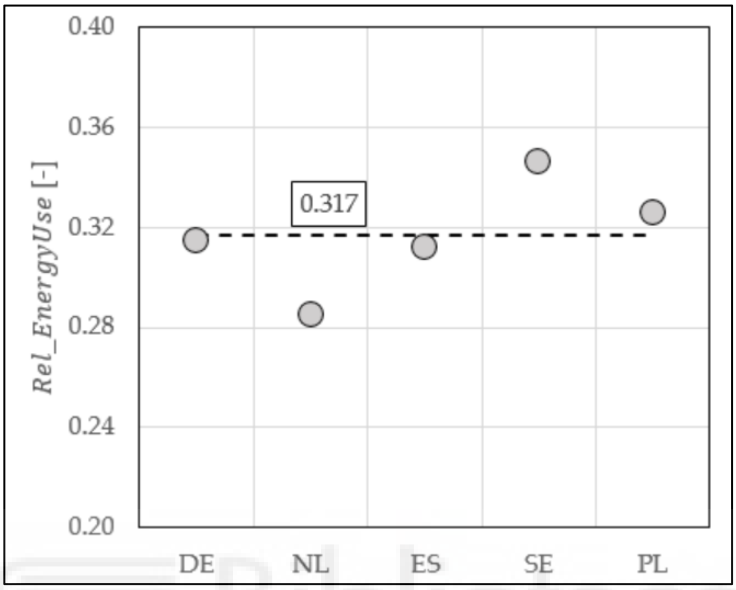

Figure 20. *Energy Use relation - Electricity (Heat pump) and gas (condensing boiler)*

Knowing that the emission factor for gas in all the EU is 202 gr CO_2/kWh, it should be 0.317 times lower than the electricity conversion factor of the country selected. This leads to a conversion factor limit of 637 gr CO_2/kWh. If the electricity conversion factor of the country is higher than this value, electricity should not be used as energy carrier because will lead to higher GHG emissions. Figure 21 shows a summary of the electricity conversion factors of all the MSs of the EU. As was to be expected, Poland has higher electricity conversion factor than the limit. Other MSs like Estonia or Cyprus are on the limit. The MSs which the electrification of heating could lead to low levels of GHG emissions are Sweden, Finland, France or Luxembourg.

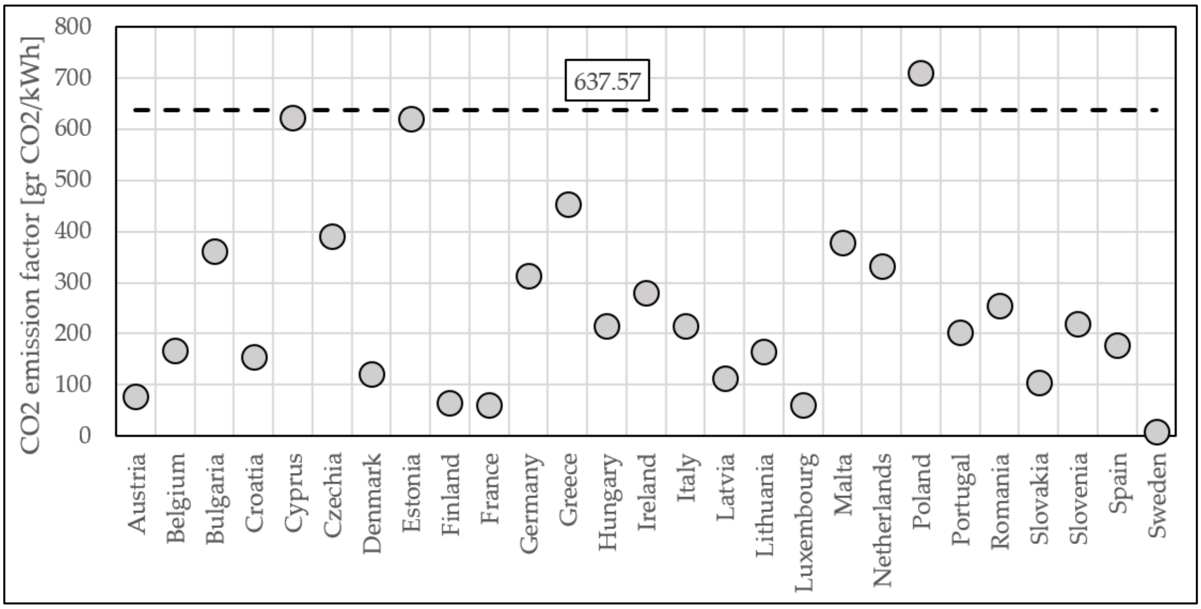

Figure 21. *Summary of the electricity conversion factor in the EU*

In the following chapter, the analysis of these decarbonisation proposals continues with buildings that do not consume gas and are 100% electrified already. The analysis of the chapter is focus what still can be done in these types of buildings to achieve the maximum decarbonisation possible

5.3. Decarbonisation of buildings 100% electrified

In the chapter above and in literature in general, the decarbonisation of the heating facilities in buildings is usually seen as removing the current boiler and installing a heat pump. This angle of research does not cover buildings that do not consume gas or do not use any type of fossil-based heating solution to provide the heating demand.

This is a common situation of buildings located in Mediterranean areas. These types of areas are specific type of regions where the cooling demand is the preference, therefore there is a need of using HVAC systems that produce cooling. Cooling needs electricity as energy carrier, this is one of the reasons why the heating in these buildings is already electrified.

In this chapter there is an evaluation of a specific case study, which covers an office building located in the city of Elche (Spain). In this case study, several experimental measures were taken into account to understand the use of the building and how the energy is consumed. This experimental data was taken for two different separate objectives: The first one was to see the total energy consumption of the building in one year. The second objective was only focus on the electricity consumption and in the heating/cooling production of the heat pump. This second objective allowed to calculate the performance curves of the heat pump with the real efficiencies and capacities. The experimental data was used to calibrate an energy model carried out in EnergyPlus to see how much the impact of potential energy efficiency measures in the building is.

5.3.1. Description of the building and its facilities

The building selected for the study has 4 floors and a total surface of 8,000 m^2. It is composed by different type of enclosures like: Individual offices, open space offices, meeting rooms, kitchen, canteen, a hall, storage enclosures, etc. It was built in 2003, following the Spanish standard of that time, which was NBE-79[5]. The building belongs to the University Miguel Hernández of Elche, and works basically all the year with the exception of the month of August. Figure 22 shows the shape of the building, comparing the energy model with a panoramic photo of the real building. The total power capacity is 250 kW.

***Figure 22**. Real and modelled Building Geometry*

Heating and cooling system. The heating and cooling system located in the building is an air/water heat pump. This heat pump is the morel ERCAS-R 1962 L of the brand CLIMAVENETA. Its main characteristics can be seen in table 8. It makes use of fan coils as indoor units. The heat pump is connected to the indoor units through a manifold and inertia water tanks. The hydronic system is a 2-pipe design, which means that it can provide either heating or cooling. It cannot provide both at the same time. Figure 23 (left) shows how the heat pump looks like.

***Table 8.** Main characteristics of the air/water heat pump*

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. The main ventilation system of the building its made though the admission of exterior air by a duct system. The ducts are connected to a fan that has a nominal electrical consumption of 1.3 kW. The conference hall has its own ventilation system, which is an independent air treatment unit (ATU). Nevertheless, this unit is only used 2 days per year, which does not have any impact in the analysis.

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

Lighting system. The lighting facility installed in the building is mainly composed by led luminaries. The capacity installed is about 5-10 W/m^2.

Fan coils. The building has more than 100 fan coils, most of them are cassette units. Some enclosures make use of fan coils that use a duct system. The electrical consumption of each fan coil is about 80-90W.

Circulation pumps. The circulation pumps installed work with fixed speed. There is one circulation pump per floor. The nominal electricity consumption of all of them is about 11 kW. Figure 23 (right) shows the circulations pumps.

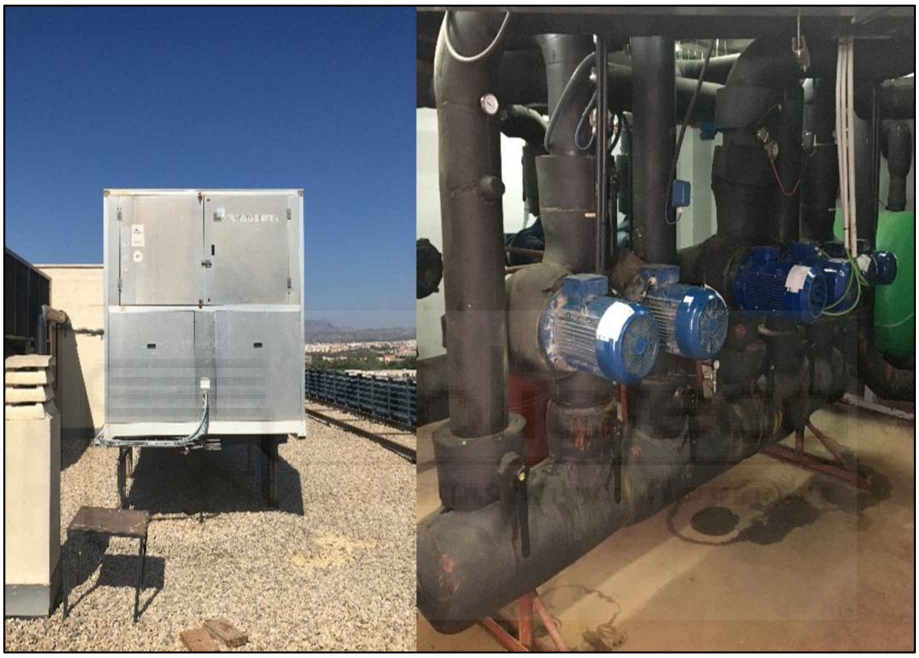

***Figure 23.** Heat pump (left) and circulation pumps (right) of the facility.*

Interior equipment. The building has the common electrical appliances of office buildings, such as: computers, vending machines or photocopying machines. It is estimated that the total capacity installed of all these elements is around 35-40 kW.

The building and its facilities has been modelled in EnergyPlus. The methodology estimated to calculate the thermal load follows the assumptions of [69].

5.3.2. Experimental measures

The first objective of experimental data was to measure the energy consumption of the HVAC systems and the building itself during a year. To do this, a power meter that was connected to the Building Management System (BMS) called "ELECGY-UP" was used. Exterior air conditions were taken from the closest meteorological station to the building [70]. Figure 24 shows the result of this experimental data. It enables to understand how energy is consumed in the building, being the months of June and July the ones when more energy was consumed.

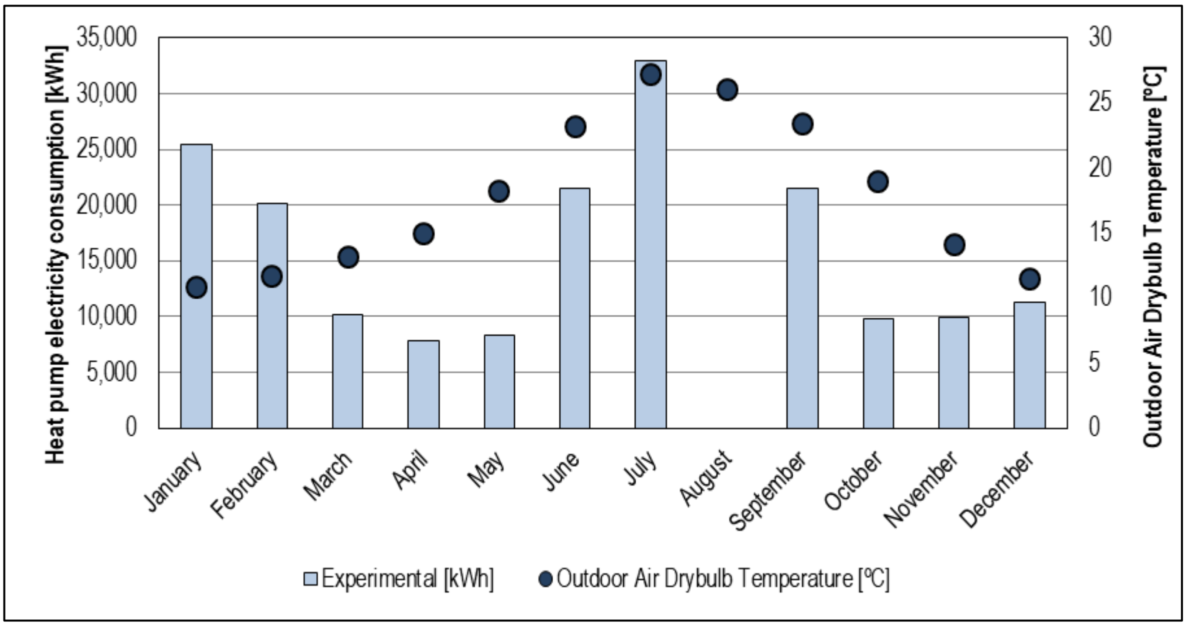

Figure 24. *Results of the experimental electricity consumption of the building*

The second objective of the experimental measures, as mentioned above, had the aim to calculate the performance curves of the heat pump. This type of experimental measures were carried out during 2 weeks of summer to calculate the cooling performance curves and in 2 weeks of winter to repeat the same procedure but in heating mode. The results of these two experimental campaigns can be seen in figures 25 and 26.

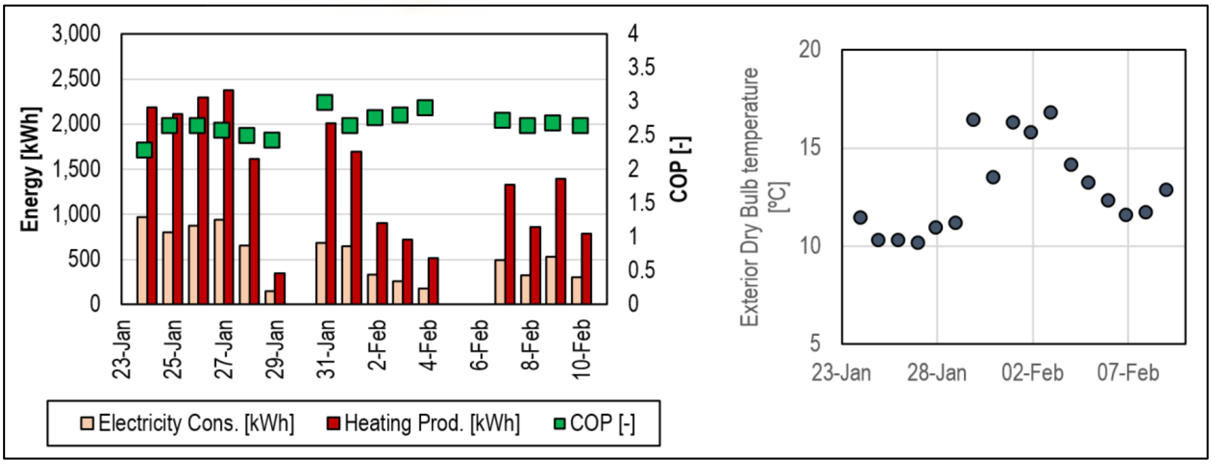

Figure 25. *Experimental data of the winter campaign*

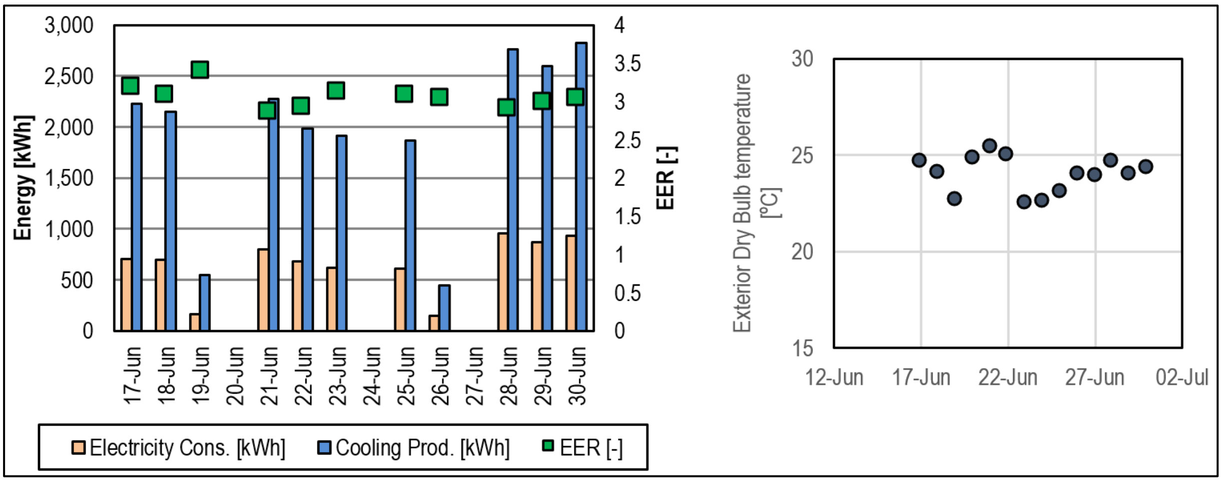

Figure 26. *Experimental data from the summer campaign*

Multiple sensors were installed in the facility to measure the heating and cooling demand. A water flow meter (measuring $\dot{m}_{water}$) and two type K thermocouples (measuring T_{IW} and T_{RW}) were used. They can be seen in Figure 27 (right part). The variables measured with these sensors were enough to calculate the heating and cooling demand ($\dot{Q}$). Moreover, a power meter (Chauvin Arnoux C. A. 8334) connected to the heat pump was employed (measuring P_{elec}). It can be seen in Figure 27 (left part). This element was connected to the electrical panel of the heat pump, where the electrical protections are located.

Figure 27. *Meters used in the study. Power meter (left) and flow meter with thermocouples (right)*

Experimental uncertainties have been estimated [71]. The power consumption was measured considering voltage and intensity. The uncertainties were lower than 1% for 95% of confidence level, leading to uncertainties in the power measures lower than 1.5%. The type K thermocouples presented an accuracy of ± 1.5ºC.

With these meters, there is data enough to calculate the heating and cooling production and the coefficient of performance (COP) of the heat pump. Since the energy efficiency parameter used by Energy Plus is the Energy Input Ratio (EIR), it has been estimated. It basically is the inverse of the COP. Equations 20 to 22 show how these parameters can be calculated.

$$\dot{Q} = \dot{m}_{water} \cdot C_p \cdot (T_{IW} - T_{RW}) \tag{20}$$

$$COP = \frac{\dot{Q}}{P_{elec}} \tag{21}$$

$$EIR = \frac{1}{COP} \tag{22}$$

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].

Once these variables are calculated, the next step is to estimate the performance curves of the heat pump. Three different curves can describe the performance of a heat pump in each mode. Since this heat pump provides with heating and cooling, a total amount of 6 curves has to be calculated. The first two curves are the ones that link the efficiency and capacity with the exterior temperature and the water production temperature (EIRfTEMP and CAPfTEMP). The last one is the one that estimates the effect of part load ratio conditions in the efficiency of the heat pump (EIRfPLR). Equations 23-25 describe these three curves.

It has to be highlighted the times when the thermal and electrical experimental data was taken into account. The heat pump was analysed during times when it was working in steady-state conditions. Following this approach, the electrical consumption could be associated with a thermal production and therefore a COP could be evaluated. This cannot be done in transient steady conditions, because these cases can report a small electricity consumption due to the pumping system and associate it with the thermal production that the building still has due to the thermal inertia. Figure 28 shows the hours of a day when the heat pump was working in steady state conditions. This methodology was applied to all the days of the measurement campaign, for cooling and for heating mode.

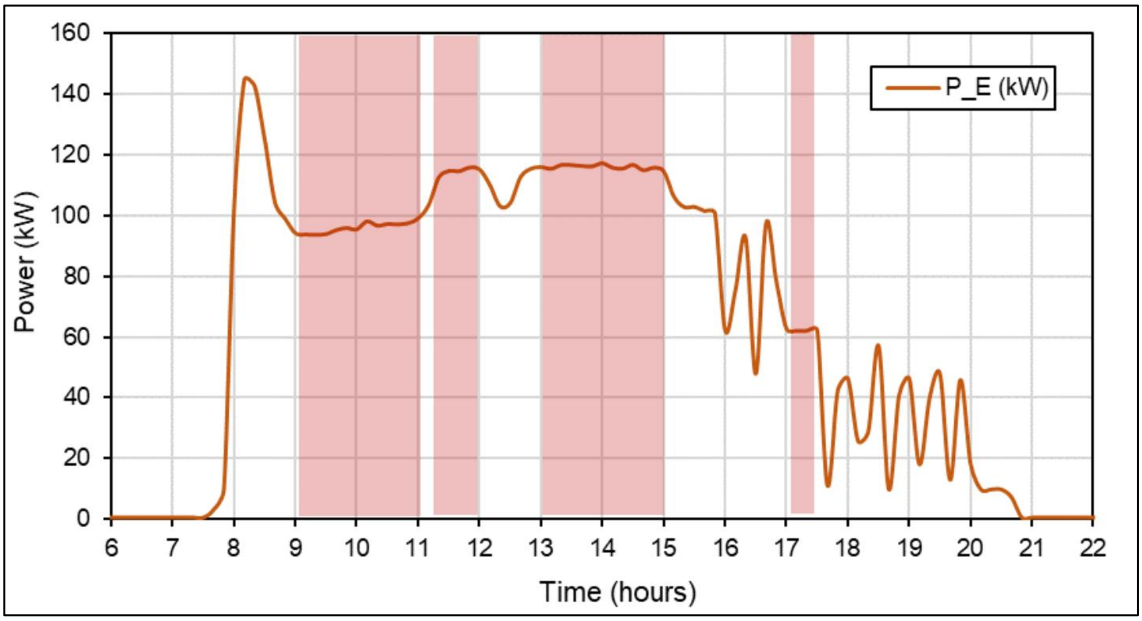

Figure 28. *Steady-state conditions highlighted in the electrical consumption*

$$EIRfTEMP = a + b \cdot T_{water} + c \cdot {T_{water}}^2 + d \cdot T_{air} + e \cdot {T_{air}}^2 + f \cdot T_{water} \cdot T_{air} \quad (23)$$

$$CAPfTEMP = a + b \cdot T_{water} + c \cdot {T_{water}}^2 + d \cdot T_{air} + e \cdot {T_{air}}^2 + f \cdot T_{water} \cdot T_{air} \quad (24)$$

$$EIRFfPLR = a + b \cdot \mathrm{PLR} + c \cdot \mathrm{PLR}^2 \quad (25)$$

Where:

T_{air}: Dry bulb exterior temperature [ºC].

T_{water}: Water production temperature [ºC].

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

The result of these three curves is a number between 0 and 1. They are used to translate the nominal conditions to the real ones. Equation 26 shows how the real electrical consumption of the heat pump can be calculated with the nominal value of electricity consumption and the coefficients of the curves. The nominal value is the one calculated at full capacity and with an air temperature of 7ºC and water temperature of 35ºC for heating. In cooling mode this nominal conditions should be provided by the manufacturer with a water production temperature of 7ºC and with an air temperature of 35ºC.

$$P_{Heat\ pump} = P_{nom} \cdot EIRfTEMP \cdot CAPfTEMP \cdot EIRFfPLR \quad (26)$$

The coefficients a-f are calculated with linear regression, similar as the procedure followed by [72]. Figures 29 and 30 show the results of the different curves obtained. It can be seen how the efficiency is lower in cooling mode with an increase of the exterior temperature and exactly the opposite in heating mode. It is important to highlight that the efficiencies are shown with the EIR coefficient, which is the inverse of the COP. This is in line with the real behaviour of heat pumps, they are more efficient to produce heating when the exterior temperature is higher, since it is easier to evaporate the refrigerant. In cooling mode, it is more efficient to condensate the refrigerant with lower exterior air temperatures, which is linked with higher efficiencies. Table 9 shows the results of the coefficients.

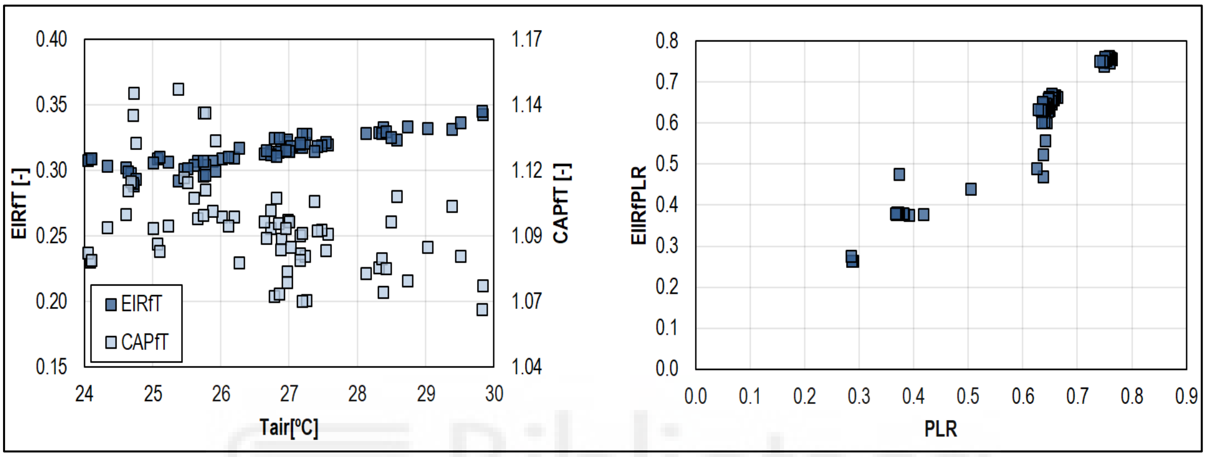

Figure 29. *Performance curves in cooling mode*

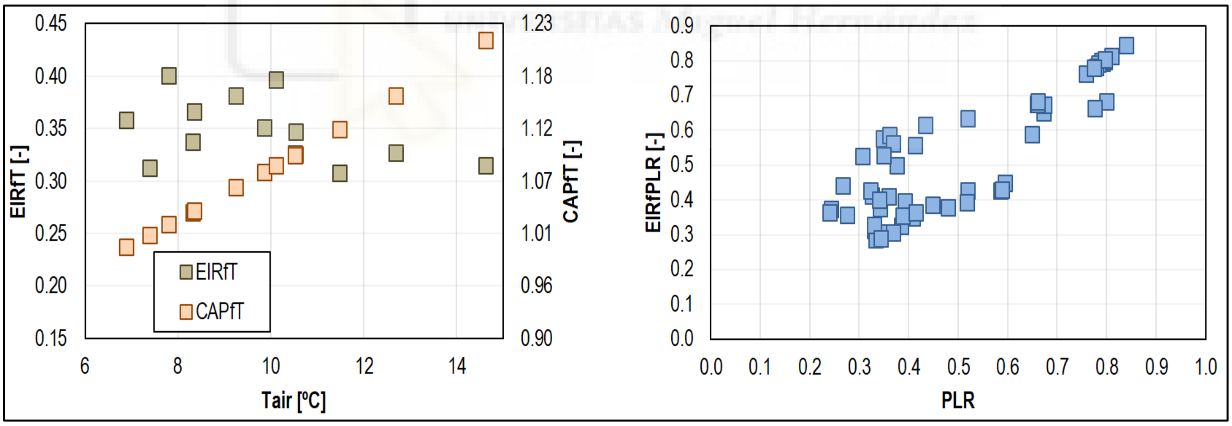

Figure 30. *Performance curves in heating mode*

Table 9. *Coefficients of the performance curves*

		A	B	C	D	E	F	R^2
Heating	**CAPfText**	0.870	-0.002	0.000	0.022	0.0004	-0.0001	0.999
	EIRfText	0.913	-0.028	0.001	0.028	0.001	-0.002	0.996
	EIRfPLR	0.551	-1.087	1.722	-	-	-	0.787
Cooling	**CAPfText**	0.916	0.039	0.00004	0.001	-0.0001	-0.0003	0.9999
	EIRfText	1.810	-0.151	0.006	-0.042	0.001	0.001	0.938
	EIRfPLR	0.090	0.604	0.361	-	-	-	0.947

The experimental measures allowed the calibration of the building energy model (BEM), which has been a crucial part of the study to estimate the real impact of the energy efficiency measures proposed.

5.3.3. Calibration of the model

The calibration of the BEM is a methodology in which some specific parameters with a high level of uncertainty are modified with the aim of matching the real energy demand with the simulated one.

The electrical consumption of the heat pump is the value selected for calibration, since there are experimental data of electricity consumption of the heat pump. Calibrating the electricity consumption of the heat pump allows to calculate the real heating and cooling demand due to the fact that the performance curves used are the real ones of the heat pump, which have been obtained with experimental data.

The parameter selected to vary during the calibration exercise has been the infiltration rate due to its high level of uncertainty. The infiltration rate is calculated with equation 27 [69].

$$Infiltration\,rate = F_{schedule} \cdot \sqrt{(c \cdot C_s \cdot \Delta T^n)^2 + \left(c \cdot C_w \cdot \left(s \cdot W_{speed}\right)^{2n}\right)^2} \tag{27}$$

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].

The electricity consumption obtained with simulation was quite similar to the experimental one by multiplying the default values of infiltration by a factor of 1.5. Figure 31 shows the results. Moreover, it is not enough that the values are similar, they have to meet a certain error criteria. Different sources were consulted to know what order of magnitude of error could be assumed: AHSRAE Guideline 14 [73], the Federal Energy Management Program [74], and the International Performance Measurement and Verification Protocol [75]. Table 10 shows a summary of the different criteria.

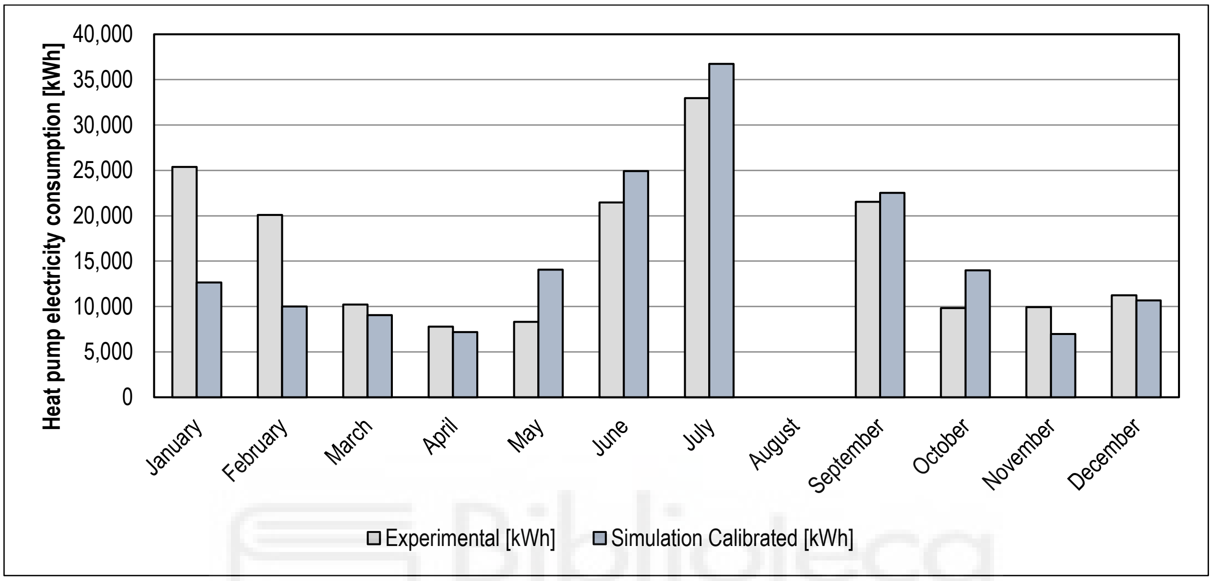

Figure 31. *Calibration exercise*

Table 10. *Error criteria of the different sources consulted*

Data type	Index	FEMP Criteria	ASHRAE Guideline 14	IPMVP
Monthly criteria (%)	NMBE	+-5	+-5	+-20
	CV(RMSE)	15	15	-
Hourly criteria (%)	NMBE	+-10	+-10	+-5
	CV(RMSE)	30	30	20

Source: [76]

The errors in in Table 10 are the Normalized Mean Bias Error (NMBE) and the Coefficient of Variation of the Root Mean Square Error CV (RMSE). NMBE represents average errors in the measurements. This error is normalized using the average value of the measurements and takes into account the number of measurements as well. NMBE could be used with seasonal data, as singular errors could be compensated during the measurement period. Equation 28 shows how NMBE is defined:

$$MBE = \frac{1}{\overline{m}} \cdot \frac{\sum_{i=1}^{n}(m_i - s_i)}{(n-p)} \cdot 100\ (\%) \qquad (28)$$

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) takes into account the difference between measured and simulated data in every hour. In this type of error, positive and negative differences are not compensated. Equation 29 shows this approach:

$$CV(RMSE) = \frac{1}{\overline{m}} \cdot \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{(n-p)}} \cdot 100\ (\%) \tag{29}$$

Since the need to calibrate seasonal results, the monthly criteria have been selected with the threshold of 20% of NMBE provided by IPMVP. Table 11 represents the final error obtained and the threshold.

Table 11. *Simulation errors*

Index	Simulation	IPMVP
NMBE	5.16%	+-20%

Once the calibration exercise is finished, the real heating and cooling demand of the building can be estimated. Figure 32 shows the final results of the calibration.

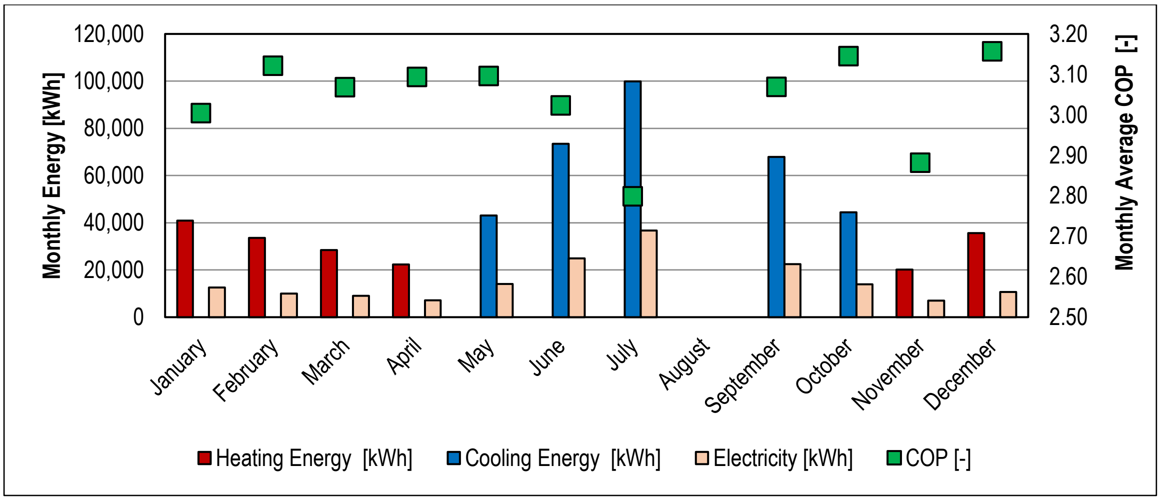

Figure 32. *Calibrated results*

The next step, once the model is calibrated, is the proposal of energy efficiency measures in the building. These measures are explained in the next subchapter.

5.3.4. Energy efficiency measures

The first step prior to propose energy efficiency measures (EEM) is to know where and how the electricity is consumed. The annual electricity consumed in the building is around 450,000 kWh. It is worth to highlight that this electricity consumption comes from the parameters that can be defined in energy plus and are shown in figure 33. Taking into account the exterior lighting or the water supply systems, the electricity consumed in the building could arise to 55,000 kWh per year.

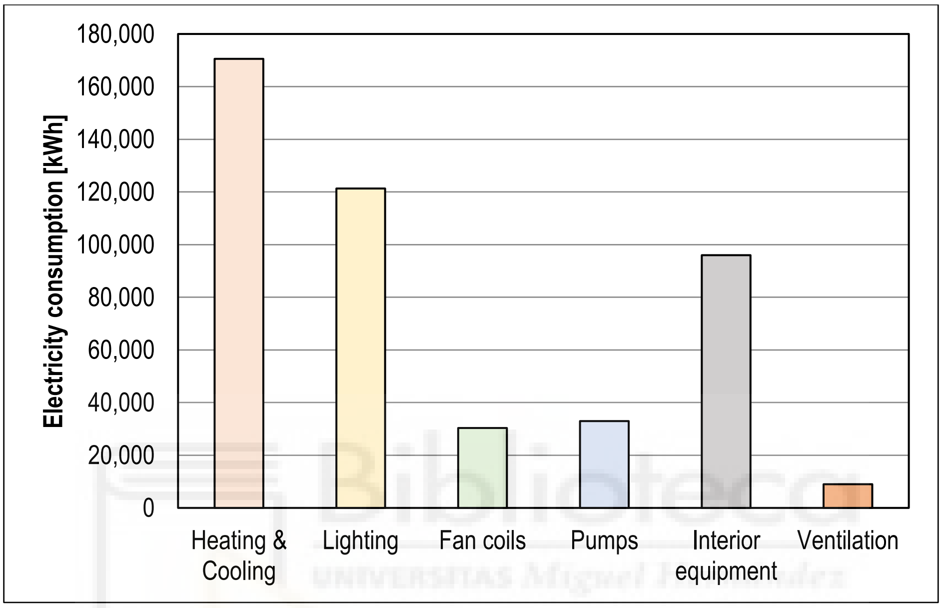

Figure 33. *Calibrated energy balance of the building*

Heating and cooling is the main electricity consumption of the heat pump, followed by the lighting and the interior equipment. Fan coils and circulation pumps have similar electricity consumption.

Since the heat pump is the main electricity consumption of the building, an energy efficiency measure should be proposed to estimate how much this consumption could be reduced. The lighting facility is almost 100% LED, which means that is difficult to reduce the energy consumption of it. The circulation pumps could be a potential candidate for energy efficiency measures, since the circulation pumps operate at fixed speed. Fan coils electricity consumption cannot be reduced due to the low consumption of the fan coils and the interior equipment is outside the scope of the study.

Circulation pumps. The first energy efficiency measure would be to install variable speed circulation pumps. This type of pumps allow to reduce the water flow in the hydronic facility at part load ratio conditions. The results of the implementation of variable speed pumps are shown in figure 34. The electricity savings of this EEM are about a reduction in 8% of the circulation pumps electricity consumption in heating mode and 4% in cooling mode. In heating mode makes a higher impact because the system is more time at part load ratio conditions. Since in cooling mode the heat pump is almost all the time at full load, the effect of variable speed pumps is lower.

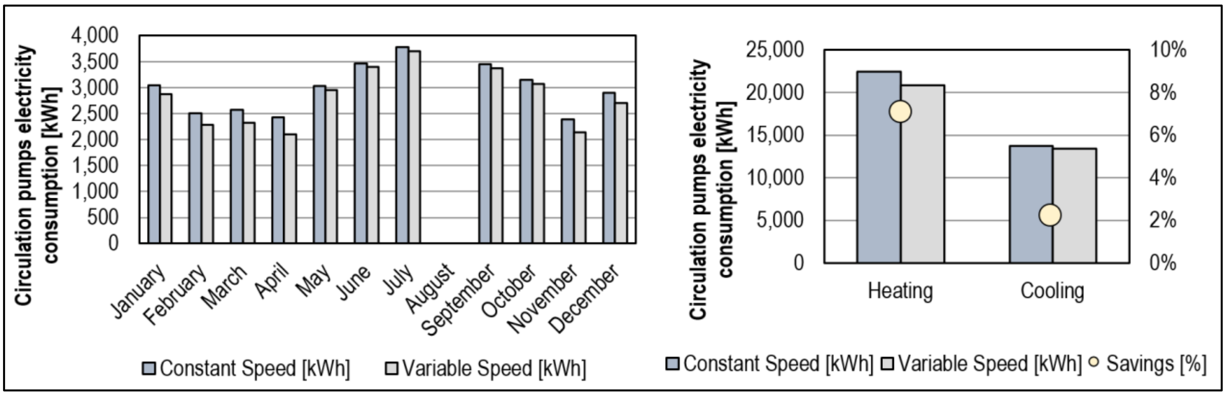

Figure 34. *EEM 1 - variable speed pumps*

Heat pump. A new heat pump has been proposed. This has been done to understand if the current heat pump consumes that much electricity due to inefficiencies (more than 15 years old). The characteristics of the new heat pump proposed are in table 12. The results of this EEM are shown in figure 35. Since the savings of installing a new heat pump are about 2-4% in electricity consumption, it can be conclude that the current heat pump satisfies the energy demand with normal energy efficiency levels, meaning that it should not be replaced.

Table 12. *Main characteristics of the new heat pump*

Cooling capacity [kW]	401
Nominal Cooling COP [-]	2.46
Heating capacity [kW]	525
Nominal Heating COP [-]	4
Number of fans [-]	8
Water flow [m³/h]	69
Number of compressors [-]	5
Refrigerant [-]	410a

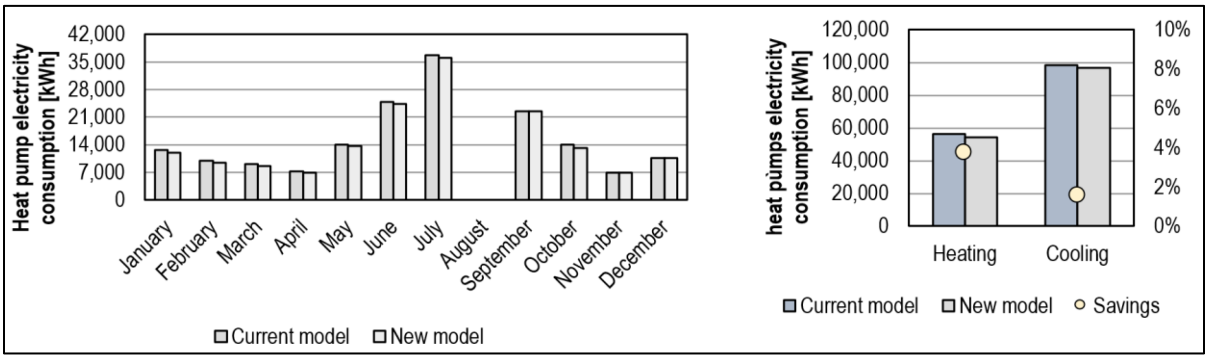

Figure 35. *EEM 2 - new heat pump*

Diming controller of the lighting facility. Since almost all the luminaries are LED, the only way to optimise the second highest electricity consumption of the building is with a diming controller. A dimming controller in a lighting facility takes into account the level of solar radiation in the rooms, reducing the intensity of the luminaries. If the minimum levels of illumination are covered by natural lighting, the diming controller could switch off the luminaries or make them work at 20-50% of the nominal capacity. Since this building is located in a Mediterranean area, the potential influence of the solar radiation can be key in the decarbonisation of the building. The results can be seen in figure 36. They show that 30,000 kWh of electricity could be saved per year with this EEM.

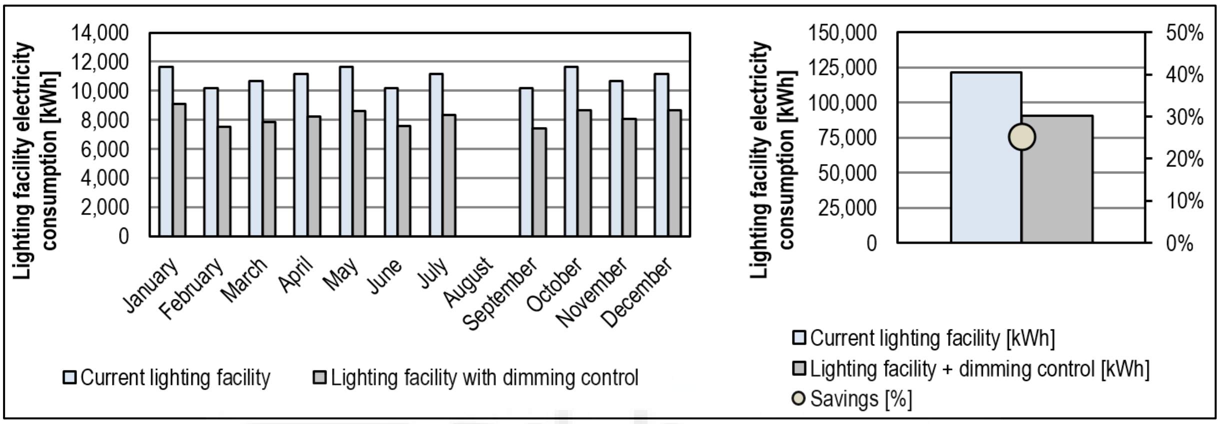

Figure 36. *EEM 3 - dimming controller*

The results of this EEM are similar with the ones obtained by [38] in New York Times headquarters, in which the authors estimated a 20% of energy consumption reduction by using this type of technology. In other work carried out in an office building in Seoul, the authors concluded that the use of daylight controls could decrease the lighting electricity consumption by 30% [39]. In the study developed by [40] the authors estimated energy savings from 27% to 80% (depending on the office enclosure). Nevertheless, the comparison of these results is just an order of magnitude. In the end, the energy savings linked to the daylight and dimming controllers depend not only on the location of the building, but also on the architecture, use of the building, etc. There are many factors to consider and only range of results should be compared.

Photovoltaic facility. Once all the current electricity consumption of the building have been optimised, then is the implementation of renewable energy should be studied. The last step in a building renovation should be the implementation of renewable energy sources. This is due to the fact that if the electricity consumptions are not reduced to the minimum prior the installation of renewable energy, it could be oversized. All the available roof has been occupied by PV modules by using the software ARCHELIOS PRO[6]. The PV facility has 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. The strings are connected to 3 inverters of 20 kW, which means that the nominal capacity of the PV facility is 60 kW. Figure 37 shows the landscape of the facility.

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

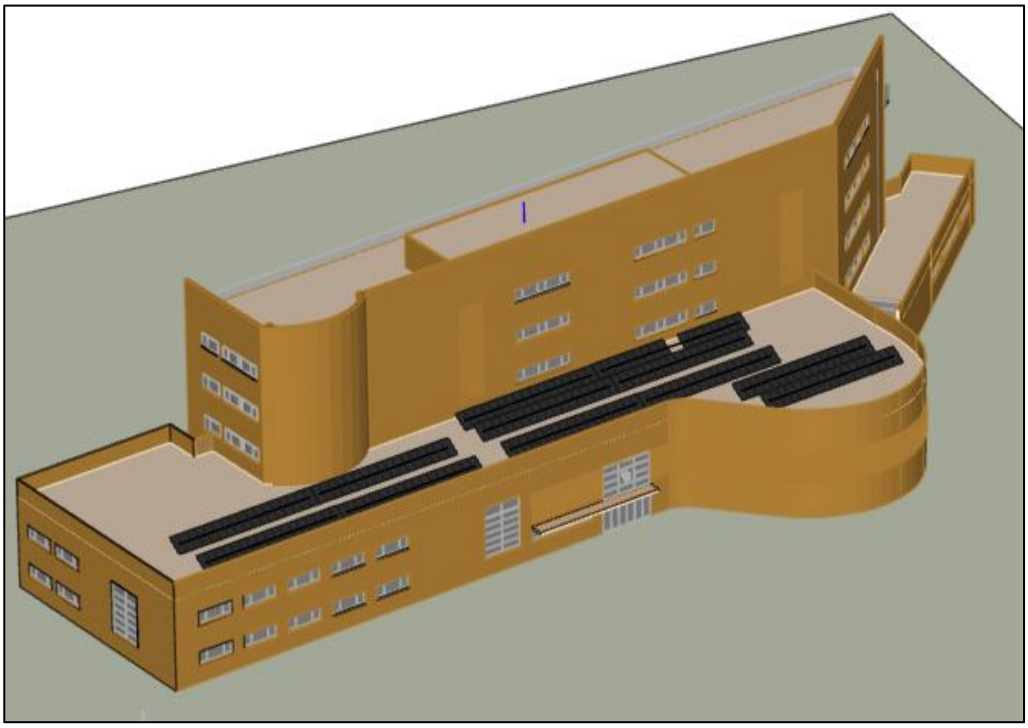

Figure 37. *EEM 4 - Photovoltaic facility of the building*

The results obtained indicate that the PV facility can provide with 110,206 kWh/year. This means that this EEM can reduce by 20% the total electricity consumed by the building. It is important to highlight that this electricity generated by the PV facility could maybe be produced when there is no energy demand. For this reason, the daily profiles of energy consumption and PV production should be compared. Figures 38 and 39 show the results of a winter and summer daily profile of the main electricity consumptions and the PV production. As can be seen in the figures, due to the high electricity consumptions of the building, the 100% of the electricity produced by the PV facility can be used. The green in figures 38 and 39 is always inside of the main electricity consumptions. In summer, the shape of the cooling demand and the PV production are quite similar, which means that more PV can be used for cooling than for heating.

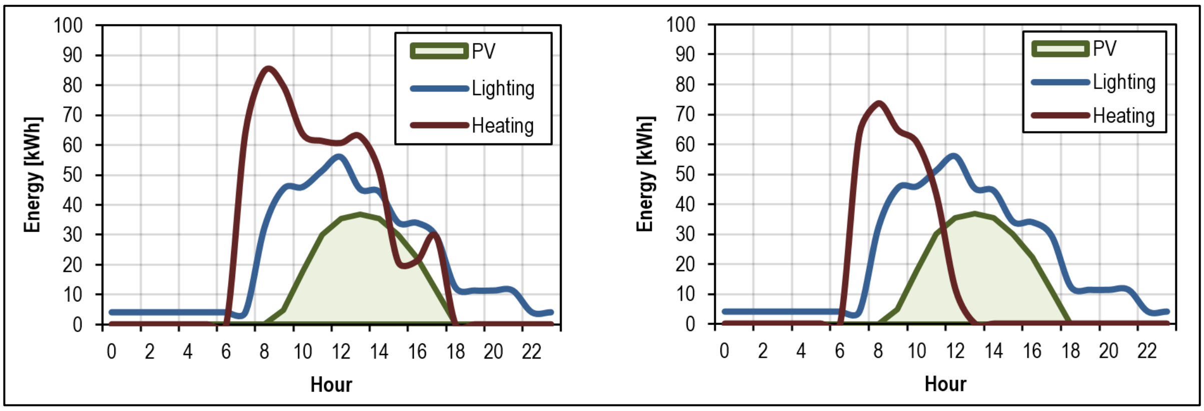

Figure 38. *Heating season days hourly profile*

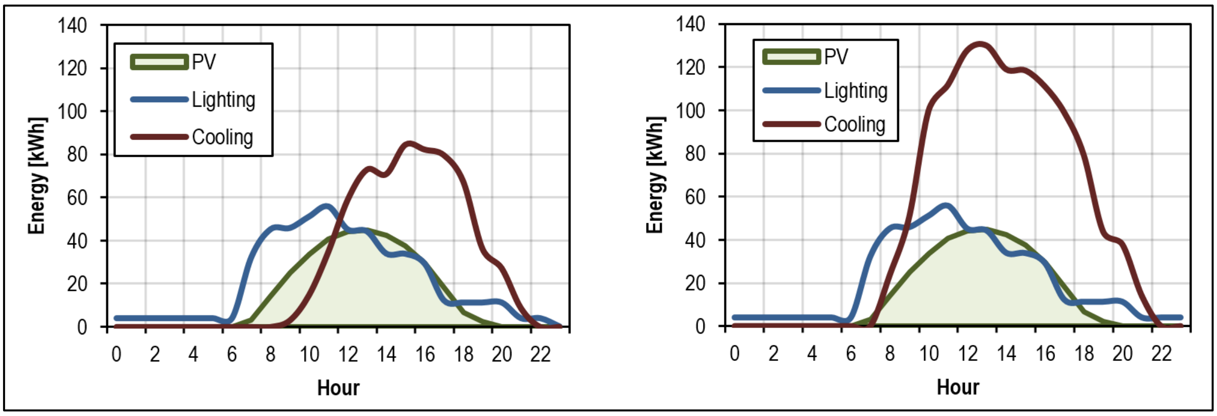

Figure 39. *Cooling season days hourly profile*

The results of this EMM are similar to the ones obtained in other studies [43, 44]. On the other hand, as it happened above with the dimming controller EEM, these results are not directly comparable but in this case the location of the buildings has more impact on the results. These studies also covered buildings located in an university, obtaining between 10-19% of CO_2 emission reduction. Considering that the studies were done in Ireland, a lower contribution was obtained due to the low solar radiation. Other factors, such as the low temperature, can increase the efficiency of the PV modules, but the low radiation levels make very difficult to directly compare results of similar EEMs carried out in mediterranean areas.

The EEMs proposed in to decarbonise 100% electrified buildings could be considered limited in terms of energy efficiency. The installation of variable speed pumps does not influence that much. It must be highlighted that circulation pumps represent around 10 kW out of the total 250 kW of the building. Nevertheless, energy savings can be achieved and much more at part load ration conditions.

On the other hand, the addition of a PV facility makes the building save around 20% of the annual electricity consumed. This makes this EEM very interesting to the carbon footprint of the building. Occupying all the rooftop available of the building, around 60 kW could be installed of PV, producing 110,000 kWh out of the 550,000 kWh of the total electricity consumed in the building. Since the PV power delivered is always lower than the electricity demand of the building, it can be assumed that all the PV consumption is self-consumed.

As a summary of the study, in table 13 can be seen a summary of the different EEMs proposed in this part of the study.

Table 13. *Summary of the EEMs*

EEM	Electricity saved [kWh]	Electricity saved [%] of total building electricity consumption]	CO_2 emission reduction [tonnes/year]
EEM 1 - variable speed pumps	1,878	0.40	0.62
EEM 2 - heat pump	3,628	0.79	1.2
EEM 3 - dimming controller	30,566	6.65	10.12
EEM 4 - photovoltaic facility	110,206	23.96	36.48

In addition to the GHG emissions reduction, an economical analysis has been carried out as well. This analysis supports not only the decarbonisation possibilities, but also if it is economically viable or not for the end-user. In order to do this, equations 14 and 15 are followed.

First, the economic savings come from the annual electricity saved, which was shown in table 13. To evaluate them, an average price of 0.116 €/kWh[7] has been considered. In the analysis, a discount rate of 3% has been assumed. The lifetime of the EEMs is 25 years. The investment of each EEM has been taken from the database database of CYPE Ingenieros called "Generador de precios"[8]. Operation and Maintenance costs considered are the ones that the Facility Management service of the university has provided. Table 14 summarises the economic results of all the EEMs proposed.

Table 14. *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

Table 14 shows how most the EEMs proposed could be considered good investments. As show in the previous chapter and in table 13, the current heat pump should not be considered for a change, due to the fact that the current one still has good levels of efficiency. Therefore, the small savings are too little when compared with an investment for 25 years.

The installation of a PV facility can be considered the best EEM in terms of GHG emission reduction and as an investment. The reduction of the 20% of electricity consumed from the grid can bring energy savings that will make the initial investment to be recovered after 9 years. This fact makes this EEM very competitive when compared with the others.

The installation of variable speed pumps can be considered a good energy efficiency measure, the electricity it saves does not justify that type of investment, even if it can be recovered before the 25 years.

Usually, a PV facility should be installed after all the electricity consumptions have been reduced to its maximum and not earlier. The results obtained in this study show that by occupying all the rooftop available, only 20% of the annual electricity consumption is saved. Furthermore, only 60 kW can be provided to a building with a potential instantaneous consumption of more than 200 kW. This means that the electricity consumption should be reduced in more than 70% to make the PV facility have less capacity. For this reason, for the specific case of this building, does not matter the order when these EEMs take place. So it is recommendable to first install the PV if the investment price is available, and then proceed with energy efficiency measures.

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[7] Average cost from the average values of tariff 6.1 TD

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

Figure 40 shows the strategy proposed for this case study in the Mediterranean area of Spain. This can be considered an indicator of how much electricity is consumed in 100% electrified office buildings. The results show that is preferable starting with renewable energy production rather than from energy efficiency if the current heating and cooling system installed is an air/water heat pump.

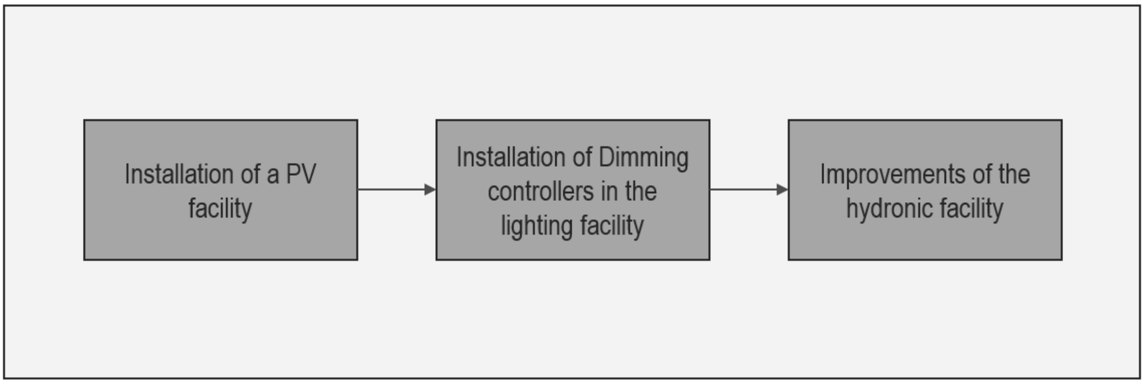

***Figure 40**. Decarbonisation strategy proposed*

The analysis carried out in this building is a clear indicator of how the decarbonisation strategies for each building should be studied in a case-by-case basis. Once a heat pump is installed and working in a building, is hard to make EEM measures focus on the efficiency of the systems if the building envelope cannot be improved. The only measures could be linked to improve the hydronic facility, but it only contributes to around 10 kW of the total amount of 250 kW consumed by the building. Considering this low order of magnitude, makes not very interesting to invest on this type of EEMs. On the other hand, the contribution of PV or dimming controllers could be more doable not only in terms of decarbonisation results, but also as investments.

6. Conclusions and future works

6.1. Version in English

The decarbonisation of the EU building stock through the upgrade of its heating and cooling facilities is a challenge. The substitution of currently installed fuel-based heating systems and the use of cleaner energy carriers are key to making the 2050 EU targets a reality.

The first research question, which was about the feasibility of upgrading from high-temperature to low-temperature heating systems, has been answered through Chapter 5.1. It is feasible, and air/water heat pumps are a good option for decarbonising buildings that use fossil fuel-fired boilers. Nevertheless, since they operate under much different conditions than heat pumps, the hydronic facility should be adjusted to be able to work under the heat pump's conditions of temperature and water flow. In some buildings, renovation is necessary to prepare them for low-temperature heating.

The second research question, when no renovation of the building is allowed and the water supply temperature has to be maintained, was answered in Chapter 5.2. An exhaustive analysis of the water supply temperature was conducted, and the options of hybrid or high-temperature heat pumps have been demonstrated to be viable options for decarbonising heating systems that cannot reduce the water temperature level.

According to these two chapters, 5.1 and 5.2, electricity is the candidate to substitute fuel-based heating facilities. For this reason, understanding how electricity is produced in every member state is crucial to determining whether electrifying heating can be considered a decarbonisation option. In most member states, the electrification of heating through the use of heat pumps contributes to building decarbonisation. But in the case of Poland, the use of gas boilers is "cleaner" than the use of heat pumps. This is because electricity in Poland is produced mainly from carbon, resulting in a high CO2 footprint for the power grid. Nevertheless, in Poland, it is still more beneficial to use heat pumps than coal boilers, as demonstrated in Chapter 5.

Full electrification of the heating demand can cause problems in the distribution grid. It was shown in Chapter 5 that at the member state level, it should not be a problem, but it has to be treated on a case-by-case basis. Different EU regions must be prepared for a prior upgrade of the power distribution grid before the deployment of heat pumps. The reduction of energy demand by improving building envelopes can play a key role in the electrification of buildings and the affordability of the power grid. The energy demand reduction of buildings can contribute to lower electricity demand by the building when heating needs are electrified, which can have an impact on the power grid.

Electrification of several buildings in a neighbourhood can lead to such an increase in the power capacity that it will not be affordable in many cases. These types of situations can lead to an increase in the size of power grid cables or the installation of transformer centers.

Initial investments can be considered a barrier. The decarbonisation of buildings can be technically possible, but if end-users cannot afford it, then it will not happen. Energy policies and economic mechanisms should support end-users in making the decarbonisation of buildings feasible for all.

It is essential to understand the relationship between the water production temperature, the surface of indoor units, and heating demand in hydronic facilities. The temperature of the water in the hydronic facility should be around 50-55 °C as the maximum to be able to use heat pumps for heating buildings. Suppose the current heating system works at higher temperatures. In that case, there are two options: Renovate the building envelope to reduce the water production temperature or install alternative systems that can produce water at the same temperature. This can be achieved with hybrid, high-temperature heat pumps or district heating.

The third research question focused on a more specific type of building. It was about the decarbonisation possibilities of buildings that are 100% electrified. This question was answered in chapter 5.3. Since an air/water heat pump is already installed in the building and the building envelope cannot be upgraded, the energy efficiency measures in these buildings are linked, for example, to the use of dimming controllers in the lighting facility. This measure could lead to a 25% reduction in lighting electricity consumption. Nevertheless, lighting accounted for only 30% of the electricity consumption of that building, making it a good option for decarbonising the building; however, the overall impact is not as significant as, for example, the installation of a PV facility.

Installing a PV facility, according to the case study analysed, can lead to a total electricity reduction of 20% from the grid. All the PV produced is consumed due to how electricity is consumed and made in the building on an hourly basis. Typically, this measure is viewed as the final step in a building's decarbonisation strategy. On the other hand, the specific situation of this building allows to understand that starting with the installation of the PV is not a problem when analysing the electricity consumptions of the building.

As a conclusion of the work carried out, the decarbonisation of buildings in the EU is feasible. On the other hand, several factors, such as water production levels, power grid capacity, feasibility of renovating the building, and high upfront costs, need to be studied on a case-by-case basis before designing a decarbonisation strategy for a building.

This work can be further developed by analysing the feasibility of using various types of heat pumps. In the chapters presented, the solutions were mainly focused on air/water heat pumps, which are widely used, but they are not the only ones. Feasibility studies of, for example, water/water heat pumps in buildings located close to the coast could be a potential line of research since these types of systems are usually more efficient than air source heat pumps.

Another field to continue the work shown in Chapters 5.1 and 5.2 is the analysis of forced convection in installed radiators. The installation of fans on the downside of the radiators can increase their heat exchange capacity, therefore, making the chances of reducing the water temperatures in the hydronic facility higher. This type of study can demonstrate how currently installed radiators, which work in conjunction with boilers, can also work with heat pumps.

The optimisation of economic tools to help end-users is crucial to achieving the decarbonisation of buildings. The impact of new policies, such as ETS 2 and the implementation of the Social Climate Fund, can be a potential candidate for exploring how these new legal frameworks can help reach the decarbonisation targets of 2030 and 2050.

Understanding the potential to decarbonise a building using the Smart Readiness Indicator (SRI) can be a potential future work for a thesis linked to the decarbonisation of buildings. The concept of SRI has been used for many years now. Still, the link this indicator has with, for example, energy performance certificates of buildings and how they can improve heating and cooling systems can be crucial in the future of a building's carbon footprint.

New refrigerants to be used in heat pumps and their efficiency are also topics to explore. The new limitations outlined in the F-GAS directive, as well as the toxicity/inflammability limitations, make this theme an interesting field to explore, as it justifies which refrigerant will be the future. This could lead to the development of refrigerants that enable the use of Volume Refrigerant Flow systems in large buildings. These systems are usually more efficient than hydronic systems and respond better to intermittent heating and cooling demand in buildings. These two characteristics make them an interesting solution when flexibility is a must in a building.

Thermal energy storage linked with the use of hydronic heating and cooling systems can be a future line of research. Producing heating or cooling in buildings when prices are lower and consuming it at different times may require energy storage systems that cannot be installed in, for example, residential buildings. For this reason, research work that demonstrates feasibility could be key to achieving the EU's decarbonisation goals by 2050.

6.2. Versión en español

La descarbonización de los edificios de la UE mediante la renovación de sus instalaciones de calefacción y refrigeración supone un reto. La sustitución de los sistemas de calefacción basados en combustibles actualmente instalados en edificios y el uso de vectores energéticos más limpios son fundamentales para hacer realidad los objetivos de la UE para 2050.

La primera pregunta de investigación, que trataba sobre la viabilidad de pasar de sistemas de calefacción de alta temperatura a sistemas de baja temperatura, ha sido respondida en el capítulo 5.1. Es factible, y las bombas de calor aire/agua son una buena opción para descarbonizar los edificios que utilizan calderas de combustibles fósiles. No obstante, dado que las calderas funcionan en condiciones muy diferentes a las de las bombas de calor, la instalación hidrónica debe ajustarse para poder funcionar en las condiciones de temperatura y caudal. En algunos edificios es necesaria una renovación previa para declarar la instalación hidrónica del edificio como apta para una reducción de temperatura.

La segunda pregunta de investigación, cuando no se permite la renovación del edificio y se debe mantener la temperatura del suministro de agua, se ha respondido en el capítulo 5.2. Se ha realizado un análisis exhaustivo de la temperatura del suministro de agua y se ha demostrado que las opciones de bombas de calor híbridas o de alta temperatura son viables para descarbonizar los sistemas de calefacción que no pueden reducir el nivel de temperatura del agua en su instalación hidrónica.

Según estos dos capítulos, 5.1 y 5.2, la electricidad es la candidata para sustituir las instalaciones de calefacción que hacen uso de combustibles fósiles. Por esta razón, comprender cómo se produce la electricidad en cada Estado miembro de la UE es fundamental para determinar si la electrificación de la calefacción puede considerarse una opción de descarbonización. En la mayoría de los Estados miembros de la UE, la electrificación de la calefacción mediante el uso de bombas de calor contribuye a la descarbonización de los edificios. Pero en el caso de Polonia, el uso de calderas de gas es "más limpio" que el uso de bombas de calor. Esto se debe a que la electricidad en Polonia se produce principalmente a partir de carbón, lo que da lugar a una elevada huella de CO_2 en la red eléctrica. No obstante, en Polonia sigue siendo más beneficioso utilizar bombas de calor que calderas de carbón, como se demuestra en el capítulo 5.

La electrificación total de la demanda de calefacción puede causar problemas en la red de distribución eléctrica. En el capítulo 5 se demostró que, a nivel nacional, no debería ser un problema, pero hay que tratarlo caso por caso. Las diferentes regiones de la UE deben estar preparadas para una mejora previa de la red de distribución eléctrica antes de la implantación masiva de las bombas de calor. La reducción de la demanda energética mediante la mejora de la envolvente de los edificios puede desempeñar un papel clave en la electrificación de los edificios y en la asequibilidad de la red eléctrica. La reducción de la demanda energética de los edificios puede contribuir a disminuir la demanda de electricidad del edificio cuando se electrifican las necesidades de calefacción, lo que puede tener un impacto en la red eléctrica.

La electrificación de varios edificios en un barrio puede provocar un aumento de la capacidad energética que, en muchos casos, resultará inasequible. Este tipo de situaciones pueden dar lugar a un aumento del tamaño del cableado de la red eléctrica o a la instalación de centros de transformación.

Los costes iniciales de las inversiones en reformas de instalaciones pueden considerarse una barrera. La descarbonización de los edificios puede ser técnicamente posible, pero si los usuarios de este no pueden permitírselo, no se llevará a cabo. Las políticas energéticas y los mecanismos económicos deben apoyar a estos usuarios, de manera que la descarbonización de edificios sea posible técnica y económicamente.

Es esencial comprender la relación entre la temperatura de producción del agua, la superficie de las unidades interiores y la demanda de calefacción en las instalaciones hidrónicas. La temperatura del agua en la instalación hidrónica debe ser de entre 50 y 55 °C como máximo para poder utilizar bombas de calor en edificios. Supongamos que el sistema de calefacción actual funciona a temperaturas más altas. En ese caso, hay dos opciones: renovar la envolvente del edificio para reducir la temperatura de producción de agua o instalar sistemas alternativos que puedan producir agua a la misma temperatura que el sistema actual. Esto se puede lograr con bombas de calor híbridas, bombas de calor de alta temperatura o con calefacción de distrito.

La tercera pregunta de investigación se centró en un tipo de edificio más específico. Se trataba de las posibilidades de descarbonización de los edificios que están electrificados al 100 %. Esta pregunta se respondió en el capítulo 5.3. Dado que ya hay instalada una bomba de calor aire/agua en el edificio y que no se puede mejorar la envolvente del mismo, las medidas de eficiencia energética en estos edificios están relacionadas, por ejemplo, con el uso de reguladores de intensidad en la instalación de iluminación. Esta medida podría suponer una reducción del 25 % en el consumo eléctrico de la iluminación. No obstante, la iluminación solo representaba el 30 % del consumo eléctrico de ese edificio; sin embargo, el impacto global no es tan significativo como, por ejemplo, la instalación de un sistema fotovoltaico.

Según el estudio de caso analizado, la instalación de un sistema fotovoltaico puede suponer una reducción total del 20 % del consumo eléctrico total del edificio. Toda la energía fotovoltaica producida se consume debido a la forma en que se consume y se genera la electricidad en el edificio de manera horaria. Por lo general, esta medida se considera el paso final en la estrategia de descarbonización de un edificio. Por otro lado, la situación específica de este edificio hace que comenzar la estrategia de descarbonización con una instalación fotovoltaica no sea un problema.

Como conclusión del trabajo realizado, la descarbonización de los edificios en la UE es factible. Por otra parte, antes de diseñar una estrategia de descarbonización para un edificio, es necesario estudiar caso por caso varios factores, como la temperatura de producción de agua, la capacidad de la red eléctrica, la viabilidad de la renovación del edificio y los elevados costes iniciales.

Una continuación del trabajo realizado en esta tesis doctoral puede ser el análisis de la viabilidad del uso de diversos tipos de bombas de calor. En los capítulos presentados, las soluciones se centraron en las bombas de calor aire/agua, que son muy utilizadas, pero no son las únicas bombas de calor en el mercado. Los estudios de viabilidad de, por ejemplo, las bombas de calor agua/agua en edificios situados cerca de la costa podrían ser una posible línea de investigación, ya que este tipo de sistemas suelen ser más eficientes que las bombas de calor aerotérmicas.

Otra línea de investigación para continuar el trabajo mostrado en los capítulos 5.1 y 5.2 es el análisis de la convección forzada en los radiadores. La instalación de ventiladores en la parte inferior de los radiadores puede aumentar su capacidad de intercambio de calor, lo que aumenta las posibilidades de reducir la temperatura del agua en la instalación hidrónica. Este tipo de estudio puede demostrar cómo los radiadores instalados actualmente, que funcionan en combinación con calderas, también pueden funcionar con bombas de calor.

La optimización de las herramientas económicas para ayudar a los usuarios finales es fundamental para lograr la descarbonización de los edificios. El impacto de las nuevas políticas, como el ETS 2 y la implementación del Fondo Social para el Clima, puede ser un candidato potencial para explorar cómo estos nuevos marcos legales pueden ayudar a alcanzar los objetivos de descarbonización de 2030 y 2050.

Comprender el potencial de descarbonización de un edificio utilizando el indicador de preparación inteligente (SRI) puede ser un posible tema de trabajo futuro para una tesis relacionada con la descarbonización de los edificios. El concepto de SRI se utiliza desde hace muchos años. Sin embargo, la relación que este indicador tiene, por ejemplo, con los certificados de eficiencia energética de los edificios y cómo pueden mejorar los sistemas de calefacción y refrigeración puede ser crucial para el futuro de la huella de carbono de los edificios de la UE.

Los nuevos refrigerantes que se utilizarán en las bombas de calor y su eficiencia son también temas que hay que explorar. Las nuevas limitaciones descritas en la directiva F-GAS sobre toxicidad/inflamabilidad, hacen que este tema sea un campo interesante para explorar, ya que podría justificar qué refrigerante será el usado en bombas de calor en un futuro. Esto podría conducir al desarrollo de refrigerantes que permitan el uso de sistemas de volumen de refrigerante variable en grandes edificios. Estos sistemas suelen ser más eficientes que los sistemas hidrónicos y responden mejor a la demanda intermitente de calefacción y refrigeración. Estas dos características los convierten en una solución interesante cuando la flexibilidad es imprescindible en un edificio. No obstante, las elevadas cantidades de refrigerante que han de usar en grandes instalaciones suelen ser un factor limitante para su uso.

El almacenamiento de energía térmica vinculado al uso de sistemas hidrónicos de calefacción y refrigeración puede ser una línea de investigación futura. Producir calefacción o refrigeración en edificios cuando los precios son más bajos y consumirla en diferentes momentos del día puede requerir sistemas de almacenamiento de energía. Dichos sistemas, como por ejemplo los depósitos de inercia, puede que no puedan instalarse, por ejemplo, en edificios residenciales. Por esta razón, los trabajos de investigación que demuestren la viabilidad tecno económica de estas instalaciones podrían ser clave para alcanzar los objetivos de descarbonización de la UE para 2050.

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Annexes

- **Annex 1.** Quality Index 1 - Roca Reina, J.C, Aguilar Valero, F.J and Vicente Quiles, P.G, “Energy model development of an office”, in XII National and y III International Conference on Engineering Thermodynamics, Madrid, 2022.

- **Annex 2.** Quality Index 2 - Roca Reina, J.C, Aguilar Valero, F.J and Vicente Quiles, P.G, “Energy balance analysis of an office,” in 13th National and 4th International Conference in Engineering Thermodynamics, Castellón de la Plana, 2023.

- **Annex 3.** Additional publication 1 – Roca Reina, J. C., Toleikyte, A., Volt, J., & Carlsson, J. (2024). Alternatives for upgrading from high-temperature to low-temperature heating systems in existing buildings: Challenges and opportunities. Energy And Buildings, 114798. https://doi.org/10.1016/j.enbuild.2024.114798

- **Annex 4.** Additional publication 2 – Roca Reina, J. C., Carlsson, J., Volt, J., & Toleikyte, A. (2025). Alternatives for Decarbonising High-Temperature Heating Facilities in Residential Buildings. Energies, 18(2), 235. https://doi.org/10.3390/en18020235

Annex 1. Quality Index 1

12CNIT-2022 - FULL PAPER

Energy model development of an office

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Keywords: *Energy efficiency, Building modeling; nZEB, Simulation*

TOPIC: ENERGY EFFICIENCY AND SUSTAINABILITY IN BUILDINGS AND INDUSTRY

1. Introduction

According to data from the European Commission [1], buildings are responsible of 41% of the European Union's energy consumption, above transport and industry, responsible of 31% and 24.8%, respectively.

The EU energy efficiency directive in buildings 2018/844 [2] modifies the previous directive and proposes short-term (2030), medium-term (2040) and long-term (2050) strategies, with the ultimate goal of achieving a decarbonized real estate stock and highly efficient by 2050. In this way, member countries are urged to establish a roadmap with measurable indicators with a view to reducing greenhouse gas emissions in the Union by 80-95% compared to with those of the year 1990.

Likewise, the long-term Strategy for Energy Rehabilitation in the Building Sector in Spain (ERESEE 2020) promotes the renovation of the national stocks of residential and non-residential buildings, both public and private, to transform them into building stocks with high efficiency energy and decarbonized before 2050.

An energy model development is a specific methodology by which we can predict energy consumption. Also, it is a useful way to analyse the energy-saving potential of buildings. In [3] and [4], the authors conduct modelling works to analyse the performance of the building facilities. Both of them have been taken into account as examples to carry out the present work.

This research project focuses on studying improvement strategies and energy saving proposals in buildings in the tertiary sector. On the one hand, an energy model has been developed for an office building located in Alicante (Mediterranean climate). On the other hand, said model has been validated from experimental measures.

2. Materials and methods

The study has been carried out by analyzing a 4-storey office building, with a total of 8000 m^2 and a habitual occupation of about 200 people.

The geometric modelling has been carried out with the software EnergyPlus. Said modelling includes the 3D representation of the building and the technical characteristics of the facilities

(HVAC, lightings, etc.). With the help of the experimental data, the building plans and the measurements conducted in the building, the characteristic parameters of the building were defined, taking into account, among others: the thermal insulation, the use profile and the internal thermal loads (occupation, lighting and equipment). Figures 1 and 2 show the 3D model of the building defined using the energy analysing software.

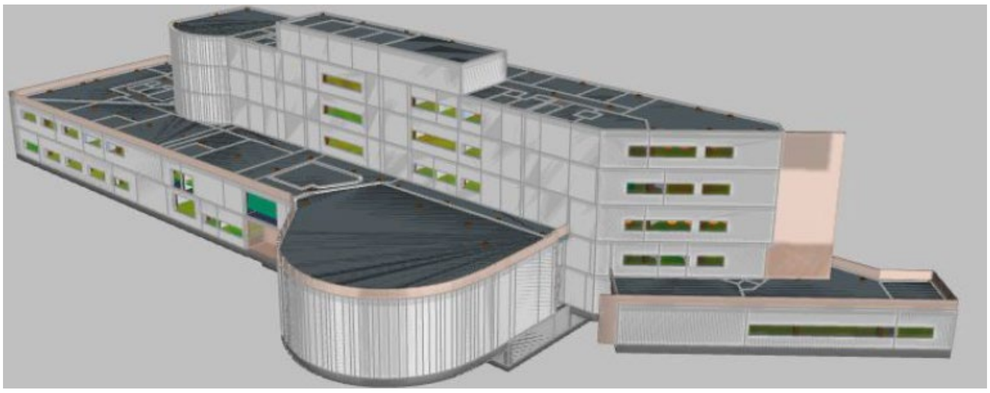

Figure 1. Building energy model – View of the main façade.

Figure 2. Building energy model – View of the rear façade.

The HVAC facility comprises an air-water heat pump located on the roof of the building with a nominal cooling capacity of 400 kW (CLIMAVENETA ERACS-R 1962 LT), two water pumps (primary and secondary circuit) and fan coils as terminal units to supply air-conditioned to the indoor spaces.

Several measuring instruments were used to collect all the data needed to calibrate the model. On the one hand, a power analyser was used to measure the electrical consumption, including heat pump, fans, compressors, water pumps, etc. On the other hand, the thermal power supplied to the air-conditioning system of the building was measured by employing a flow meter and temperature sensors (thermocouple type K). The useful thermal power supplied by the heat pump can be known by means of Equation 1.

$$\dot{Q} = \dot{m}_{Water} \cdot Cp \cdot (T_{Inlet\,Water} - T_{Outlet\,Water}) \qquad (1)$$

Finally, the heat pump's energy efficiency is calculated as the ratio between the useful thermal power and the electrical consumption, according to Equation 2.

$$EER = \frac{P\ (kW_E)}{\dot{Q}\ (kW_T)} \qquad (2)$$

Some of these measurements are shown in Figure 3 (power meter on the left and thermal energy measure on the right).

Figure 3. Measuring instruments.

Figure 4 describes the workflow applied to calibrate the model. Once the model was finished and the simulation was run, the obtained results were compared to the experimental data. All the parameters of the model (ventilation, control temperatures, use profiles, etc.) were properly adjusted in order to reach as accurate as possible results.

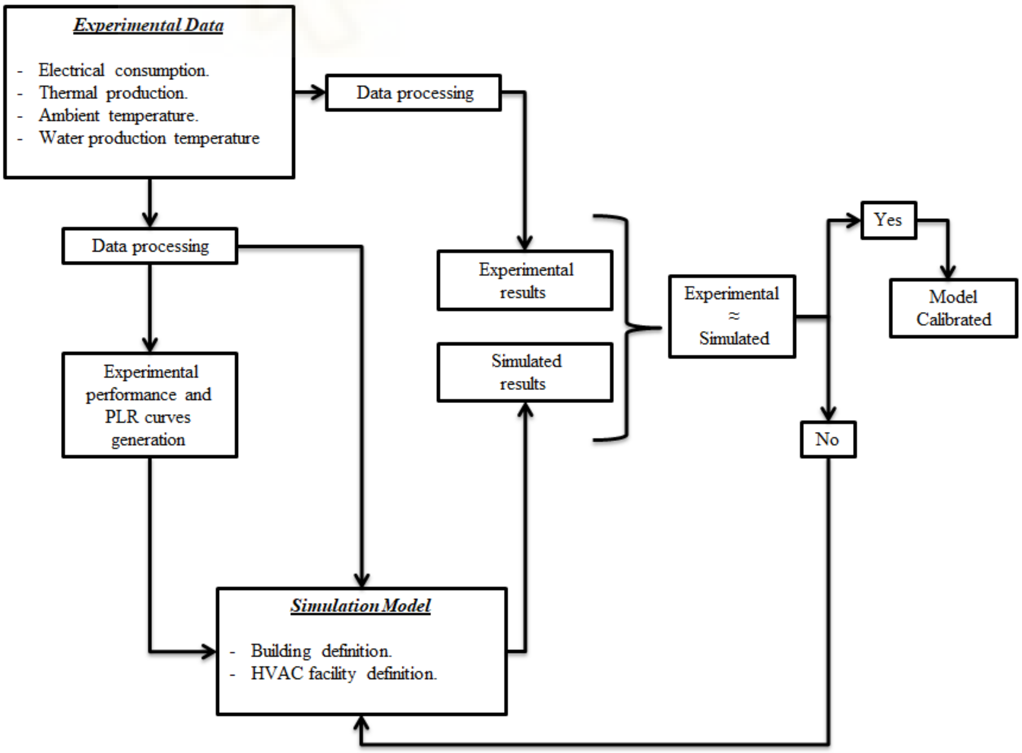

Figure 4. Workflow followed.

3. Results and discusions

3.1. Experimental energy results

The experimental work took into consideration more than two weeks of measurements to know the actual performance of the HVAC system in summer conditions. In this sense, Figure 5 shows the daily average results of the heat pump analysis, including electrical consumption, useful thermal energy and energy efficiency ratio. These measurements were conducted with an average outdoor air temperature of about 25ºC and a leaving water temperature (LWT) constant at 7ºC, resulting in an average heat pump's energy efficiency between 3.0 and 3.3. These results are close to that provided by the manufacturer in the technical datasheet, where the EER in these conditions is 3.3.

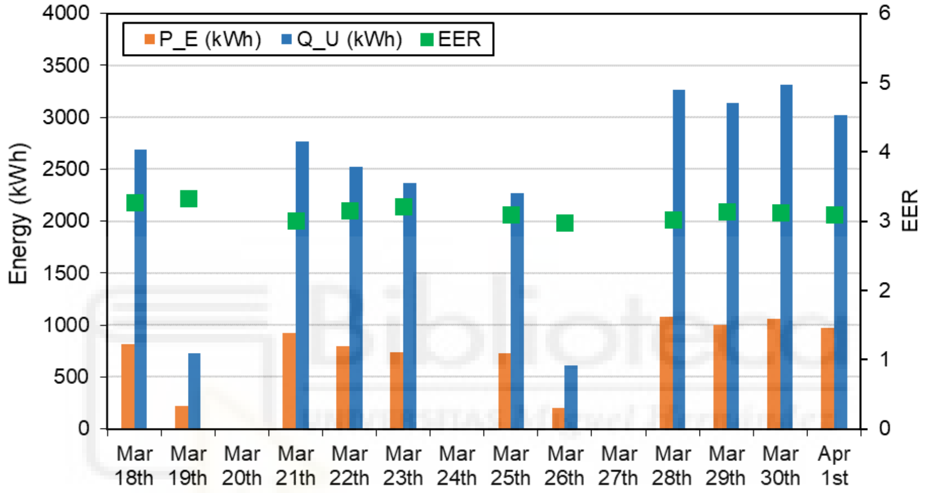

Figure 5. Experimental results of the HVAC system in cooling conditions: Electrical consumption, useful thermal energy and energy efficiency ratio.

3.2. Calibration results

An air-water heat pump in EnergyPlus is defined by means three different performance curves. Two of them modify the nominal energy input ratio (EIR – inverse of COP), while the other one is used to modify the nominal thermal capacity of the heat pump depending on the working conditions.

- Thermal Capacity (*CAPfTEMP*) It is the variation of the cooling capacity depending on the operating temperatures
- Temperature Energy Input Ratio (*EIRfTEMP*): It is the curve that expresses the variation of the electrical energy ratio (EIR) as a function of the operating temperatures.
- Part-load ratio (*EIRfPLR*): It is the curve that modifies the electrical energy ratio (EIR) as a function of the partial load factor (PLR).

These performance curves can be generated by fitting the manufacturer's catalogue data or measured data during a previous experimental task. Both methods have been applied to define and adjust them in this work.

First of all, experimental data have been analysed and filtered to use only those where the heat pump was working in steady states. Secondly, these data have been organised and grouped in the function of their thermal load levels and external temperatures. This task has allowed getting almost one hundred representative experimental data, using them to define the heat pump's performance curve and calculate their coefficients.

Figure 6 shows the electrical consumption of the heat pump during one day of study, where the steady-state periods are highlighted in red.

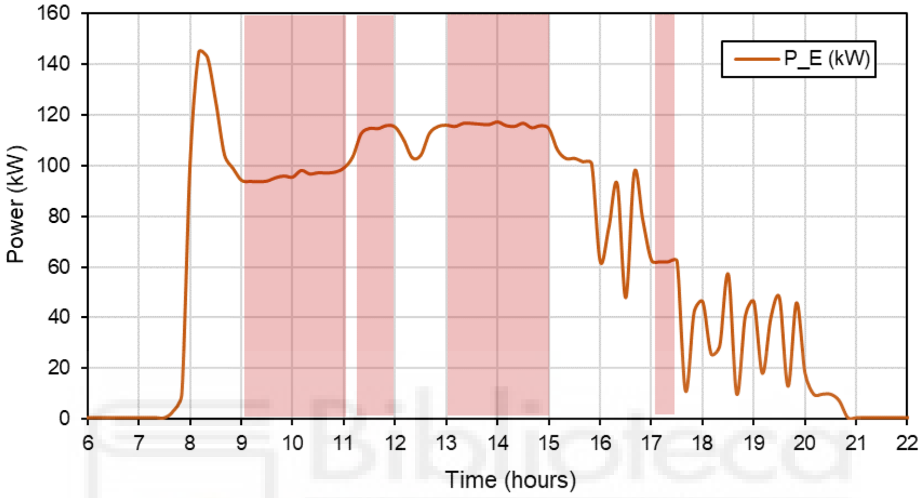

Figure 6. Steady-state conditions highlighted in the electrical consumption.

Equation 3 describes the biquadratic regression of the capacity as a function of the outdoor air temperature (T_{air}) and the leaving water temperature (T_{water}), both in Celsius degrees. It is necessary to take into account that in this work the leaving water temperature has been considered constant at 7ºC so that this equation could be lightly simplified.

$$CAPfTEMP \; = \; a + b \cdot T_{water} + c \cdot T_{water}{}^{2} + d \cdot T_{air} + e \cdot T_{air}{}^{2} + f \cdot T_{water} \cdot T_{air} \tag{3}$$

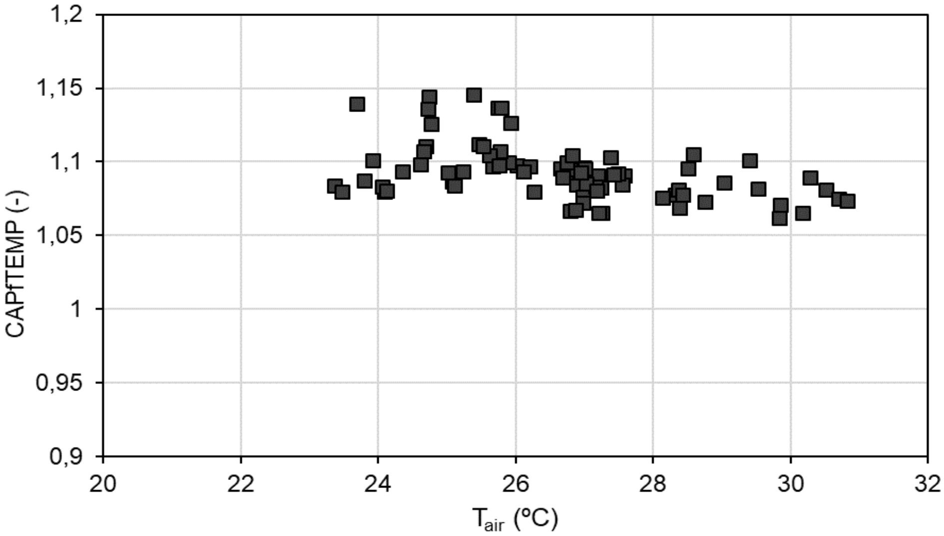

Figure 7. Thermal capacity curve *CAPfTEMP*.

Figure 7 represents the thermal capacity curve. All the points are higher than one because experimental test were carried out with outdoor temperaure lower than 35ºC (nominal conditions).

The second curve that has been used is the Energy Input Ratio depending on the temperature. This biquadratic curve is described in the Equation 4.

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

This equation has been developed using both experimental data and manufacturer data, compering the obtanained results in Figure 8. As can be seen, the energy input ratio obtained with experimental data is a little bit higher than the ones obtained with the manufacturer's data. This phenomenon can be explained by the age of the equipment, since as the years go by, the HVAC installation tends to have poorer efficiency.

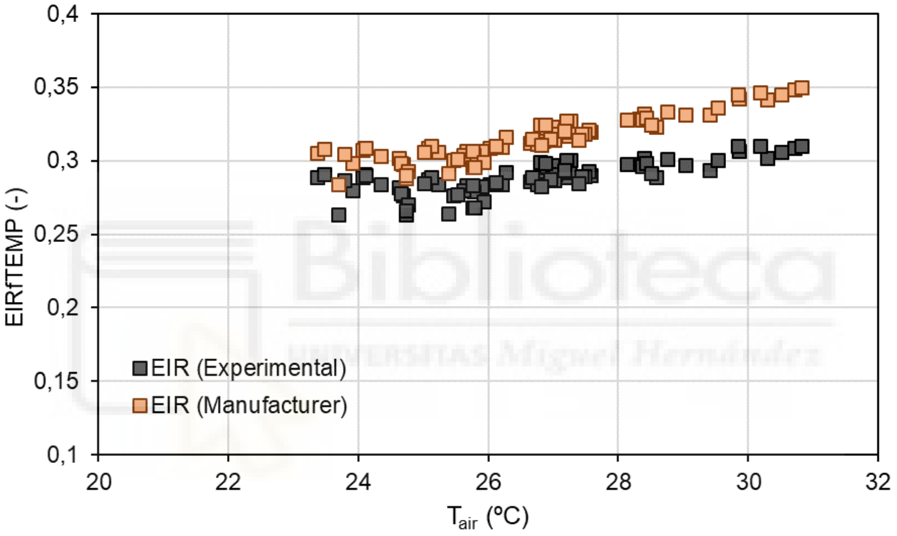

Figure 8. EIRfT results (Experimental vs. manufacturer).

The corresponding coefficients of the two defined curves are included in Table 1.

Table 1. Coefficients as function of temperature

	Coefficients CAPfTEMP (Manufacturer)	*Coefficients EIRfTEMP (Experimental)*	*Coefficients EIRfTEMP (Manufacturer)*
a	0.916229318	1.809766	1.723312
b	0.038680417	-0.151375	-0.113788
c	4.47547E-05	0.005691	0.003484
d	0.000598995	-0.042278	-0.042681
e	-0.000115199	0.001024	0.000947
f	-0.000278632	0.001275	0.000894

The last calculated curve is the Energy Input Ratio as a function of the Part Load Ratio (EIRfPLR). According to the Engineering Reference of EnergyPlus [5], this curve can be defined as a polynomial of degree 2. The experimental EIRfPLR could be obtained as Equation 5 shows.

$$EIRfPLR = \frac{P_{HeatPump}}{P_{nom} \cdot CAPfTEMP \cdot EIRfTEMP} = a + b \cdot PLR + c \cdot PLR^2 \tag{5}$$

Where:

$P_{HeatPump}$:Heat Pump Power (W).

P_{nom}: Heat Pump Power at the nominal conditions (W).

PLR: Heat Pump Production/ Maximum Heat Pump production at specific condicition.

Results of the coefficients of this curve can be seen in Table 2, while a comparison with a reference curve can be observed in Figure 9.

Table 2. Coefficients of EIR as a function of PLR

	Coefficients
a	0.090224
b	0.603960
c	0.361246

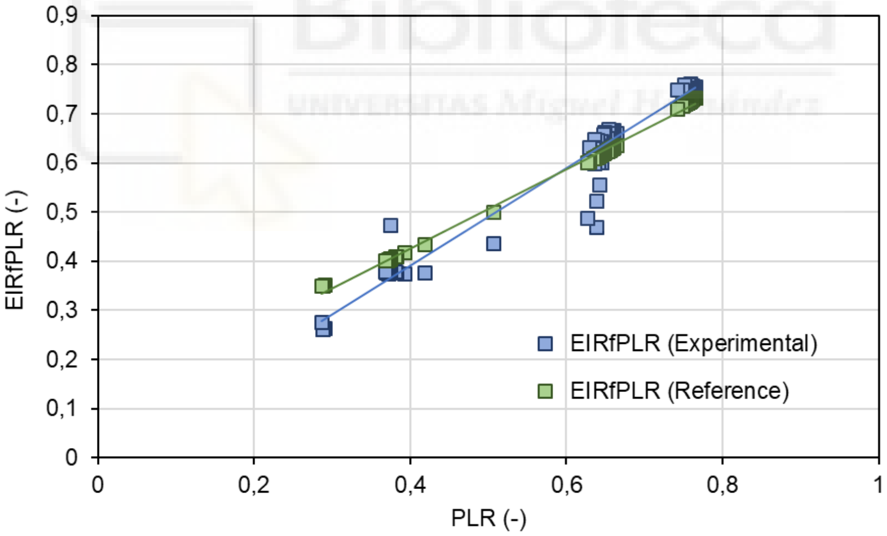

Figure 9. Comparison of the EIRfPLR curve obtained with a reference curve.

Once the influence of the temperature and the part load ratio on the heat pump's performance have been studied, this information can be used to know the effect of these parameters on the energy efficiency ratio (EER). Figure 10 shows this analysis.

It can be seen that a higher outdoor air temperature a lower heat pump efficiency. Also, results show how the heat pump reaches higher efficiencies when it works at a lower part-load ratio.

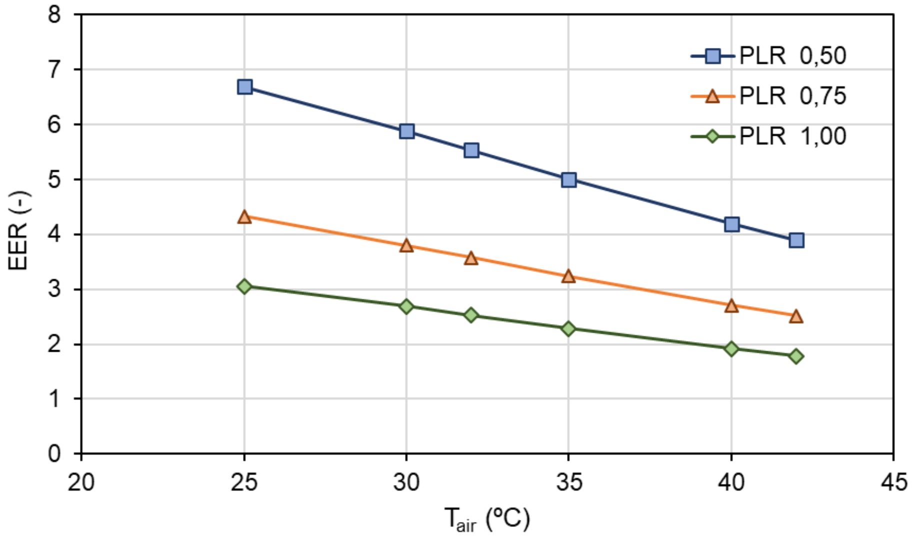

Figure 10. Influence of the part load ratio and the outdoor air temperature on the Energy Efficiency Ratio.

3.3. Validation results

Once the building modelling is finished and the heat pump performance curves are defined, this information can be used to conduct the simulation using EnergyPlus. The simulation data will be compared to the experimental one in order to validate the model and to know its accuracy level.

Firstly, Figure 11 shows the hourly evolution of the useful thermal power and the power consumption for three days of study in July.

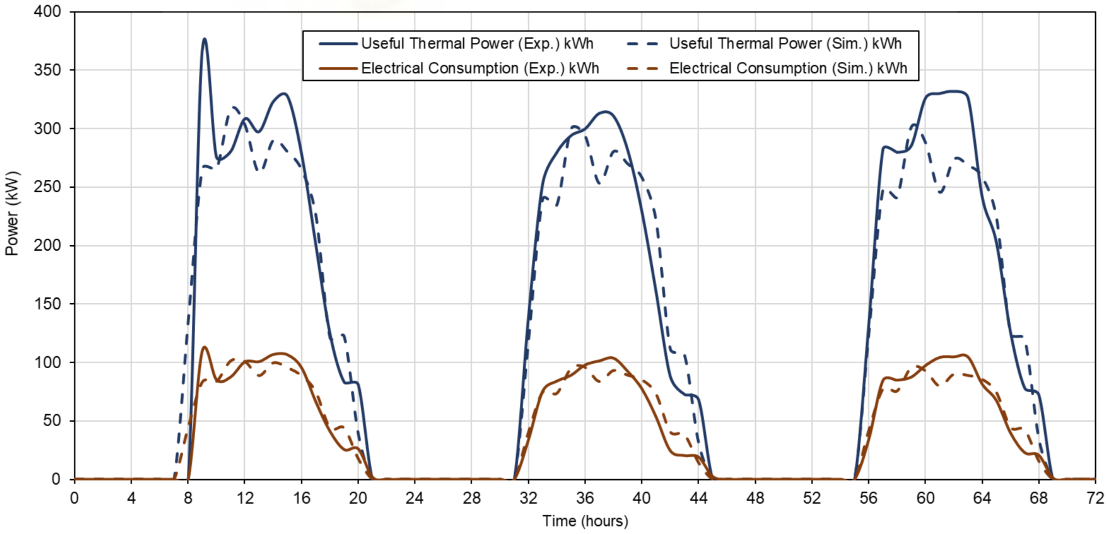

Figure 11. Hourly results. Comparation between experimental and simulation data.

Secondly, Figure 12 compares experimental and simulation energy results in three days of June.

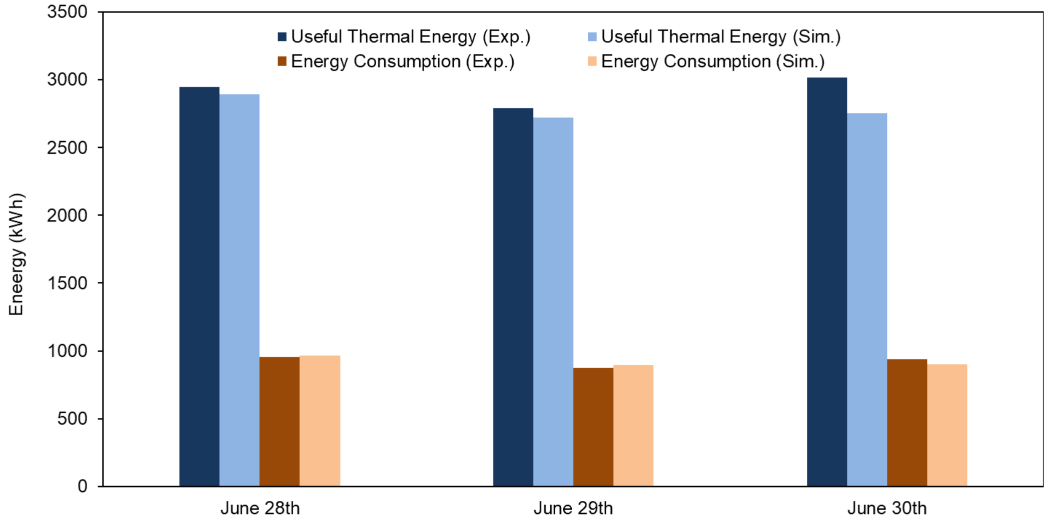

Figure 12. Daily results. Comparation between experimental and simulation data.

Finally, Table 3 includes seasonal values of the useful thermal energy, the energy consumption and the seasonal energy efficiency ratio (SEER). It can be seen that the experimental and simulation results are similar in both power and energy terms, which means that the model is quite accurate.

Table 3. Seasonal results of the study.

	Energy Production kWh	Electricity Consumption kWh	SEER
Experimental	19,341.43	6,164.64	3.14
Simulated	22,244.60	7,325.79	3.04

Taking into account the study included in this section of the article, the energy model developed can be considered validated.

4. Conclusions

- An energy model of an office building located in Alicante has been developed using the software EnergyPlus.
- Experimental measures have been conducted in the HVAC system to analyse the performance of an air-water heat pump located on the roof of the building with a nominal cooling capacity of 400 kW.
- The experimental results have been used to calibrate and validate the energy model.
- The experimental and simulation results are similar in both power and energy terms, which means that the model is quite accurate and it can be considered validated.

5. Future works

Once the energy model has been validated, it will be used to analyse the impact of several energy-saving proposals in terms of final energy, non-renewable primary energy and CO2 emissions. Said proposals will be conducted on three levels: 1) Thermal envelope (insulations, windows, shadow protections, etc.), 2) Facilities (lighting, HVAC, etc.) and 3) Renewable energies (photovoltaic and thermal solar energy).

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Annex 2. Quality Index 2

13CNIT-**ID018**

Energy balance analysis of an office

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1. Introduction

Buildings account for 40% of the final energy consumption in Europe and contribute to 36% of greenhouse gas (GHG) emissions [1]. This highlights the importance of the building sector in the energy transition and the decarbonisation of the European Union (EU). Heating and cooling energy demands constitute a significant portion of the total energy consumption in buildings. Therefore, it is crucial to have accurate tools that can estimate and understand energy usage and building behaviour.

The aim of the present work is to study the energy use of a building. Furthermore, results obtained from simulations with EnergyPlus have been compared with measured data. This allows to validate the calculations and to evaluate several energy savings measures afterwards, which could lead to the reduction of CO_2 emissions and to the thermal comfort of the final user.

In the work developed by Roca Reina et al. [2], a similar approach was carried out but in cooling mode. The present work is focused on the definition and validation of the heating system, showing other results like lighting electricity consumption..

2. Methodology

The building analysed in this work is an office building with five floors located in Elche (Alicante, Spain). The total surface is about, 8000 m^2. It has different kinds of rooms, like individual offices, shared offices, corridors, a restaurant, etc. The building only uses electricity as an energy carrier, and it does not have a hot water facility. In figure 1, there is a representation of the building model, and the real building.

Fig. 1. Building model

The model considers various thermal zones within the building, selected based on the different indoor units and available thermostats in each room. Over 100 different thermal zones are modelled, all of which utilize fan coils as indoor units. Some zones are equipped with cassette fan coils, while others have fan coils with duct distribution. The water loop that connects these indoor units is a 2-pipe loop, meaning that simultaneous heating and cooling is not possible. The facility's HVAC production system features an air/water heat pump situated on the rooftop. The heat pump has a capacity of 438 kW (A7/W35) and belongs to the CLIMAVENETA ERACS-R 1962 L model. Additionally, internal thermal loads from lighting, occupancy, and equipment have been taken into account. Furthermore, the model includes the definition of the real water pumps and fan coils.

The experimental measures were carried out in winter, when the building demands heating. These measures include the thermal energy demand and the electricity consumption. Several probes were installed in the heating facility, including a water flow meter and two thermocouple type K to measure the heating demand. Finally, a grid analyser measured the electricity consumed by the heat pump. Figure 2 represents all these elements. Once all these data are obtained, it is possible to calculate the heating production and the coefficient of performance (COP). Equations 1 and 2 show the methodology.

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

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

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).
- T_{IW}: Water supply temperature (ºC).
- T_{RW}: Water return temperature (ºC).
- P_{elec}: Electricity consumed (kW).

Fig. 2. Measuring instruments

3. Results and discussions

3.1. Experimental measurements

The experimental measurements took place between the end of January and the beginning of February. Figure 3 displays the daily results of the experiment, showing the heating production and the electricity consumption of the heat pump. Additionally, the average COP was also calculated as the ratio between these measurements. The measurements were obtained at exterior temperatures ranging from 5ºC to 25ºC. The COP values obtained varied between 2 and 3, which align with typical values for this technology. Additionally, the manufacturer specifies a nominal COP of 3 (A7/W35). Considering that the water production temperature falls between 45ºC and 50ºC, it is reasonable to observe slightly lower COP values in the measurements.

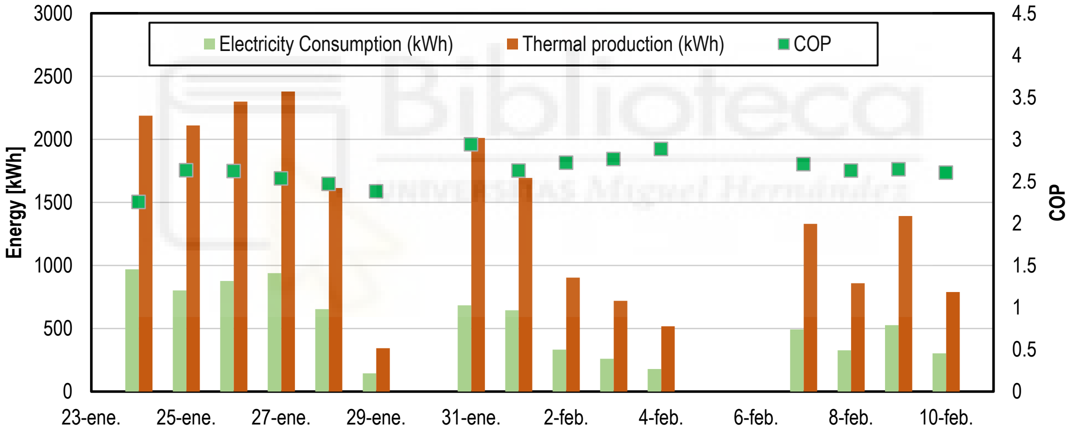


Fig. 3. Daily measurements and daily COP estimation

3.2. Calibration results

The calibration carried out in the current study starts with the calculation of the performance curves of the air/water heat pump. These curves are:

- CAPfText: This curve illustrates the relationship between the maximum heating capacity of the heat pump, based on water supply temperature and exterior air temperature. It takes the form of a biquadratic equation with two independent variables.
- EIRdText: EIR (Energy Input Ratio) represents the inverse of COP and is dependent on water supply temperature and exterior air temperature. Similar to the capacity curve, this curve is also biquadratic.
- EIRfPLR: This curve considers the variation in heat pump efficiency under part load ratio conditions. It is solely dependent on the part load ratio and takes the form of a second-order polynomial.

These curves were calculated using data obtained under steady-state conditions, which closely aligned with the nominal conditions for EIRfText. Transient condition data were not taken into account due to potential high levels of error in the measured values.

Equation 3 represents the CAPfTExt curve, which depends on the water supply temperature and the exterior air temperature. The curve is depicted in figure 4. In that figure, the output of CAPfText is a coefficient close to 1, representing the relationship between the maximum capacity under those conditions and the nominal capacity of the heat pump (A7/W35). The CAPfText curve was calculated using manufacturer-provided data, as the capacity measured at each moment may not necessarily be the maximum under those conditions, thus lacking sufficient information for estimation.

Equation 4 models the EIRfText curve, taking a similar approach to the CAPfText curve. This coefficient represents the relationship between electricity consumption under specific conditions and electricity consumption under nominal conditions. The EIRfText curve was calculated using experimental data and compared with the manufacturer's data, yielding similar results.

$$CAPfTEMP \ = \ a + b \cdot T_{water} + c \cdot {T_{water}}^2 + d \cdot T_{air} + e \cdot {T_{air}}^2 + f \cdot T_{water} \cdot T_{air} \tag{3}$$

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

Equation 5 is the polynomial that represents the influence of the part load ratio conditions in the efficiency of the heat pump. The calculation of the parameter is based on the EnergyPlus Engineering reference [3]. Once the parameter is determined, it is correlated based on the polynomial equation.

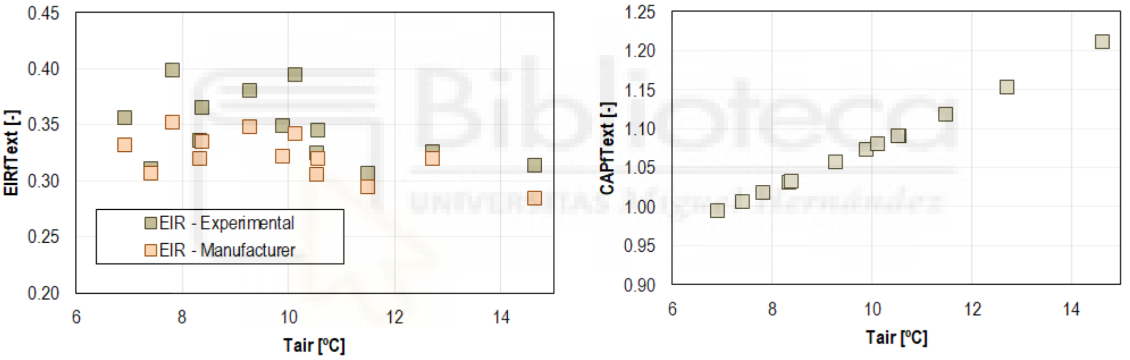
$$EIRfPLR \ = \frac{P_{HeatPump}}{P_{nom} \cdot CAPfTEMP \cdot EIRfTEMP} = a + b \cdot PLR + c \cdot PLR^2 \tag{5}$$

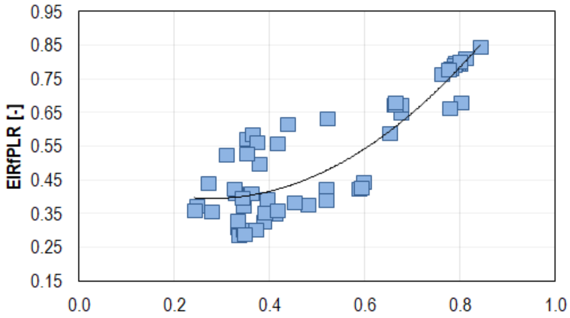
$P_{HeatPump}$:Heat Pump Power (W).

P_{nom}: Heat Pump Power at the nominal conditions (W).

$EIRfPLR$: Heat Pump Production/ Maximum Heat Pump production at specific condition.

The results of the three curves are shown in Figure 3, illustrating the positive correlation between capacity and efficiency as the exterior air temperature increases. Additionally, it is worth mentioning the positive effect of part load ratio conditions on heat pump efficiency. Note that EIR is the inverse of COP.





	CAPfText	EIRfText	EIRfText (Mnfctr)	EIRfPLR
a	0.86991967	0.91256583	0.569162405	0.55080475
b	-0.00196829	-0.0282718	0.004041571	-1.0869814
c	2.8442E-05	0.00088272	0.000203084	1.72203124
d	0.0222672	0.02779982	0.001684605	-
e	0.00037541	0.00132984	-0.00019427	-
f	-5.15E-05	-0.0018237	-0.000461946	-
R2	0.9994988	0.99628608	0.979727459	0.78723872

Fig. 4. Performance curves of the heat pump and coefficients

3.2. Validation results

These curves were utilized to simulate the building in EnergyPlus and to compare the results with the experimental data. Figure 4 represents the results of a typical day of the two-week measurement period. The simulations exhibit a peak in the morning, followed by a rapid transition to part load ratio conditions. In the measured data, the heat pump operates for a longer duration near nominal conditions and then gradually reduces its activity level after midday.

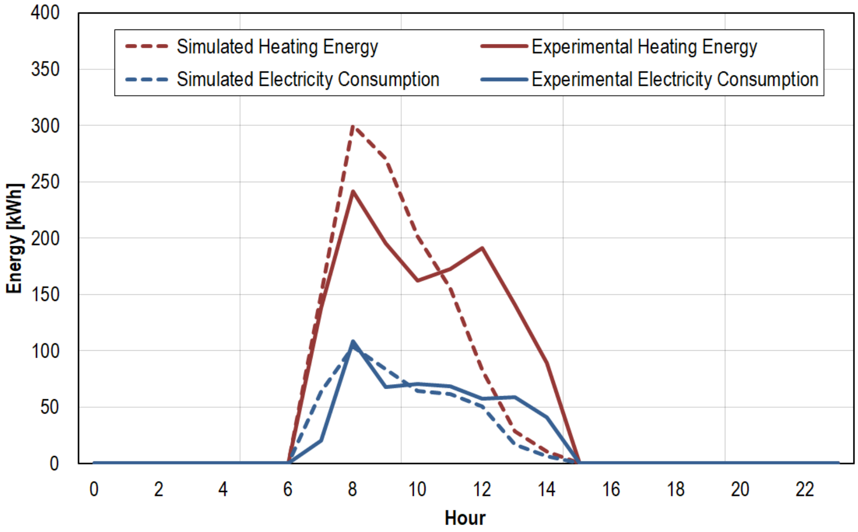


Fig. 5. Hourly results of a typical day

Furthermore, a seasonal comparison of the results was conducted to validate the model. Table 1 presents the seasonal heating production, seasonal electricity consumption of the heat pump, and the seasonal performance factor (SCOP) for the two-week measurement period. The results demonstrate a similar order of magnitude, with a SCOP exceeding 2.5.

Table 1. Seasonal results of the study

	Heating production	Electricity consumption	SCOP
	kWh	kWh	-
Experimental	21,153.93	8,819.18	2.40
Simulated	21,482.77	8,180.06	2.63

Considering the obtained seasonal results, the energy model can be considered validated. Furthermore, the simulation takes into account additional parameters in a building's energy balance, such as electricity consumption for lighting facilities or thermal fluids pumping. Figure 5 illustrates the results of all the simulated parameters.

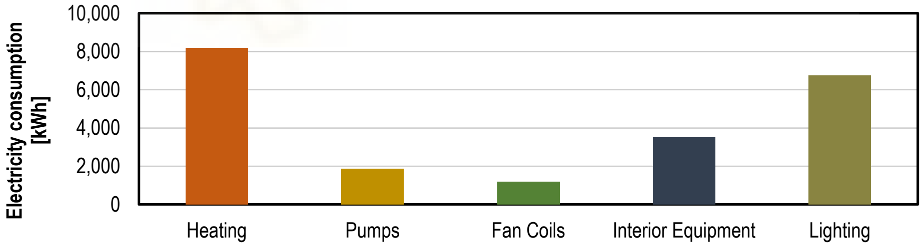


Fig. 6. Simulation of the building energy balance (Simulation of two weeks)

4. Conclusions

- An energy balance of an office building in Alicante has been carried out.
- Performance curves of the heat pump have been obtained with a high level of accuracy. The curves were obtained following the proposed methodology and implemented in the building simulation.
- The model has been validated by using experimental data.
- The electricity consumption for lighting is comparable to the electricity consumption for heating in the analysed building. Based on this observation, energy efficiency measures should prioritize heating and lighting systems. Potential measures could include the implementation of variable-speed pumps for water circulation or the use of more efficient fan coils.

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Annex 3. Additional publication 1

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Alternatives for upgrading from high-temperature to low-temperature heating systems in existing buildings: Challenges and opportunities

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ABSTRACT

The decarbonisation of heating and cooling in buildings is key to achieving the European Union (EU)'s climate and energy targets. Energy consumed in buildings represents a significant proportion of the total energy consumed in the EU; improving their energy performance is therefore fundamental to achieving these targets. This paper outlines a methodology for supporting the energy transition in the sector, emphasising the substantial decarbonisation opportunities that existing buildings present, as well as the potential bottlenecks they may encounter. The impact of changing from fossil-based boilers to heat pumps is compared in typical building typologies in different climatic conditions across the EU, providing insights into the implications of switching from high to low-temperature heating systems regarding both costs and CO_2 emissions. The results show that a significant reduction in CO_2 emissions can be achieved by switching from gas and oil boilers to air/water heat pumps in the analysed countries. The paper also looks at the required enhancements of the hydronic facilities, and building envelope thermal insulation. Effective and well-targeted policies are needed to support the uptake and installation of clean heating systems, supporting homeowners in purchasing the right ones for their homes while supporting our climate goals.

1. Introduction

Buildings account for 40 % of the EU's energy consumption and 36 % of its greenhouse gas (GHG) emissions [1]. It is thus clear that decarbonising our buildings' heating and cooling consumption is crucial to achieving the EU's goal of reducing GHG emissions by 55 % compared to 1990 levels by 2030 and being climate-neutral by 2050. The total final energy consumption for residential space heating in the EU amounted to 1784 TWh in 2020, which was 64 % of the total energy consumption in residential buildings [2]. Most energy used for space heating is still derived from gas and oil, with gas accounting for 39 % and oil and petroleum making up around 10 % [3]. Reducing the use of fossil fuel-based heating combined with building envelope renovations and behavioural changes, are the main ways to reduce building-related GHG emissions, especially for single-familly buildings. Reducing gas usage became even more politically important with REPowerEU, a plan launched in 2022 to make the EU independent of Russian fossil fuels well before 2030 [4].

Heat pumps are an obvious alternative to existing gas and oil boilers. Most renewable heating and cooling pathways towards full decarbonisation in 2050 show that ambient heat with geothermal will strongly increase and will cover almost 30 % of the total final energy demand for space heating, cooling, and hot water [5]. An analysis by the European Commission's Joint Research Centre (JRC) shows that heat pumps are crucial in phasing out the use of gas in the residential sector. The study estimates that replacing 30 million fossil fuel boilers in residential dwellings with heat pumps would reduce the EU's gas and oil consumption by around 36 % in these dwellings, given the 2022 national electricity mixes [6].

Heat pumps have become the leading technology in new buildings and are becoming more important in replacing gas and oil boilers in existing houses. New buildings are perfectly suitable for heat pumps to work very efficiently due to the high energy efficiency standards of the envelope and low-temperature heating distribution systems. Existing buildings are very diverse in terms of the quality of the building envelope and their heating distribution supply.

The efficiency of heat pumps depends on the temperature of the heat source and the supply temperature of the delivered heat. Moreover, other parameters also influence the efficiency, such as the heat load, the design (sizing of radiators), and the mode of operation (weather

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compensation law). Underfloor heating offers the advantage of allowing the lowest maximum flow temperatures (35–45 °C), resulting in higher heat pump efficiency due to its very large heat transfer surface area compared to radiators or mixed transfer systems (radiators in combination with underfloor heating) [7]. A German study monitored the performance of 56 heat pumps installed in existing residential houses with different efficiency levels and concluded that heat pumps can work effectively in all types of buildings, but they work better in well-insulated buildings [8].

Newer and renovated buildings typically have more efficient radiator systems operating at maximum temperatures of 45 °C to 55 °C, or even 35 °C in the case of floor heating [8-10]. Older houses were designed to supply high temperatures from 65 °C to 75 °C on colder days, yet several studies show the surface area of radiators in those buildings is often over-dimensioned to ensure a safety margin, allowing lower temperatures in the radiators. One study analysing the situation in Denmark showed that approximately 80 % of heating systems are over-dimensioned relative to their current design heat load. The over-dimension was mostly between 20 %–30 % [11]. A similar study in Sweden also indicated that the total radiator surface areas are almost universally oversized [12]. Similar results can be seen in the Netherlands, where an analysis of 220 existing dwellings showed that the minimum supply temperature can be lower than 55 °C for 60 % of the dwellings during design weather conditions [13]. This implies that heat pumps can already work effectively in most existing buildings.

This paper analyses the challenges and opportunities when switching from a fossil fuel-based heating system to a heat pump. We illustrate these using three existing buildings by assessing the type of heating distribution system (radiator size, capacity) and the quality of the envelope. We analyse the relationship between the heat pump efficiency and these parameters. Furthermore, we propose various strategies and approaches for upgrading existing buildings from high-temperature to low-temperature heating systems.

Finally, this paper analyses and summarises policies related to the decarbonisation of the heating and cooling sector. This approach provides an overview of the energy transition areas addressed by current and future policies. Additionally, it enables a comparison of the technical barriers in the renovation process with the policies designed to support it.

2. Methodology

This section presents a methodology for evaluating heating energy demand, the performance of the heating supply system, and the capacity and size of radiators for buildings transitioning from a fossil fuel-based boiler to a heat pump. The main challenge discussed is how to ensure that the new heating system can provide the same level of comform (i.e. amount of heat) at different temperature supply levels.

Fig. 1 illustrates the methodology for determining a building's energy demand using JRC's EBEM model. It involves an hourly energy demand calculation considering the balance between heat gains and losses through the building envelope. We then demonstrate how to evaluate the performance of various heating systems, including fossil-fuelled boilers and air/water heat pumps. Additionally, we present a methodology for assessing the size and capacity of radiators for both high- and low-temperature heating supplies. Finally, we look at the effects of energy renovations.

Three reference houses are analysed to illustrate the impact of these parameters when transitioning from a fossil fuel-based boiler to a heat pump. These houses are representative of typical single-family homes located in different countries across the EU. The insights collectively contribute to understanding the opportunities and challenges of transitioning from high to low-temperature heating systems.

2.1. Input data: Buildings and climate

We rely on two primary sources of information: the TABULA WebTool [14] and the PVGIS database [15]. The TABULA project provides data on typical generic houses across the EU, providing essential information for the energy calculation, such as U-values of building elements, ventilation rates, heated floor areas, or opaque and transparent elements' surfaces. The PVGIS database provides meteorological information, including exterior conditions and radiation, obtained from a typical meteorological year (tmy) representing representative outdoor conditions at a given location.

We conduct a comparative analysis of three single-family houses from the 1970 s, located in Sweden, Germany, and Spain, to illustrate the varying impacts of climatic conditions on energy performance and renovation needs across different climatic regions. Table 1 provides information about the building envelope, including the U-values, the surface of building elements, and the heated floor area. They have an annual heating demand of 164, 157, and 170 kWh/m^2, respectively. This heating demand is calculated by applying the methodology explained throughout Chapter 2, following the formulas outlined in Chapter 2.2. Two renovation levels are applied: R1 takes into account the substitution of windows and renovation of the walls, R2 is R1 but adding renovations in floor and roof.

Climate data for the study, including temperature and solar radiation

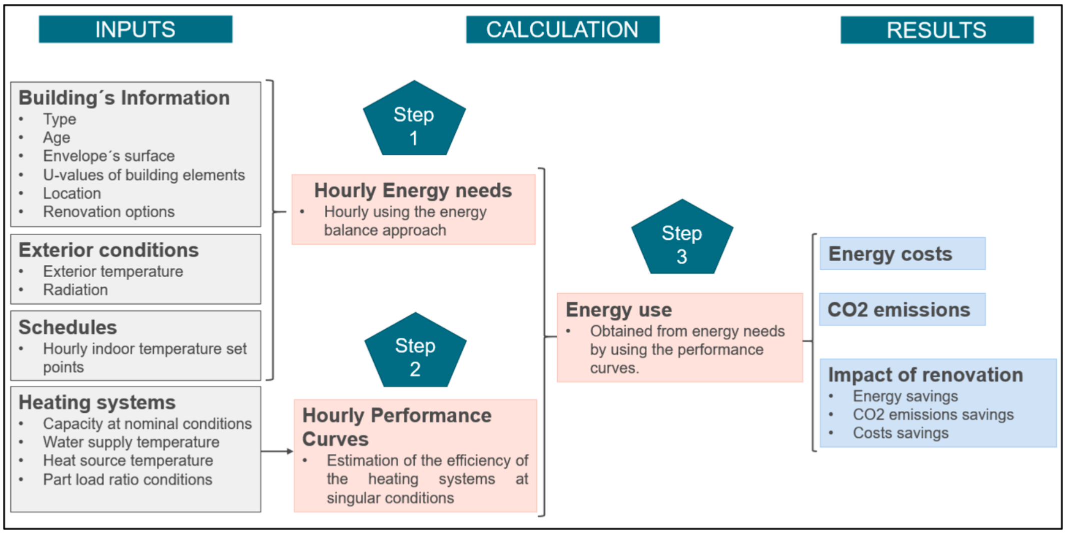

Fig. 1. Methodology to determine a building's energy demand.

Table 1
Building U-values of examined houses in Sweden, Germany and Spain (NR: Non-renovated, R1: Renovation level 1, R2: Renovation level 2).[6.]

	SE	NR	R1	R2	DE	NR	R1	R2	ES	NR	R1	R2
	Surf	U	U	U	Surf	U	U	U	Surf	U	U	U
	m2	W/m^2·K	W/m^2·K	W/m^2·K	m^2	W/m^2·K	W/m^2·K	W/m^2·K	m^2	W/m^2·K	W/m^2·K	W/m^2·K
Walls	200	0.31	0.21	0.21	178	1	0.22	0.22	312	1.33	0.64	0.5
Roof	125	0.21	0.21	0.1	183	0.5	0.5	0.19	63	4.17	4.17	0.8
Floor	125	0.32	0.32	0.24	152	0.86	0.86	0.3	90	0.85	0.85	0.85
Windows	22	2.3	0.9	0.9	34	2.8	1.3	1.3	12.6	4.59	1.84	1.84
Heated floor area	106	–	–	–	173	–	–	–	170	–	–	–

[6] The U-values for R2 of the spanish house were selected taking into account the values of the spanish building code, as there was no information of R2 in TABULA database.

levels, are sourced from the capital regions [15].

2.2. Heating demand estimation

The heating demand has been analysed by calculating the building's energy balance, considering both energy losses and gains in heating. The considered losses include conduction, ventilation and radiation. Conduction losses take into account the heat lost through the building envelope due to the temperature difference between the interior of the building and the exterior air. The rate of ventilation in a building directly affects its ventilation losses. Since incoming outdoor air needs to be heated to match the indoor temperature, this process contributes to heat loss, which the heating system compensates for. Finally, the radiation losses due to the envelope being at a different temperature than the sky are also considered. Equations (1) and (2) show how the losses are calculated.

$$\phi_{losses} = \phi_{cond} + \phi_{vent} + \phi_{rad} \tag{1}$$

$$\phi_{losses} = \left[\left(\sum A_i \cdot U_i \cdot b_i\right) \cdot (T_b - T_{ext})\right] + \left[n_{air} \cdot V \cdot C_p \cdot (T_b - T_{ext})\right] + F_{sky} \cdot h_{re} \cdot \Delta T_{sky} \tag{2}$$

Where:

ϕ_{losses}: Total heating losses of the building [kWh].

ϕ_{cond}: Conduction losses due to the difference of temperature between the exterior and the interior air in the building [kWh].

ϕ_{vent}: Ventilation losses due to the renovation rate of the interior air in the building [kWh].

ϕ_{rad}: Radiation losses from the building envelope to the sky, due to the difference of temperature between them [kWh].

A_i: Is the area of element i of the envelope in contact with the exterior air [m$^{2]}$.

U_i: Is the U-value of element i of the envelope in contact with the exterior air [W/m^2·K].

b_i: Adjustment factor soil, based on TABULA methodology [-].

T_b: Is the interior air temperature [°C].

T_{ext}: Is the exterior air temperature [°C].

n_{air}: Renovation rate of air. Represents the exterior air that enters the building in one hour [1/h].

V: Volume of the interior conditioned air in the building [m^3].

C_p: Specific heat coefficient of the exterior air, considered as 0.34 (W/m3·K).

F_{sky}: Sky factor [-]. 0.5 for the vertical envelope and 1 for the horizontal envelope.

h_{re}: Radiative heat transfer coefficient [W/K].

ΔT_{sky}: Difference between sky temperature and the temperature of the building envelope exterior part. The temperature of the building envelope is considered to be the same as the exterior air temperature. An average difference of 11 K is a suggestion of ISO 52016–2017.

On the other hand, the energy balance also counts heating gains. The heating gains are the internal gains of the building and solar radiation through transparent and opaque elements. The internal gains are linked to the internal occupation of the building, lighting facilities and objects that can also radiate heat. The amount of solar absorbed depends on the properties of the surface, such as colour and reflectivity. Equations (3), (4) and (5) show how to calculate the heat gains.

$$\phi_{gains} = \phi_{solar} + \phi_{int} \tag{3}$$

$$\phi_{solar} = F_{sh} \cdot (1 - F_F) \cdot F_W \cdot g_{gl,n} \cdot \left(\sum A_{w,j} \cdot I_j\right) + F_{ob} \cdot \alpha_{op} \cdot R_{se} \cdot U_i \cdot A_i \tag{4}$$

$$\phi_{int} = \varphi_{int} \cdot A_c \tag{5}$$

Where:

ϕ_{gains}: Total heating gains in the building [kWh].

ϕ_{solar}: Heating gains from solar radiation in the building [kWh].

ϕ_{int}: Interior heating gains from occupation, lighting and interior equipment [kWh].

F_{sh}: Is the reduction factor external shading.

F_F: Is the fraction of the opaque part of the window.

F_W: Is a reduction factor that considers radiation non-perpendicular to the glazing.

$g_{gl,n}$: Is the total solar energy transmittance for solar radiation perpendicular to the glazing.

$A_{w,j}$: Is the area of the windows with orientation j (North, South, East or West).

F_{ob}: Form factor between the buildings and the sky.

α_{op}: Absorption coefficient of the opaque envelope. It is assumed to equal 0.6, as it is the value of the average colours of buildings.

R_{se}: External thermal surface resistance. It is assumed equal to 0.04 m^2·K/W. This value comes from ISO 6946, considered an average value.

I_j: is the average global radiation on surfaces with orientation j.

φ_{int}: Is the average energy delivered to the building by internal heat sources per square metre.

A_c Is the heated floor area of the building.

The balance between heating losses and gains establishes, as a result, the energy needed to maintain the interior conditions in, for example, one hour. When the interior temperature is not constant, for example, when the heating system starts and stops, the inertia of the building needs to be taken into account. For instance, if the building is at 19 °C and the occupant wants to increase the temperature to 20 °C, the heating system needs to provide enough energy to overcome the losses but also provide enough energy to increase the interior temperature of the building. Equation (6) shows the energy balance.

$$Q_{heating} = \phi_{losses} - \phi_{gains} + C_b \cdot \frac{dT_b}{dt} \tag{6}$$

Where:

$Q_{heating}$: Heating demand of the building [kWh].

ϕ_{losses}: Thermal losses of the building [kWh].

ϕ_{gains}: Thermal gains of the building [kWh].

C_b: Effective heat capacity of the building, which is the energy needed to increase or decrease in one unit the temperature of the building. This value is obtained from TABULA database [14]. This database establishes this value in 45 Wh/m^2.

T_b: Internal temperature of the building [°C].

2.3. Heating systems

The performance of heating systems is defined using performance curves and capacity at nominal conditions. The performance curves of a heating system allow calculating the performance of the heating system under different conditions, for example, different temperatures of the heat source, various part load ratio conditions, or different water supply temperatures. These curves are based on one or two variables. Curves depending on a single variable are defined as polynomials, and those dependent on two variables are defined by biquadratic equations.

- COPfText: This biquadratic curve depends on the exterior and water supply temperatures. This curve is used in air source heat pumps, like air/air, air/water, or high-temperature air/ water heat pumps. The final output of the curve is the COP of the heat pump.

$$\mathrm{COPfText} = a + b \cdot T_{water} + c \cdot T_{water}^2 + d \cdot T_{air} + e \cdot T_{air}^2 + f \cdot T_{water} \cdot T_{air} \tag{7}$$

Where:

a, b, c, d, e, f: Coefficients of the curve calculated by linear regression.

T_{water}: Water supply temperature (°C).

T_{air}: Exterior air temperature (°C).

- CAPfText: This is the same kind of curve as the one before. The only difference is that this curve represents the maximum capacity of the heat pump in function of the exterior temperature and water supply temperature. It applies to air source heat pumps.

$$\mathrm{CAPfText} = a + b \cdot T_{water} + c \cdot T_{water}^2 + d \cdot T_{air} + e \cdot T_{air}^2 + f \cdot T_{water} \cdot T_{air} \tag{8}$$

- EfffPLR: This curve represents the boiler's performance as a function of the capacity delivered at each moment. It is a polynomic curve of grade two, and the only input is the part load ratio of the boiler, as the water supply temperature is fixed depending on the boiler type. Part load ratio is the relation between the heating needs the heating system provides and the boiler's nominal capacity.

$$EfffPLR = a + b \cdot PLR + c \cdot PLR^2 \tag{9}$$

Where:

PLR: Part Load Ratio coefficient.

These curves adjust for the capacity of the heating system and its performance at nominal conditions. For example, for air–water heat pumps, the nominal capacity and efficiency in heating mode are calculated with an exterior air temperature of 7 °C and a water supply temperature of 35 °C [16]. Furthermore, there are other parameters like the minimum load of the heating systems. It refers to the minimum thermal energy that a heating system can provide. This minimum load could be around 20–25 % of the rated capacity. If the demand is lower than the heating system's minimum load, the heating system cannot work and stops until the demand reaches the minimum load again. One approach to control the minimum part load ratio conditions is by setting a maximum water return temperature. If the water return temperature exceeds the maximum, the heat pump stops.

The heating systems could be hybrid, meaning that heat pumps can be combined with another heating technology. Typically, a hybrid system consists of at least two appliances with different energy sources. The management of which element of the system produces the heat depends on the exterior temperature and the capacity of the system. Two temperatures are defined in these systems: bivalent (Tbiv) and off temperature (Toff). The bivalent temperature determines if the backup system is used or not. For example, the backup system never works if the exterior temperature exceeds the bivalent temperature (status 1). If the exterior temperature is lower than the bivalent temperature but higher than the off temperature (status 2), only the main system will work unless the heating demand exceeds its maximum capacity. For security reasons, only the backup system works at temperatures below the off temperature (status 3). Fig. 2 shows this approach in a scheme.

Calculating the heating system performance allows us to estimate the energy consumption needed to provide the heating demand. This calculation is essential to estimate a heating system's CO$_2$ emissions and yearly fuel expenses. Equation (10) shows this approach.

$$\phi_{use} = \eta \cdot Q_{heating} \tag{10}$$

Where:

ϕ_{use}: Energy use of the heating system [kWh]. It could be electricity or gas.

η: Efficiency of the heating system [-]. It can represent the efficiency of a boiler or the COP of a heat pump.

$Q_{heating}$: Theoretical heating demand [kWh].

2.4. Energy demand adaptation

The results obtained by applying the methodology explained above are the theoretical values. There are always discrepancies between theoretical and actual energy consumption; for example, the theoretical building envelope composition can differ from reality, or the human activities inside the buildings are not adequately represented. For this reason, the results obtained are adapted to get results closer to reality.

The theoretical results are adapted based on the TABULA methodology [14]. The approach calculates a factor called the "utilisation factor" (Uf), which is obtained based on the energy use of the building. The Uf is determined as shown in equation (11), and once calculated, the real energy demand of the building is determined using formula 10. Fig. 3 illustrates this relationship between energy use and Uf.

$$U_f = 1.07262 - 0.0013 \cdot \phi_{use} \tag{11}$$

$$Q_{heating,real} = U_f \cdot Q_{heating} \tag{12}$$

Where:

$Q_{heating,real}$: Real heating demand [kWh].

U_f: Utilization factor [-].

$Q_{heating}$: Theoretical heating demand [kWh].

This factor has been applied to the results obtained and presented in Chapter 3 to show results closer to reality. Nevertheless, the results should not be compared to other houses with similar characteristics, as the methodology applied within the study still has a theoretical approach.

2.5. Radiators

The indoor units set the water supply temperature of the heating

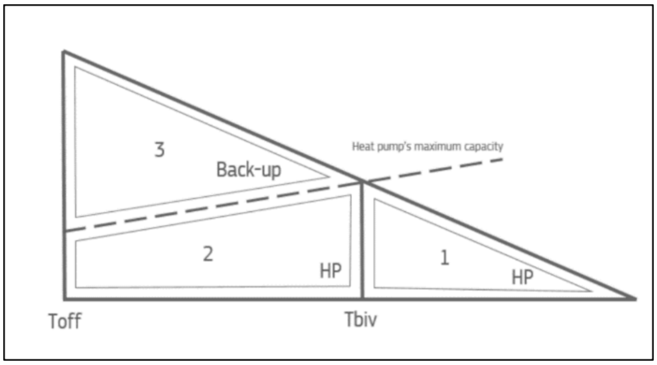

Fig. 2. Contribution from a heat pump and a backup of a hybrid system.

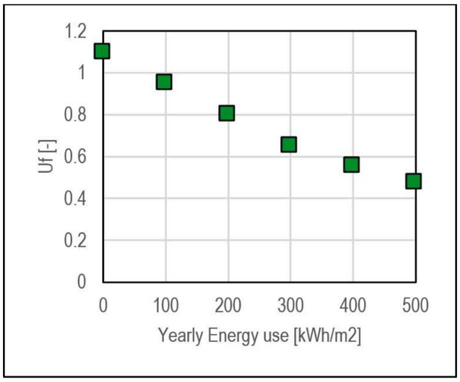

Fig. 3. Utilization factor based on TABULA methodology.
Source: [14]

systems. In this study, indoor units like radiators and floor heating are used. Some radiators could work with different heating generators like boilers or heat pumps. This can be a problem when a heat pump replaces a boiler where the heating system has radiators sized to operate with a supply temperature of 80 °C or 70 °C with a ΔT of 20 °C. Heat pumps with a hydronic loop, like geothermal or air/water heat pumps, usually can supply water at 45 °C or 50 °C, depending on the brand and exterior conditions. They are normally designed to work with a ΔT of 5 °C, although a ΔT of 8–10 °C is acceptable. Indoor units are heat exchangers that transfer heat from the water in the loop to the air in the room. As they are heat exchangers, a reduced temperature difference between the radiator and the room would decrease the heat transfer rate. For this reason, the capacity of the indoor units is evaluated following the EN 442 [17] standard that defines the parameters of indoor units like radiators and convectors. According to this standard, the capacity of a radiator could be defined as:

$$\dot{Q}_1 = K_m \bullet \left(T_{rad,1} - T_{room}\right)^n \tag{13}$$

$$T_{rad,1} = \frac{T_{sup,1} + T_{ret,1}}{2} \tag{14}$$

$$CAP_{rad} = U \bullet S \bullet \Delta T_1 \tag{15}$$

Where:

$\dot{Q}_1$: Heat exchanged in the radiator at design conditions (kW).
K_m: Radiator constant.
n: Radiator exponent. The value adopted for the study is 1.3.
$T_{rad,1}$: Average temperature in the radiator at design conditions (°C).
T_{room}: Room temperature (°C).
$T_{sup,1}$: Water supply temperature at design conditions (°C).
$T_{ret,1}$: Water return temperature at design conditions (°C).
U: U-value of the radiator (W/m^2·K).
S: Radiator Surface (m^2).
ΔT_1: Difference of temperature between the inlet and the outlet of the radiator at design conditions (°C).

As mentioned above, equation (15) shows the reduction in heat exchange in the radiator with decreased average temperature. Moreover, if the radiator temperature is reduced, the capacity could remain constant if the radiator's surface increases proportionally. A lack of space often presents a barrier to these types of interventions. This issue is discussed further in Chapter 3.

This issue appears when radiators are sized exactly for the exterior conditions of the maximum heat load. Studies have shown that the radiators are often oversized, meaning they can sometimes be maintained even if the new heat source works at lower water temperatures. Approximately 80 % of heating systems are over-dimensioned relative to their current design heat load, and this share could rise to about 92 % as expected energy renovations are carried out towards 2050 [11]. Also, a common practice when there is a lack of information about, for example, specific weather conditions, envelope composition, or user behaviour is to calculate heating facilities with conservative assumptions [18]. Another study concluded that the water supply temperatures could be lowered to 55 °C in 60 % of the dwellings analysed in the Netherlands [13]. However, in this study, we assume that the radiators or the building envelope must be upgraded as the heating demand is greater than 150 kWh/m^2 for all three buildings.

Another aspect to consider of radiator size and water supply temperature is estimating the lowest water supply temperature needed to satisfy the heating demand. Usually, the surface of radiators has been calculated under design conditions with a percentile of exterior air temperature of about 95–99 %. The temperatures are not that extreme most of the time; for this reason, the current radiator size could allow them to operate at lower temperatures at certain times during the heating season. The calculation starts with the ΔT in the new conditions, which is calculated according to the formula (16):

$$\Delta T_2 = \frac{\dot{Q}_2}{\dot{Q}_1} \bullet \Delta T_1 \tag{16}$$

Where:

$\dot{Q}_2$: Heat exchanged in the radiator at different conditions (kW).
ΔT_2: Difference of temperature between the inlet and the outlet of the radiator at different conditions (°C).

Using equations (13), 14 and 16, the minimum water supply temperature that could provide the new demand of heating at different conditions would be:

$$T_{sup,2} = \frac{\Delta T_2}{2} + T_{room} + \frac{T_{sup,1} - \frac{\Delta T_1}{2} - T_{room}}{\sqrt[n]{\frac{\dot{Q}_1}{\dot{Q}_2}}} \tag{17}$$

2.6. *Evaluating the investment in heating systems*

This subchapter presents methodological approaches for calculating the GHG emission and cost savings while switching from a fossil fuel-based boiler to an air/water heat pump. Specifically, it covers energy efficiency enhancements of the building envelope and the transition from fossil fuel-based boilers to heat pumps. In more detail, we assess the performance of the following technologies: air/water heat pumps and two levels of envelope renovations — partial and deep renovation. The outcomes enable a comparison of the economic viability of these technologies, considering factors including fuel cost savings and cumulative discounted cash flow.

The calculation of the costs follows the steps:

- Define the reference buildings. We identify "typical" users with similar occupation patterns and internal temperatures. For the technical building characteristics, the model uses the reference buildings from the project TABULA as described in the section above.
- Calculate the yearly energy use by the reference system (Gas boiler).
- Select the new heat supply system and energy efficiency measures.
- Calculate the energy use after applying the energy efficiency measures.
- Calculate the costs of investments.

The cost-effectiveness of the investment from switching from a gas boiler to an air/water heat pump is calculated as the net present value of the cash flow over the lifetime according to EN15459, the "Total Cost". Total cost as a decision criterion is also used in cost-optimality calculations for determining the minimum building energy performance requirements in the EU Member States [19,20]. The economic calculation presents the end-user perspective. To calculate the costs of investments, the following parameters need to be taken into account: investment costs (CAPEX), operation and maintenance costs (OPEX), energy cost savings, and discount rates. We calculate the Net Present Value (NPV) to determine if an investment is worthwhile in the given timeframe.

$$\mathrm{NPV} = \sum_{j=1}^{n} \frac{\mathrm{CS_j} - \mathrm{O\&M_j}}{(1+\mathrm{i})^{j}} - \mathrm{C_0} \tag{18}$$

Where:

n: years (technical lifetime of technology).

j: Specific year.

$\mathrm{CS_j}$: Energy cost savings (annual benefits) in year j.

$\mathrm{O\&M_j}$: Operation and maintenance costs in j (OPEX).

i: Discount rate.

$\mathrm{C_0}$: investment costs (CAPEX).

The definition of discount rates has a significant impact on the viability of investments in energy efficiency measures [19,21,22]. The discount rates weigh the future cash flows (primarily energy cost savings), allowing us to compare the investments today with the future energy cost savings. For this calculation, we use a discount rate of 3 %.

Energy cost savings are calculated as follows:

$$\mathrm{CS_j} = Q_{base,j} \bullet p_{base,j} - Q_{new,j} \bullet p_{new,j} \tag{19}$$

Where:

$\mathrm{Q_{base,j}}$- heating energy consumption with gas boiler in year j [kWh].

$\mathrm{p_{base,j}}$– natural gas price in year j [€/kWh].

$\mathrm{Q_{new,j}}$- heating energy consumption with heat pump in year j [kWh].

$\mathrm{p_{new,j}}$– electricity price in year j [€/kWh].

3. Results

The section presents the results of applying the described methodology to three reference houses, each situated in a distinct climate zone. These results enable us to understand the impact of changing the heating systems, including radiators and piping, and the effects of refurbishing the building envelope.

3.1. *Decarbonisation through a change of heating systems*

The energy carriers naturally play a key role in determining the CO_2 emissions of a building. The emissions are evaluated by considering the selected heating system's gas, oil, or electricity consumption. A CO_2 conversion factor for generating a kWh is applied for the latter and it enables to quantify the CO_2 emitted. The conversion factors for electricity used in this paper are seen in Table 2 and come from the European Environment Agency [23]. The factors used for gas and oil are the same for the three Member States, which are 202 gCO_2/kWh for gas and 267 gCO_2/kWh for oil [24].

Fig. 4 illustrates the CO_2 emissions from using gas or oil boilers—both condensing and non-condensing—compared to an air/water heat pump in the same building. In terms of CO_2 emissions, oil heating systems have the highest emissions in the three selected climate regions, with gas emissions follow closely behind in all regions. Switching from oil to gas boilers reduces emissions by at least 20 % in all cases.

The emissions of condensing and non-condensing boilers depend on their overall efficiency, which depends on how the boiler is used, water supply temperatures, and the time the boiler operates under part load ratio conditions. Given that condensing boilers are often more efficient than non-condensing boilers and can even surpass 100 % efficiency, they typically result in lower CO_2 emissions. Similarly, the efficiency of heat pumps depends on the type (e.g., air/air, air/water, ground/water), water production temperature, and heat source conditions.

Table 2
CO_2 emission factors for energy generation[7] [23].

	Sweden	Germany	Spain
gCO_2/kWh	8	314	177

Electrification of heating through heat pumps yields the lowest CO_2 emissions among the three cases analysed. Thanks to the performance of heat pumps (in this case an air/water heat pump), the electricity consumed usually amounts to 30 % of the heating delivered, resulting in a significant reduction in the energy used to deliver the same heating demand and a reduction of the CO_2 emissions. For instance, in Sweden, low-carbon electricity (renewable and nuclear energy) sources account for nearly the entire country's electricity production. This enables nearly complete decarbonisation of the heating delivered in a building simply by electrifying the heating system.

Germany and Spain currently generate approximately 49 and 60 % of their electricity from low-carbon sources, and as the decarbonisation of their power systems progresses, the CO_2 emissions from heat pumps will decrease. Decarbonising space heating with heat pumps still achieves significant CO_2 savings today, exceeding 60–70 %.

The results show that the reduction of fossil fuels in heating and the electrification of heating through the use of heat pumps lead to considerable CO_2 emission reductions. Switching from a boiler to a heat pump often means lowering the heating facility's water supply temperature, which sometimes can lead to insufficient heat exchange capacity of the radiators.

Fig. 5 compares how the radiators' surface needs to increase to exchange the same amount of heat when transitioning from a condensing boiler operating with water at 65 °C to a heat pump. It is assumed that the boiler is designed to work with a ΔT of 10 °C, resulting in an average hydronic facility temperature of 60 °C. The heat pump can work at 55 °C or 45 °C with a ΔT of 5 °C, which translates to an average hydronic facility temperature of 52.5 °C and 42.5 °C, respectively.

The results show that for a condensing boiler with a supply temperature of 65 °C replaced by a heat pump with a water supply temperature of 55 °C, the surface of the radiators should increase by nearly 50 % to provide the same amount of heat. If the temperature level of the water supply of the heat pump is reduced to 45 °C, the radiator surface needs to be two times larger. This concerns only the design conditions, calculated for the worst exterior conditions or conditions under a certain percentile. If the energy demand is lower than at design conditions, the heating demand could be met with water at lower temperature levels without changing the surface of the radiators. It is assumed that the radiators of the studied buildings are not oversized throughout the rest of the paper.

The yearly heating demand of the three houses studied is higher than 150 kWh/m^2. If a boiler replaces a heat pump, all three houses must increase the radiator surface area to ensure sufficient heat supply during cold winter days, according to the proposed methodology. A potential issue is that there might be limited space for larger radiators. In that case, other measures are required to ensure the efficient operation of the heat pump, such as improving the building envelope, which would reduce the heat demand and allow for the lowering of supply temperatures, or using a hybrid heat pump.

3.1.1. *Hydronic facility: Opportunities and challenges*

The piping system is an integral component of heating systems, distributing the water heated throughout the building. The design and layout of these pipe loops are important in the overall efficiency and functionality of the heating system. Moreover, the flow dynamics within the pipes directly impact the pressure drop throughout the water loop. The pressure head of the circulation pump of the heating system is designed for nominal conditions.

The sizing and materials selected for the piping system contribute to the nominal pressure drop that the water loop will have under rated conditions. In this way, the heating system will be able to supply all the heat in the worst conditions with the hydronic system selected. When

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[7] Note that the electricity CO_2 conversion factor is higher than the one used for gas or oil in Germany, but since heat pumps also make use of ambient energy the CO2 emission per kWh of heat is 1/3 that of gas.

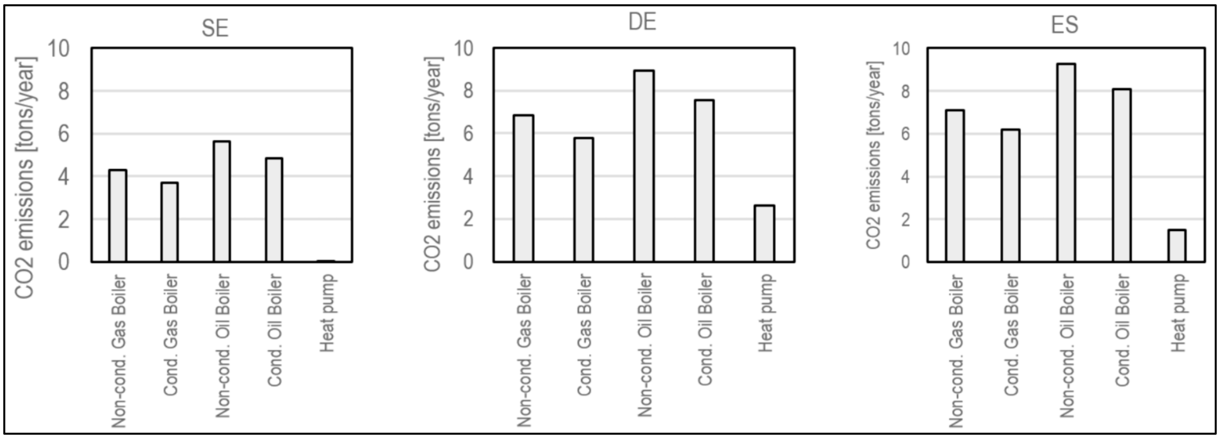

Fig. 4. CO_2 emissions comparison for different heating systems and climate conditions.

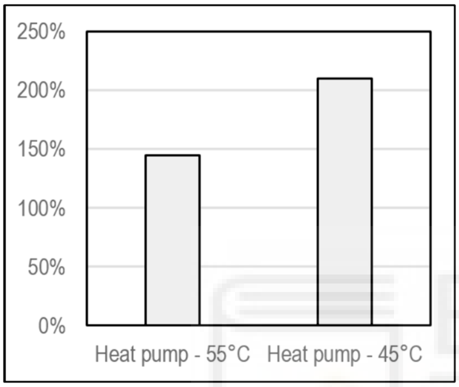

Fig. 5. Increase in radiators surface for equal heat supply if replacing a condensing boiler with a heat pump.

Table 3
Comparison of different drop pressures in the piping system.

Heating system	ΔT(°C)	Water flow (l/s)	Di (mm)	Speed (m/s)	Press drop (mmwc/m)	Long (m)	Press drop (bar)
Boiler	20	0.287	20	0.9	49	10	0.064
Heat pump	5	1.148	20	3.6	593	10	0.77
Heat pump	5	1.148	22	3	374	10	0.48
Heat pump	5	1.148	33	1.3	53	10	0.068

lower water flow is required, several approaches could be considered to follow the heating demand, like the installation of variable speed pumps.

The challenge comes when the new heating facility needs greater water flow than it was initially designed for. A gas boiler that works, for example, with a ΔT of 20 °C has four times less water flow rate than a heat pump working with a ΔT of 5 °C for the same capacity. This statement can be explained with equation (20):

$$\dot{Q} = \dot{m} \bullet C_p \bullet \Delta T \tag{20}$$

Where:

$\dot{Q}$: Thermal energy [kW].
$\dot{m}$: Water mass flow [kg/s].
C_p: Specific heat [kJ/kg·K].
ΔT: Fluid thermal drop [°C].

If the ΔT decreases four times for the same thermal energy to exchange, the water flow needs to increase proportionally to keep the constant thermal energy transfer rate. Table 3 shows a comparison of pressure drops in a 10-metre long copper pipe at different diameters and flow rates. The pressure drop calculations follow the Colebrook-White formula [25], and are calculated. The diameters selected for the study are DN22 and DN35 with a thickness of 1 mm. The diameter shown in Table 3 is the interior diameter.

Based on the results in Table 3, if a copper pipe of DN22 works with a boiler replaced by a heat pump, increasing the water flow by four times results in a tenfold increase of the pressure drop. This would lead to issues with the water pump, as it is likely that the current pump cannot generate the required pump head. Furthermore, the flow speed in the pipe increases by more than three times, reaching values higher than 3 m/s, which could lead to noise issues.

A DN35 pipe working with a heat pump would have a similar pressure drop as a DN22 working with a boiler. This means the piping diameter should increase by 60 % to have the same pressure drop as in the current situation.

These issues sometimes exclude installing a heat pump in current hydronic systems designed for use with boilers. The main issue in adapting the system is the drop of pressure. This could be overcome with a hydraulic separation, such as an inertia water tank. This allows the heat pump to warm the water inside the tank without moving all the water in the loop. However, an external circulation pump has to be integrated into the loop that connects the water tank with the radiators. Fig. 6 shows this approach.

Another benefit of using an inertia tank is the reduction of the heat pump start/stop cycles. Usually, the control of the heat pump takes into account the return water temperature to start or to stop, and this temperature is influenced by the quantity of water in the loop. Without an inertia water tank, the heat pump will stop as soon as there is no heating demand, reducing its performance. The inertia tank will increase the time between the starts and stops of the heat pump, making it work in steady-state mode longer, reducing the stops/starts cycles and increasing the lifetime of the heat pump.

3.2. *Decarbonisation through the improvement of the building envelope*

In addition to replacing heating systems, decreasing the heating demand represents an alternative strategy for decarbonising the building sector. In this study, we are testing the impact of two levels of renovation. Renovation 1 encompasses upgrades of the thermal insulation of walls and the windows of the houses. Renovation 2 extends the scope to include refurbishments of the roof and the floor. These levels of renovations are also presented in Table 1.

U-values are the parameter that, from the modelling point of view,

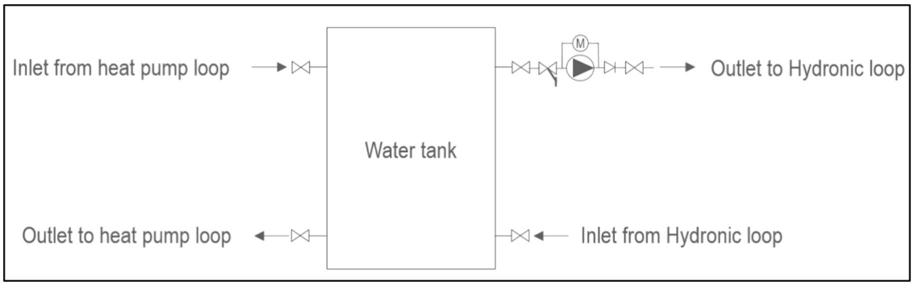

Fig. 6. Inertia tank installation scheme.

measures the capacity of the building to maintain the interior conditions during the heating season. As these values represent the conductivity of the building envelope, the lower the value, the lower the conductivity of the building envelope, which means lower conduction losses.

Fig. 7 shows the yearly heating demand per square meter of applying the two renovation levels to the selected buildings. Furthermore, Fig. 8 represents the influence of building renovations on CO_2 emissions. These emissions have been calculated assuming that the buildings use a condensing gas boiler, which allows us to compare the impact of the renovations on the emissions for the three buildings. Building renovation has a lower impact on the decarbonisation of buildings compared to the electrification of the heating in Sweden since Swedish houses built in the 1970 s already have low initial U-values of 0.2 $W/m^2 \cdot K$, which are challenging to improve. Instead, electrifying heating in Sweden reduces CO_2 emissions to almost zero, as the power grid has a very high contribution from renewable and nuclear energy sources.

The houses in Spain and Germany show a similar tendency. Renovating these houses' envelopes can reduce CO_2 emissions by 50 %–60 %. Concerning CO_2 emissions, changing the energy carrier saves more than renovating the envelope. However, whether the same hydronic facility can work satisfactorily with low-temperature heating systems without modifying the radiator surface is uncertain.

As discussed in the previous subchapter, renovating the building envelope when installing a heat pump can help avoid increasing the surface area of radiators. The main issue is determining the required reduction in heating demand. Fig. 9 shows the results obtained by applying the methodology described in Chapter 2 that considers the EN 442 standard [17]. The comparison is between the systems analysed in Fig. 5: Condensing gas boiler working at 65 °C and a heat pump working at 55 °C or 45 °C.

Fig. 9 shows the needed reduction in heating demand compared to a non-renovated building to efficiently use a heat pump without replacing radiators. For instance, replacing a condensing boiler with a water supply temperature of 65 °C at an average water loop temperature of 60 °C with a heat pump supplying water at 55 °C and an average water loop temperature of 52.5 °C requires a 35 % reduction in heating demand. If the same boiler is replaced by a heat pump supplying water at 45 °C at an average water loop temperature of 42.5 °C, almost 60 % reduction of heating demand is necessary.

This shows the importance of an adequate hydronic facility when the heat is supplied at lower temperatures compared with the design conditions. However, as was shown in Chapter 2, there is evidence that some hydronic facilities are oversized; for this reason, supplying heat at lower temperatures is not always linked to removing the current hydronic facility.

Considering the results obtained in Chapters 3.1 and 3.2, properly decarbonising the existing building stock with high energy consumption of more than 150 kWh/m^2/year should typically upgrade both building envelope renovation and the upgrading of the heating system.

Additionally, low-temperature heating systems work with lower ΔT than high-temperature heating systems. This means that, for the same capacity, the volume of water to be circulated in the pipe loop will be greater. Hence, the pipes might have to be replaced too, see Chapter 3.5 for more information.

3.3. *Cost evaluation*

The cost evaluation carried out used public economic data on fuel costs. This data allows us to compare different heating systems,[1] and calculate, for example, yearly savings if there is a technology upgrade. The data has been sorted by technology and Member State. It is worth highlighting that the results obtained are theoretical and depends on the described assumptions.

- Electricity and gas prices: The prices used for these energy carriers were taken from VaasaETT [26]. This source provides monthly average energy prices for the capital of different EU Member States. These prices are averages of the energy prices from January 2022 to August 2023 (Table 4).
- Oil prices: These prices have been obtained from the Weekly Oil Bulletin of the European Commission [27]. The data extracted is called "Gas oil de chauffage Heating gas oil Heizöl" and refers to prices inclusive of duties and taxes. The original data is in €/100L. For this reason, an energy content of 10.6 kWh/l is assumed. The prices are in Table 5.

The costs of energy efficiency measures influence the final user's decision. Using the average costs of electricity and natural gas from 2022 until the first quarter of 2023, we compare the yearly fuel costs of different heating systems. Fig. 10 shows the yearly energy heating costs for the same building but with different heating systems in Sweden, Germany and Spain.

The fuel costs of replacing different heating systems vary per Member State. For instance, Sweden's electricity prices are similar to gas prices, but the energy use is reduced by 2/3, which reduces fuel costs by around 65 % by replacing a gas boiler with a heat pump.

In Germany, electricity is considerably more expensive than gas and oil. A condensing boiler's yearly gas costs equal the heat pump's electricity costs, making the change less attractive for the final user. A heat pump has lower operating costs than a non-condensing boiler but higher than an oil boiler due to the low oil costs in Germany. Spain has a similar result to Sweden but with less difference in terms of prices between energy carriers, due to the higher prices of electricity. In Spain, replacing a condensing boiler with a heat pump could reduce operating costs by 45 % annually.

The influence of building renovation has been considered as well. Fig. 11 shows the costs of renovating the building envelopes of the houses selected. It was assumed that the three buildings were heated by the same heating system (condensing gas boiler), so the only cost impact was due to renovation. As mentioned earlier, all the buildings analysed were built in the 1970 s, which allows us to compare the renovation

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[1] Upgrading to heat pumps also including upgrading radiators and pipings.

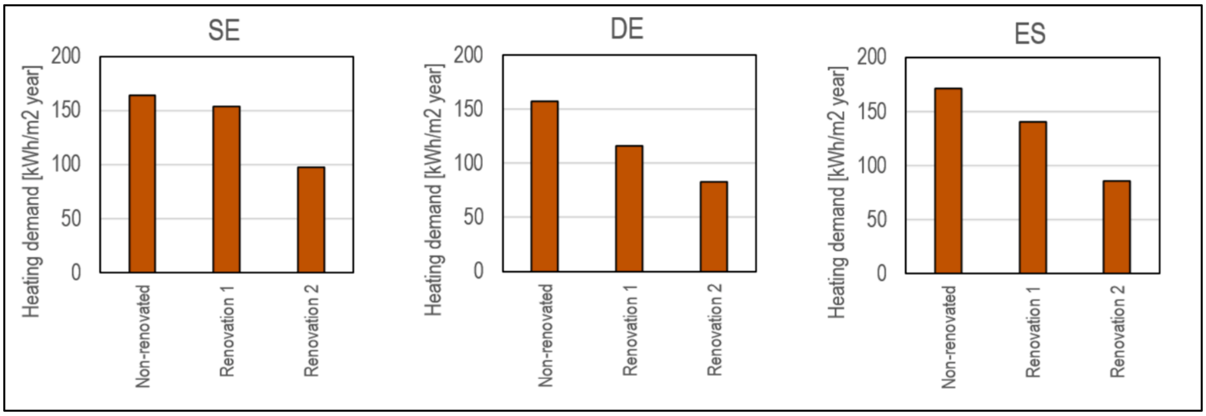

Fig. 7. Impact of building renovations on the heating demand.

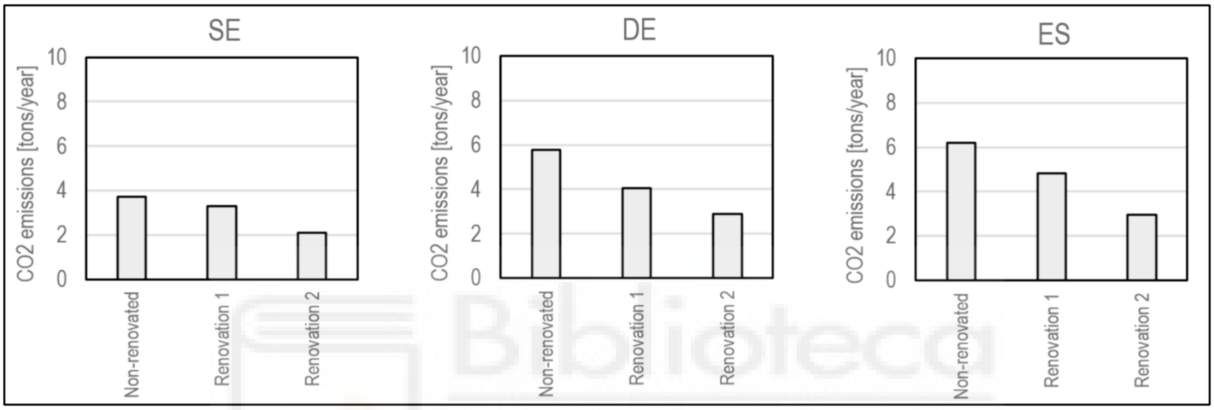

Fig. 8. Impact of building renovations on CO_2 emissions.

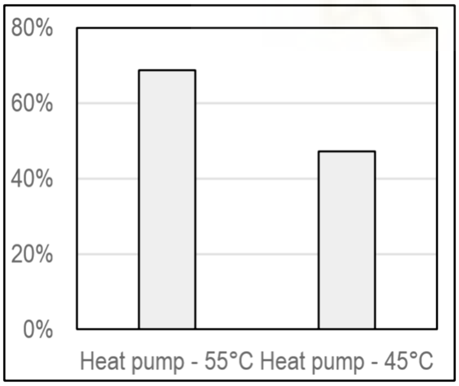

Fig. 9. Levels of heating demand reduction to maintain the same indoor units.

Table 4
Electricity and gas prices used. Units: €/kWh.

	Sweden	Germany	Spain
Electricity	0.24	0.40	0.27
Gas	0.25	0.13	0.12

Table 5
Oil prices used. Units: €/kWh.

	Sweden	Germany	Spain
Oil	0.12	0.08	0.08

effect between different member states in buildings of the same age.

Annual energy cost savings from building envelope renovations range from 10 % and 30 % for level 1 (windows and walls) and up to 50 % with renovation for level 2 (renovation 1 + roof + floor). The effectiveness of the renovations depends on the initial quality of the building envelope. In countries like Sweden, which have more higher insulated envelopes, a level 2 renovation is needed to see significant energy demand reduction. In Germany and Spain, with lower initial quality of envelopes, level 1 renovations have a significant impact on energy savings.

Combining building envelope renovation with upgrading the heating system can lead to even higher annual cost savings, as shown in Fig. 12. For example, a house from Spain can reduce its yearly fuel costs by €3,000, resulting in a 75 % decrease. A similar reduction can be achieved in Sweden by upgrading the heating system alone (building envelope improvement was not considered since it would not save much energy). The house in Germany can also cut its fuel costs in half, but when the heating system is upgraded, the annual costs remain the same due to the four times higher price of electricity than gas.

Another approach to evaluate energy efficiency measures is by calculating the NPV as shown in Chapter 2, which allows for estimating the profitability of an investment, taking into account the time value of money during the lifetime of the energy efficiency measure. A positive NPV indicates that the investment is worthwhile. The payback time is another measure which indicates how long it takes for an investment to be recovered. For example, if a heat pump replaces a boiler, the savings that are considered are the ones obtained during the 18 years of the lifetime of a heat pump.

We have analysed the energy efficiency measures from the point of view of the final user, showing what it means for them to change to these

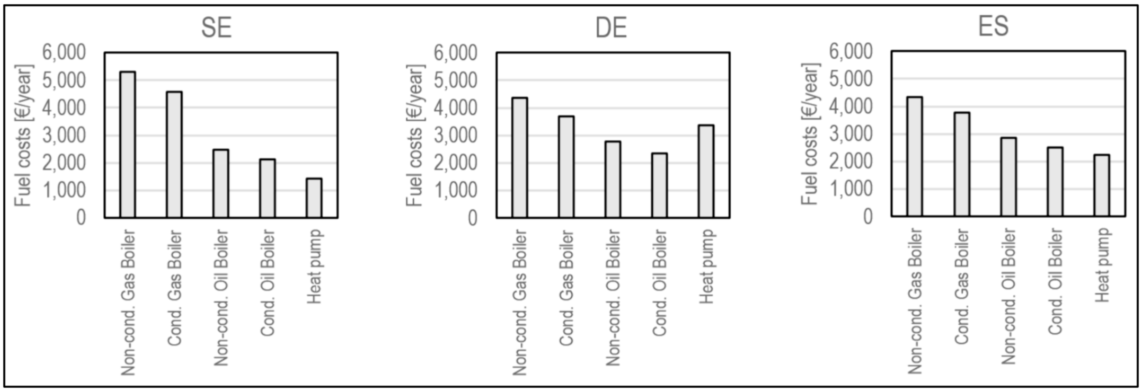

Fig. 10. Comparison of yearly heating costs for different heating systems and buildings (using average energy prices for electricity and gas described, and without renovating of the building envelopes).

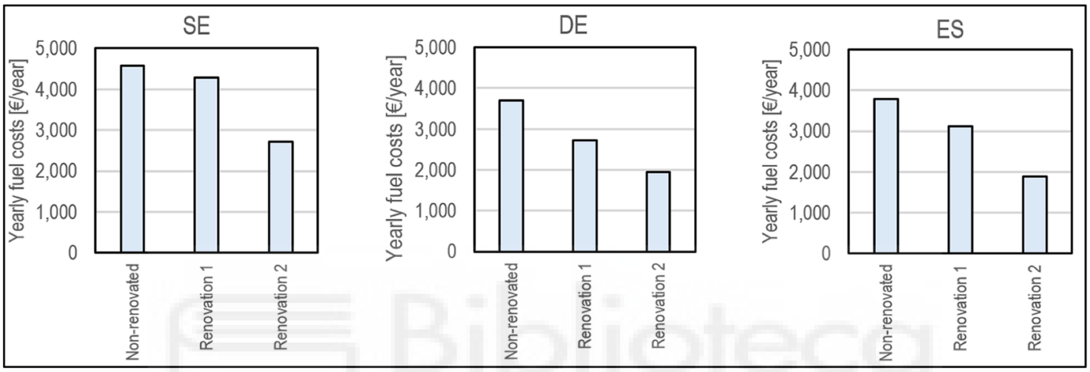

Fig. 11. Effect of building renovations on yearly fuel costs (using average energy prices for electricity and gas described).

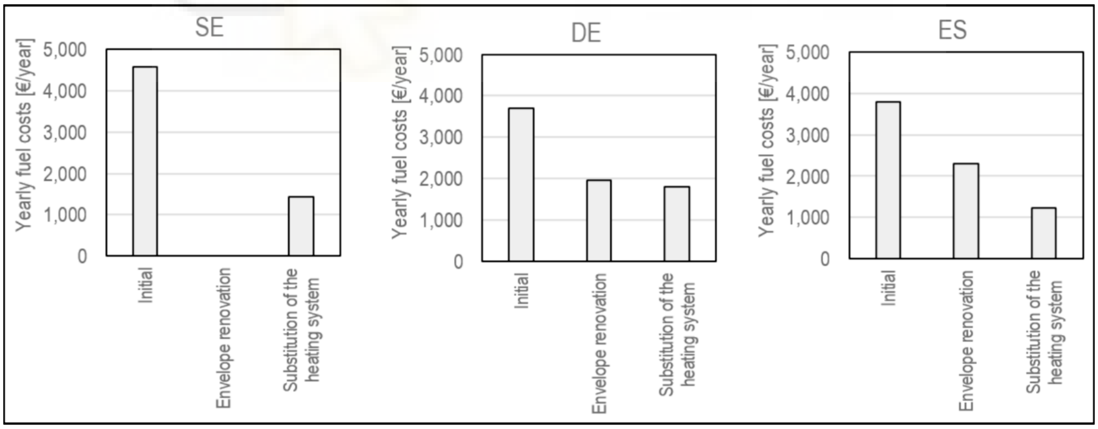

Fig. 12. Annual fuel costs of the combined strategy proposed for the three different houses.

types of technologies. We compared two approaches: One only changing heating systems (Table 6) and one taking into account the renovation of the building envelope and changing the heating systems (Table 7).

Table 6 summarises the economic analysis of upgrading the heating system without renovating the building envelope, obtained by applying the methodology described in Chapter 2. The reference system taken into account is a non-condensing gas boiler. This allows the final user to compare between changing to a condensing gas boiler or an air/water heat pump. The boiler considered is a common residential gas boiler, which could have a capacity of around 20–24 kW. The capacity of the heat pump is obtained by applying the methodology described in Chapter 2. The discount rate used is 3 % and the lifetime of the heating system considered is 18 years.

Heat pumps could be considered a good investment for the final user due to the savings they could bring during their lifetime and their short payback periods. The upfront investments in air/water heat pumps are higher than those in gas boilers, but due to the potential energy savings, the NPV is significantly higher, and the payback periods are in the same order of magnitude, except for Germany.

Considering the strategies proposed in Chapter 4, we also studied what it means for the final user to upgrade the building envelope and the heating system. For a building renovation, 30 years are considered for the NPV calculation. In this case, only the houses in Spain and Germany will be analysed as the one in Sweden is already well-insulated.

Table 6
Financial comparison of condensing boilers and air–water heat pumps for the case of no building envelope renovation.

	Condensing boiler			Air/water Heat pump		
	SE	DE	ES	SE	DE	ES
Heated area [m^2]	106	173	171	106	173	171
Heating demand [kWh/m^2*year]	164	157	171	164	157	171
Capacity [kW]	20	20	20	11	16	19
Heating generator [€]	2,824	2,430	2,325	10,874	10,460	10,639
Installation cost [€]	1,481	1,421	760	5,105	4,897	2,620
Indoor unit adaptation [€]	–	–	–	7,083	9,563	7,738
Total investment [€]	4,305	3,851	3,085	23,063	24,921	20,998
NPV [€]	6,098	5,924	4,917	44,463	6,549	21,315
Payback [years]	7.0	6.7	6.6	4.0	14.1	6.2

Table 7
Financial comparison of investing in renovating the building envelope and upgrading the heating system.

	DE	ES
Heated area [m^2]	173	171
Heating demand [kWh/m^2*year]	157	171
Capacity [kW]	11	12
Heating generator [€]	8,127	8,245
Installation cost [€]	5,105	2,801
Renovation costs [€]	96,366	52,386
Total investment [€]	109,598	63,432
NPV [€]	−59,000	786
Payback [years]	59	28

According to the results shown in Table 7, the investment is worthwhile for the house in Spain. However, for the house in Germany, as renovation is more expensive and the savings from changing from gas to electricity are very low. However, the fact that the investment is expensive does not mean its a bad investment, just that the whole cost wont be recouped through energy savings. Renovation often comes with other benefits such as a more comfortable home, increase in property value and an extended lifetime of the building. However, the results also highlights the importance of subsidies to incentivise more homeowners to make these type of investments.

3.4. *The challenge of the power system*

Decarbonising buildings through heat pumps can also create another challenge: if the power system cannot support increased electricity demand. The amount of electricity heat pumps consume depends on several aspects, such as exterior conditions or user behaviour.

A macro-level estimation of the impact of heat pumps on the power system by JRC, examined the EU electricity market in 2030 based on the REPowerEU scenario, using the Metis energy economic equilibrium model to simulate hourly dispatch of generation technologies, taking into account generation mix, demand profiles, commodity prices, and grid constraints [6]. The study concluded that across the EU, an expected 52.1 million heat pumps will be installed by 2030, the electricity demand from these heat pumps could account for as much as 11 % of the total grid demand on a cold winter day. This demand could rise further if, for example, some buildings have a lower set point temperature overnight and in the morning they want to increase this set point of the interior temperature. For example, a building could demand during the day 20 °C but during night 16 °C, this situation can potentially increase the peak demand by a few percentage points. Despite this, the additional burden on power grids from heat pump usage is projected to be manageable from the macro perspective.

The macro analysis [6] also identified the impact of the deployment of heat pumps by Member State. The heat pumps were allocated in every Member State depending on the number of boilers installed. The assumption was to allocate more heat pumps in Member States with a larger share of boilers. Furthermore, two scenarios were analysed, taking into account building renovations. Scenario 1 had the assumption of accompanying the deployment of heat pumps with 60 % of building renovation, which means that the 60 % of buildings where heat pumps were allocated also renovated their envelope. Scenario 2 was a similar assumption but with 30 % of building renovation.

Fig. 13 shows the impact on the power system depending on how many buildings are renovated. The renovation of buildings reduces the heat demand and the electricity consumed by the heat pump, reducing the impact of these systems on the power grid. This effect is significant in Member States like Germany or Italy, with high shares of boilers in the heating consumption.

The higher load on the power grid also contributes to the electricity prices. The work done in [6] estimated that following the previous Scenario 2 could lead to higher annual electricity prices, with an average of 6 % higher prices in all the Member States.

Another perspective is to analyse this challenge not on a macro level, but on a local level. The work done by Fesefeldt et al. [28] analyses the impact of the deployment of heat pumps in the Swiss city of Yverdon-lesBains. The study concluded that, on the coldest winter days, there could be severe under-voltages and line overloading on the power grid. To mitigate this effect, authors propose strategies for cable reinforcements and the use of cogeneration or photovoltaic units to mitigate the voltage reduction. Moreover, the work done by Knittel et al. [29] shows that in the British Columbia in Canada, an increase of the peak demand of 37 % could appear with a full electrification of the gas used for space and water heating.

3.5. *Policy context*

The section will outline the primary policies that the EU has implemented and plans to implement to decarbonise its building stock, addressing the urgent need to transition to sustainable heating solutions and improving energy efficiency.

3.5.1. *Frameworks and strategic plans*

The *European Green Deal* [30] is a comprehensive framework, approved in 2020, to make the EU the first climate-neutral continent by 2050. As part of this plan, the EU established climate protection targets specifying that by 2030, the EU should achieve a net reduction of 55 % in greenhouse gas emissions compared to 1990 levels. Additionally, the EU is committed to achieving climate neutrality by 2050.[2] Central to the Green Deal is the *Renovation Wave* strategy [31], which aims to accelerate the renovation of buildings to improve energy efficiency and reduce carbon emissions.

The Recovery and Resilience Facility [32] (RRF) is an instrument launched in 2021 that supports the mitigation of the impact of the COVID-19 pandemic and to achieve the climate neutrality targets for 2050. The latest data available shows that 34 TWh have been reduced in the EU by using this instrument [33]. The instrument will be available until 31/12/2026.

The European Commission launched the *REPowerEU* plan in 2022 to make Europe independent from Russian fossil fuels before 2030. Further increasing the use of renewable energy sources and installation of heat pumps play a key role in this plan as there are still more than 80 million gas boilers used for heating in the EU.

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[2] In February 2024, The European Commission proposed reducing the EU's net greenhouse gas emissions by 90% by 2040, relative to 1990's emission levels. When this paper is written, the legislative process of agreeing on the 2040 target has just started.

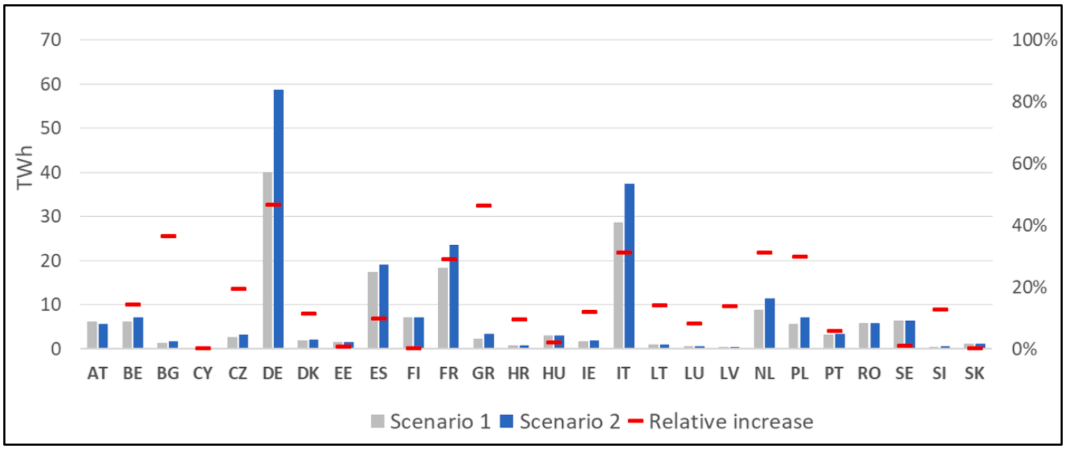

Fig. 13. Impact on the power system of the deployment of heat pumps following the REPowerEU target. .
Source: [6]

3.5.2. *Directives*

The *Energy Performance of Buildings Directive* [34] (EPBD) is the main directive used to achieve a decarbonised building stock. It was first introduced in 2002 and sets out requirements for improving the energy efficiency of new and existing buildings across the EU. For example, it mandates Energy Performance Certificates (EPC), defines Zero-Emission Buildings, and requires Member States to develop Building Renovation Plans. The latest revision also introduces provisions including a minimum energy performance standard (MEPS) for existing buildings, to trigger renovations of the worst-performing buildings. Furthermore, Member States are asked to set out policies and measures to achieve a complete phase-out of the use of fossil fuels in buildings by 2040.

The *Renewable Energy Directive* [35] (RED) also supports the decarbonisation of buildings by mandating and incentivising the integration of renewable energy technologies. Under the RED, Member States are required to increase the share of renewable energy in their overall energy consumption. The overall target for the EU is to achieve at least 42.5 % of renewable energy by 2030. This directive encourages the deployment of renewable energy systems such as solar panels, wind turbines, and heat pumps in buildings, thereby reducing reliance on fossil fuels for heating, cooling and electricity.

The *Energy Efficiency Directive* [36] (EED) aims to improve the union's energy efficiency levels, and thus help reduce overall energy consumption. The latest revision established the 'energy efficiency first' as a principle of EU energy policy, to stress that we not only need to reduce fossil fuel consumption, but also reduce our overall energy production through efficiency improvements. The latest revision (2023) mandates Member States to ensure that regional and local authorities prepare local heating and cooling plans in municipalities having a total population higher than 45,000. In these plans, municipalities will identify the best way to decarbonise their heating and cooling sector.

The *EU's Emission Trading System* (EU ETS), functioning as a cap-and-trade scheme, was initially launched in 2005. Through its mechanism of pricing carbon,[3] it has proven successful in mitigating emissions, notably within the energy production and industrial sectors. The new EU Emission Trading System (ETS 2), coming into effect in 2027, will also cover emissions from fuel combustion in buildings. The carbon pricing mechanism will make it more expensive to use fossil fuels for heating compared to renewable energy sources.

3.5.3. *Financial instruments*

There are multiple financial instruments and support programs to facilitate the decarbonisation of buildings. There is a large variety of actions to support energy renovations and heat pumps, including grants, loans, tax credits, use of energy saving obligations and energy performance contracts. The EU supports Member States in setting up suitable programmes through the *European Structural and Investment Funds* and lately through the *Recovery and Resilience Facility*.

Most Member States offer financial incentives to encourage homeowners or businesses to install heat pumps and renovation. These incentives typically comprise tax credits or grants, with the amount contingent on the previous heating system (e.g. a larger subsidy if replacing an inefficient oil boiler) or renovation depth.

The French MaPrimeRénov programme provides financial assistance to homeowners and landlords who want to make energy upgrades to their buildings. The objective is to reduce energy consumption and greenhouse gas emissions in the residential sector and to promote the use of renewable energy sources for heating and cooling. Higher financial support is eligible for deep renovations and zero-carbon buildings. The available support for a heat pump depends on the income of the family, the location of the building, and the type of heat pump [37].

The German KfW programme offers financial incentives and low-interest loans to individuals, businesses, and public organizations to encourage the use of energy-efficient technologies, such as heat pumps, as a way to reduce energy consumption and greenhouse gas emissions. The subsidy covers between 25 and 40 % of the installation cost, depending primarily on the heat pump type and the old technology being replaced [38].

Similarly, the Czech Nová zelená úsporám supports investments in energy renovations of buildings. The main objective of the programme is to improve the state of the environment by reducing greenhouse gas emissions. Among other measures, the scheme covers up to 50 % of the costs of a heat pump or energy saving measure.

3.5.4. *Advisory instrument*

Several countries have introduced advisory instruments to assist homeowners with technical guidance and support. The low awareness of the possible technical solutions and the potential benefits has been identified as one of the main barriers to renovation and clean heating installations. One example to overcome this is the *renovation passport*, which is an individual renovation roadmap, setting out an optimal renovation pathway to decarbonise the building. The instrument recommends an optimal sequence of measures to ensure the right actions are taken and that they are taken at the right time. It enables a building to become a zero-emission building through several stages [39]. The

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[3] The system also encompasses emissions resulting from the combustion of other greenhouse gases, namely methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride. Their emissions are being translated into carbon dioxide equivalents based on their global warming potential.

instrument already exists in a few countries (e.g. Belgium, France and Germany). Another example is the one-stop shop for renovation, which is a service offering integrated renovation solutions for households to simplify the renovation process. The most ambitious services guide households from the first idea of improving something until the final result, including services like technical and financial assistance, the first diagnosis of the buildings, contact with professionals, planning and implementation of renovation works, and quality assurance [40]. Both instruments have been included in the latest revision of the EPBD (2024).

4. Discussion

Decarbonising the existing building stock can be achieved by increased use of low-temperature heating systems, such as heat pumps. Due to EU goals and commitments, the electricity mix is also meant to become cleaner over time. Difficulties in existing buildings can appear when replacing a high-temperature heating system (e.g., fossil-fueled boilers), with systems that deliver the heat at lower temperatures (e.g., heat pumps).

These heating systems operate under very different conditions. Boilers could have a water temperature production of 80 °C and work with ΔT of 20 °C, while normal heat pumps can produce the water at 45–50-55 °C with a ΔT of 5–10 °C. This implies that to deliver the same heating supply with a low-temperature heating system, a larger heat transfer surface is needed (e.g., larger radiators, underfloor heating, etc.) and, as the ΔT is lower, we need more water flow, which implies the use of bigger pipes in the hydronic system. This is usually not a problem in new buildings, as everything is already designed for low-temperature heat supply.

Chapter 3 explained that an existing radiator's heat transfer capacity reduction is between 35 % and 60 % when you decrease the water production temperature. This challenge could be overcome by increasing the surface of radiators. However, this might not be possible due to lack of space. One option is to consider elevating the heat transfer by using fans under the radiator. This type of system increases the convection part of the heat transfer process. A study determined that, with a system producing water at 40 °C, a fan system at low speed could increase the radiator capacity by a factor of two [41]. Other authors have studied the use of fans in radiators from a techno-economic point of view [42], being able to reduce water supply temperatures that were already low (from 42 to 39 °C) with a payback time of 63 days.

On the other hand, the heating demand of the building could also be reduced by lowering the envelope conductivity. The challenge here resides in what is the quality level of the current envelope and where the building is located. The study done by [43] showed that energy inefficient buildings in Frankfurt would need 15 cm of more isolation to be low-temperature ready. The study concluded that, in terms of investments, it is not economically viable with current gas prices for the building owner to improve the envelope quality for the buildings they studied. This is in line with the research done by [44], in which the authors mentioned that this type of renovation should not be considered as an economic investment criterion due to the long payback times. Nevertheless, the investment could still be worthwhile since improving the quality of the building envelope helps the existing building stock to be low-temperature ready and decreases the heating demand of buildings, meaning that the stress on the power grid will be lower. In our study, we conclude that it can be a good option for a house in Spain, but subsidies are needed for a house in Germany to support the high initial investment that the house owner should make. For houses in Sweden, as the power grid is very clean and the envelope of the house is already well-insulated, changing the heating system is a good path which most single-family building owners already have followed.

In Chapter 3 we presented how the size of radiators should be increased to maintain the heat supply when switching from a high to a low temperature supply. This can imply that the hydronic facility has to be upgraded by installing larger diameter pipes. Not changing the existing pipes could lead to high water speeds inside the water loop of about 4 m/s, which increases the pressure drops significantly and can cause a problem with noise.

We propose a strategy based on the results obtained in the previous subchapters. Starting with the building envelope is the most logical way for less efficient building envelopes, as the heating demand can be reduced, therefore the new heat pump installed can be calculated for this new heating demand. However, if the building envelope already has low conductivity, it could make sense to start directly from the point of changing the heating system.

All three houses studied can lower their heat demand by improving their building envelopes, however for the case of Sweden it is limited since the house is already well-insulated so it becomes less cost-efficient. In order to know if the building envelope needs renovation, we assume that if the heating demand can be reduced to a level that allows the final user to maintain the radiators, the envelope should be renovated before changing the heating system. As shown earlier, using a heat pump that works at 55 °C of water supply temperature, the heating demand should be reduced by 40 %.

This happens in the three houses selected, being the one in Sweden very on the edge. For this reason and because, as shown in Chapter 3.1, CO_2 emissions are almost null by only changing the heating system, we do not propose building envelope renovations for the house in Sweden. Fig. 14 shows the results of the CO_2 emissions of the three houses studied. The initial case is the CO_2 emissions with no renovation and using a condensing boiler, the second case is applying a building envelope renovation, and the third one is adding a heat pump to the building with the envelope renovated.

Fig. 14 shows that only by changing the heating system in Sweden (previous adaptation of the radiators and pipes), the CO_2 emissions be reduced to almost zero. A high level of reduction is achieved in Spain and Germany as well, but with a building envelope renovation before upgrading the heating system.

One risk when planning your energy and cost savings from a renovation is the rebound effect, which refers to the reduction in expected savings due to post-renovation changes in behaviour, overestimation of efficiency gains, or issues with the implementation of energy-saving measures. The fact that the savings made could be spent on heating is called the Jevon's paradox or the rebound effect [45]. This effect is not taken into account in this paper, as we consider that all the heating systems are used at the same conditions of use.

Electrification through high-temperature heating systems like hybrid heat pumps can be interesting in countries where the share of boilers and the heating demand is high. Moreover, if electrification of the heat supply of the region is not a problem for the power grid and the facility has been calculated to work at high temperatures, high-temperature heat pumps could play a key role. Those technologies are outside the scope of this paper.

The impact of heat pumps on the power grid is higher in the winter season, as the heating demand is higher. The problem seems more important in specific local areas than at the Member State level. According to the studies presented in Chapter 3, at macro-level of Member States, they are prepared for the deployment of heat pumps, while in specific regions, the local distribution grids are a bottleneck. For example, in Mediterranean areas it may not be as big problem as the heating demand is not that high and there are several buildings using air conditioning, while in colder climates with a large share of boilers (e.g. Germany) the impact on the power grid can be considerable.

5. Conclusions

The selection of clean energy carriers and improving the energy efficiency of buildings are crucial for advancing building decarbonisation. The electrification of heating, through heat pumps, will play a key role in the decarbonisation of the heating sector and reduce the use of fossil

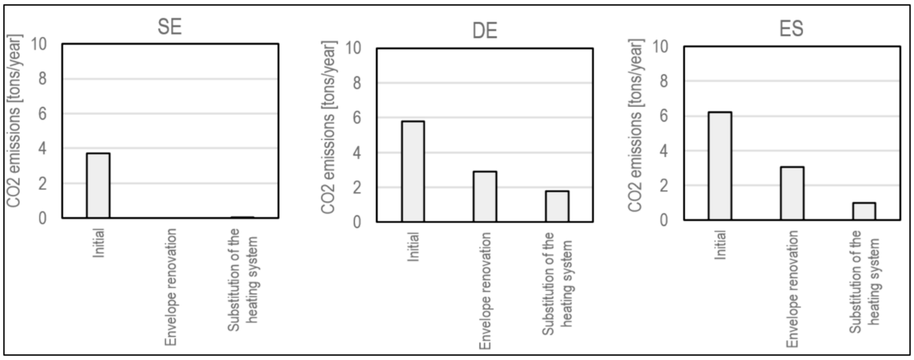

Fig. 14. Levels of heating demand reduction to maintain the same indoor units(Note that for the case of the house in Sweden the step "Envelope renovation" does not appear because it is not calculated as we do not recommend building renovations for this house, not because the CO2 emissions are 0.).

fuels in buildings. If electricity is supplied from renewable energy sources, using heat pumps could contribute to achieving a carbon–neutral building stock.

Air/water heat pumps are low-temperature heating systems compared to boilers. The upgrade of heating systems to those which work at lower water supply temperatures needs to be studied on a case-by-case basis, considering the possibility of either maintaining existing radiators or upgrading them. In some cases, it is important to adapt radiators to the new heating system to fulfil the heating demand. However, the current supply temperature and radiator size should be considered; these are oversized in many cases and could accommodate a lower supply temperature.

In economic terms, heat pumps are, in most cases, competitive, being able to save between 25–80 % of fuel costs. They can result in reduced yearly heating expenses and energy use, leading to considerable savings over their lifetime. For this reason, even if the upfront investment is high, the savings could lead to payback periods of less than 15 years. If the building envelope is renovated before installing the heat pump, the payback periods are longer due to the larger investments relative the savings obtained.

The reduction of energy demand is also essential to the decarbonisation of buildings. Renovating the building envelope could result in significant savings. Furthermore, it could help to deliver heat at lower temperatures using the current hydronic system. Where upgrading the hydronic system in buildings is challenging, improving the building envelope should be considered. In economic terms, the attractiveness depends on the geographic area where the building is located. The payback periods for upgrading building envelopes are often long, so incentives are needed to make them more attractive to the final user. Nevertheless, it improves energy efficiency by reducing the electricity consumption of the heat pump. This also decreases its impact on the power system, as the heating demand will be lower.

Combining both solutions: renovating the building envelope and upgrading the heating systems, can reach significant levels of reduction in CO_2 and should be taken into account before making specific decisions.

Disclaimer

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

CRediT authorship contribution statement

J.C. Roca Reina: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Writing – original draft, Writing – review & editing. **A. Toleikyte:** Writing – review & editing, Methodology, Investigation. **J. Volt:** Writing – review & editing, Writing – original draft, Conceptualization. **J. Carlsson:** Writing – review & editing, Supervision, Formal analysis.

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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Annex 4. Additional publication 2

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Article

Alternatives for Decarbonising High-Temperature Heating Facilities in Residential Buildings

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Abstract: The European Union aims to become carbon-neutral by 2050 and to reduce CO_2 emissions by at least 55% by 2030 compared to 1990 levels. The buildings sector accounts for about 40% of its total energy consumption and is responsible for 36% of the total CO_2 emissions. For this reason, decarbonising the heat consumed in buildings is key to meeting these targets. CO_2 emission reduction in buildings typically involves upgrading heating facilities to enable heat supply at lower temperatures, or renovating buildings, both of which can be challenging for end users. This paper analyses reducing emissions from residential buildings using high-temperature or hybrid heat pumps that can produce water at the same temperature as condensing boilers. This enables a significant reduction in emissions from buildings for owners who cannot afford or do not want to undertake a full renovation or upgrade of their current hydronic facility. The methodology followed makes use of a simplified hourly energy model based on ISO 52016-1:2017. The results indicate that, depending on the EU region, reducing CO_2 emissions in buildings through these types of systems is feasible, leading to CO_2 emission reductions of 40% to 70%.

Keywords: energy; buildings; decarbonisation; high-temperature heating; hybrid; heat pumps

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1. Introduction

Buildings account for 40% of the EU's energy consumption and are responsible for 36% of its greenhouse gas (GHG) emissions [1]. For this reason, CO_2 emission reduction in buildings will play a key role in meeting the European Green Deal targets, including carbon neutrality in 2050. An essential element of building decarbonisation lies in the energy carriers selected to provide the energy needed. In terms of heating, the majority of new space heating installations in residential buildings are still gas and oil boilers in the EU. In most Member States (MSs) of the EU, electric heat pumps would be a significantly cleaner heat source than gas or oil boilers in terms of CO_2 emissions. For this reason, electrifying the heating demand can be considered a pathway to decarbonising fuel-based heating systems in buildings.

Taking into account policy aspects, the European Commission launched the REPowerEU Plan [2] in 2022, which aims to make the EU independent of Russian fossil fuels before 2030. In addition, the Energy Performance of Buildings Directive [3] (EPBD) is designed to decarbonise the building stock through the use of efficient systems and renewable energies. Furthermore, the Renewable Energy Directive [4] (RED) incentivises the decarbonisation of the energy system, including the building stock. For instance, the RED targets a contribution of at least 42.5% of renewable energy by 2030. Lastly, the Energy Efficiency Directive [5] (EED) aims to reduce the EU's energy consumption and increase energy efficiency levels.

Using more efficient systems which incorporate renewable energy could be an ideal solution to reach all the targets. According to [6], energy taken from heat sources by heat pumps can be considered renewable under certain conditions. These systems can extract more heat from their heat source than electricity consumed, so they can be considered energy-efficient systems using renewable energy sources such as ambient energy. However, installing heat pumps in existing buildings with fossil-based heating facilities already installed is not always straightforward for different reasons, such as the level of temperature they provide for heating.

Gas boilers produce heat at much higher temperatures than heat pumps. For example, non-condensing boilers work with water supply temperatures of 80–70 °C. In condensing boilers, this temperature could be around 65 °C. Conventional heat pumps produce water at 45 °C or 50 °C on average. The heat is delivered at lower temperatures with heat pumps, which can be a challenge for existing buildings with poor thermal insulation. In existing buildings, hydronic facilities are sized to work at the temperatures of the installed high-temperature heating system, for example a gas or oil boiler. The pipe diameters are chosen according to the transportation of water at good levels of speed, and radiators are sized to exchange sufficient amounts of heat from the heat generator (80–65 °C) to the room (19–21 °C). If the water supply temperature is lower, then more water flow and a larger radiator surface are needed to exchange the same amount of heat. This means that if a heat pump replaces a fossil fuel-based boiler, the hydronic installation would not work properly unless it was originally oversized. Several studies suggest that some hydronic facilities are oversized due to a lack of information or the use of conservative calculation margins [7–9]. Furthermore, indoor units connected to a hydronic facility like embedder pipes can facilitate the integration of heat pumps in buildings. The review performed by [10] shows a comprehensive overview of heating and cooling systems that make use of this type of indoor units.

Building renovations can facilitate the installation of conventional heat pumps. They reduce the heating demand of the building, allowing the hydronic facility to work at lower temperatures than the design temperatures if the heating demand decreases sufficiently [11,12]. Furthermore, they allow for better indoor conditions and increase the final user's quality of life. This type of energy efficiency measure is not taken into account in this study, as we only apply energy efficiency measures focused on heating systems.

In our previous study [11], we analysed how to decarbonise buildings using regular air/water heat pumps and what should be taken into account when lowering the water supply temperature in heating systems. But what are the options if there is no oversized heating facility and the building cannot be renovated?

This paper aims to answer these questions. We introduce heat pump systems that work at the same temperature level as condensing boilers. Hence, there are no requirements for upgrading the hydronic facility or renovating the building. These systems are high-temperature heat pumps and hybrid heat pumps.

High-temperature heat pumps use the same technology as conventional heat pumps but can deliver water at higher temperatures, albeit with lower efficiency. In a previous study [13], the authors concluded that these systems can reduce CO_2 emissions by 30–90% in multifamily buildings in five different ASHRAE (American Society of Heating, Refrigerating and A-C Engineers) climate zones. The high temperatures can be achieved by using, for example, two refrigerant loops that work at different pressure levels. A low-pressure circuit delivers heat to the high-pressure one, achieving a higher final condensing temperature in the system. This can be achieved by using, for example, a loop with R410a (low pressure) and another with R134a (high pressure).

Hybrid heat pumps work at the same temperature level as regular air/water heat pumps, but when the hydronic facility demand exceeds a certain water temperature, the back-up system boosts the heat pump so it can meet it. This back-up system could be, for example, a condensing boiler. According to some studies, these types of systems can reduce CO_2 emissions by, on average, 74% relative to conventional oil-fired boilers [14].

2. Methodology

This section outlines how we evaluated the buildings included in the study. It provides an overview of how we calculated the energy balance of the buildings and estimated the CO_2 and cost impact of every fossil-free solution.

First, we present the databases used for weather and building geometries. Then, we introduce our calculation and how we model the buildings and obtain a heating demand. Then, we calculate the energy use of the buildings taking into account the different heating systems proposed. Once we know the energy use of the buildings, we can estimate the CO_2 emissions and running costs of every heating solution proposed. Figure 1 summarises this methodology.

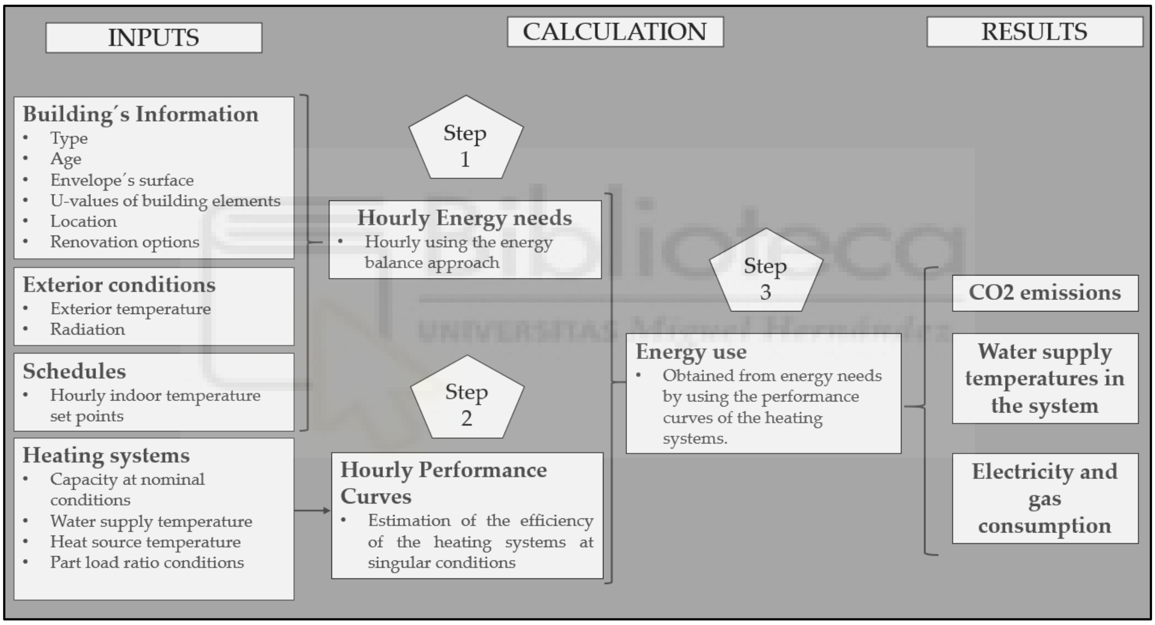

Figure 1. Methodology followed in the calculation.

2.1. Buildings and Climate

We selected different building typologies from EU Member States. The building typologies come from the TABULA WebTool [15], which contains typical residential buildings' typologies across the EU.

Once the buildings were selected, the climate conditions were obtained from the PVGIS database [16]. The climate conditions represent a typical meteorological year (tmy). It is a fictitious year that represents the most common climate conditions of one specific location.

It was assumed that all the buildings selected initially used a condensing boiler as a heating system. We then compared the CO_2 emissions, costs, or energy use if a high-temperature or hybrid heat pump were installed.

The buildings selected for the study are single-family houses (SFHs) built in the 1970s. They are located in Germany, the Netherlands, Sweden, Spain, and Poland. As described in the previous chapter, we are not considering renovations of the selected buildings. Table 1 shows the building geometry characteristics. As we can see in the data collected, all the houses have between 100 and 170 m^2 of heating floor area. On the other hand, depending on the MS, the U-values of the building envelope vary quite significantly.

Table 1. General characteristics of the buildings.

	Germany		Netherlands		Spain		Sweden		Poland	
	Conditioned area		Conditioned area		Conditioned area		Conditioned area		Conditioned area	
	m^2		m^2		m^2		m^2		m^2	
	173		135		170		106		131	
	Heating demand		Heating demand		Heating demand		Heating demand		Heating demand	
	$kWh/m^2 \cdot year$		$kWh/m^2 \cdot year$		$kWh/m^2 \cdot year$		$kWh/m^2 \cdot year$		$kWh/m^2 \cdot year$	
	157		135		170		164		180	
	Surf m^2	U $W/m^2 \cdot K$	Surf m^2	U $W/m^2 \cdot K$	Surf m^2	U $W/m^2 \cdot K$	Surf m^2	U $W/m^2 \cdot K$	Surf m^2	U $W/m^2 \cdot K$
Walls	178	1	105	2.32	312	1.33	200	0.31	105	1.03
Roof	183	0.5	79	1.16	63	4.17	125	0.21	77	0.5
Floor	152	0.86	60	5.88	90	0.85	125	0.32	70	1.6
Windows	34	2.8	32	2.9	12.6	4.59	22	2.3	23	2.6
Heated floor area	173	-	135		170	-	106	-	131	-
Roof 1	Flat roof with 6 cm insulation		Pitched roof		Ventilated pitched roof, wooden frame, and suspended ceiling		Horizontal wind		Pitched roof insulated on ceilings	
Roof 2	-		Flat roof		-		-		-	
Wall 1	Masonry		Only U-value provided		cavity wall: brick, air cavity		Only U-value provided		Hollow blocks	
Wall 2	-		-		-		-		-	
Floor 1	Concrete ceiling with 2 cm insulation		Only U-value provided		Flooring on the ground		Concrete slab		Solid ground floor	
Floor 2	Concrete ceiling with 2 cm insulation		-		-		-		-	
Windows	Wooden window with dual-pane glazing		Single glass		Metal frame, single glazed, no thermal break		Only U-value provided		Wood frame, double glazed, air-filled (7.5 mm gap)	

2.2. Heating Demand Estimation

We analysed the heating demand of the buildings selected by calculating energy balances, taking into account losses and gains. The model used to develop the energy balances of the buildings is a simplified hourly energy model based on ISO 52016-1:2017 [17], which provides the heating demand with an hourly resolution. The losses considered were conduction through the building envelope, ventilation, and radiation. Conduction losses are the ones that appear when the interior of the building is at a different temperature than the exterior, losing heat through the building envelope. Ventilation takes into account the ventilation rate of the building. The new air entering the building needs to be heated to the indoor level. Finally, radiation losses consider the losses that the building envelope has due to the effect of being at a different temperature than the sky.

$$\phi_{losses} = \phi_{cond} + \phi_{vent} + \phi_{rad} \tag{1}$$

$$\phi_{losses} = \left[\left(\sum A_i \cdot U_i \cdot b_i\right) \cdot (T_b - T_{ext})\right] + \left[n_{air} \cdot V \cdot C_p \cdot (T_b - T_{ext})\right] + F_{sky} \cdot h_{re} \cdot \Delta T_{sky} \tag{2}$$

where ϕ_{losses} are the total losses of the building in kWh; ϕ_{cond}, ϕ_{vent}, and ϕ_{rad} are conduction, ventilation, and radiation losses in kWh. A_i is the area of the building envelope element i in m^2, U_i is the U-value of the building envelope element i in $W/m^2 \cdot K$, and b_i is the factor soil of the building envelope element i, without units. T_b and T_{ext} are the interior temperature of the building and the exterior temperature, respectively, both in °C. n_{air} is the renovation rate of air in the building in 1/h. V and C_p are the volume of air conditioned and the air-specific heat coefficient in m^3 and W/m^3·K, respectively. F_{sky} is the sky factor; the value is 1 for the horizontal envelope and 0.5 for the vertical envelope. h_{re} is the radiative heat transfer coefficient in W/K and ΔT_{sky} is the difference in temperature between the building envelope and the sky. As suggested by ISO 52016-2017, 11 K is used.

In the energy balance, as mentioned before, we also include the heat gains of the building. We consider as gains the solar gains through the building envelope (transparent and opaque elements) and the interior gains, which come from occupation, lighting, and building appliances. Equations (3)–(5) represent these heat gains:

$$\phi_{gains} = \phi_{solar} + \phi_{int} \tag{3}$$

$$\phi_{solar} = F_{sh} \cdot (1 - F_F) \cdot F_W \cdot g_{gl,n} \cdot \left(\sum A_{w,j} \cdot I_j\right) + F_{ob} \cdot \alpha_{op} \cdot R_{se} \cdot \left(\sum U_{i,j} \cdot A_{i,j} \cdot I_j\right) \tag{4}$$

$$\phi_{int} = \varphi_{int} \cdot A_c \tag{5}$$

where ϕ_{gains} is the total gains, ϕ_{solar} is the solar gains (opaque and transparent elements), and ϕ_{int} is the interior gains in the building, all of them in kWh. F_{sh} is the factor of external shading, F_F is the fraction of the frame in the window, F_W is a reduction factor which takes into account the effect of perpendicular radiation on the glazing, and $g_{gl,n}$ is the total solar energy transmittance, or the more commonly named “solar factor”, of the glass. All these factors are unitless. $A_{w,j}$ is the area of windows with orientation j in m^2. F_{ob} is the form factor between the buildings and the sky, and α_{op} is the absorption coefficient of the opaque envelope, which assumed to equal 0.6 as it represents the average colours of buildings. R_{se} is the external thermal surface resistance, which assumed to be 0.04 m^2·K/W according to ISO 6946 [18]. U_i is the is the U-value of the building envelope element i in W/m^2·K with orientation j. $A_{i,j}$ is the area of the opaque element i with orientation j in m^2. I_j is the average global irradiation on surfaces with orientation j in W/m^2. φ_{int} represents the internal heat gain due to occupation and internal appliances in W/m^2. Finally, A_c is the heated floor area of the building.

Finally, the building inertia is taken into account in the calculation. The building inertia represents how much energy is needed to increase or decrease the temperature of the building. Equation (6) represents how it is considered in the model.

$$Q_{heating} = \phi_{losses} - \phi_{gains} + C_b \cdot \frac{dT_b}{dt} \tag{6}$$

where $Q_{heating}$ is the energy to be provided by the heating system to maintain the interior conditions selected. In the calculation, we consider that the building should be at 20 °C during all the heating season. C_b is the effective heating capacity of the building in kWh/K, which means how much energy is needed to increase the temperature of the building in 1 °C. The value per m^2 selected is the one used in the TABULA database, which is 45 Wh/(m^2·K). This value is multiplied by the conditioned area of the building (A_c) to obtain the effective heating capacity of the building.

Applying Equations (1)–(6) allows us to estimate the hourly heating demand needed in that specific hour to maintain the indoor conditions (Tb). We make this calculation in all the hours of the heating season. The yearly heating demand is calculated by summing all the hourly results and applying an utilization factor of the heating facility based on TABULA methodology [15]. We apply this factor because the results obtained by applying the methodology explained above are considered theoretical. The final use of the heating facility depends on the final user behavior, which can differ from the theoretical assumption considered.

The theoretical heating demand is adapted using an utilization factor U_f [-], which is obtained based on the energy use of the building. This factor is calculated according to Equation (7):

$$U_f = 1.07262 - 0.0013 \cdot \phi_{use} \tag{7}$$

where ϕ_{use} is the yearly energy used in the building in kWh/m^2. Figure 2 shows the order of magnitude of the U_f. Finally, the real heating demand is calculated by multiplying this factor by the theoretical heating demand calculated in Equation (6). Equation (8) shows this approach:

$$Q_{heating,\ real} = U_f \cdot Q_{heating} \tag{8}$$

where $Q_{heating}$ is the yearly heating demand calculated in Equation (6).

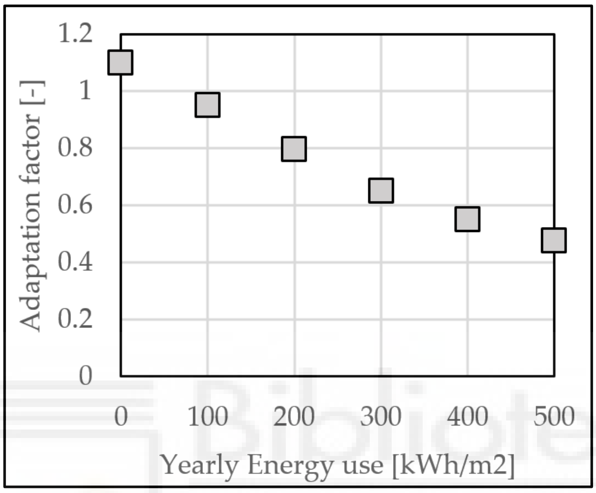

Figure 2. Utilisation factor obtained from TABULA methodology [15].

2.3. Definition of the Heating Systems

The heating systems considered in this paper are modelled using their performance curves, which could depend on one or two variables. When the equation includes one variable, we consider the performance curve a polynomial. If it includes two variables, the curves are considered biquadratic.

The heat pump efficiency, in this case for air/water heat pumps, was modelled with two different equations that represent their efficiency: Capacity and Coefficient of Performance (COP) as functions of the exterior air temperature and water supply temperature (Equations (9) and (10)). The efficiency of the boiler depends on the water supply temperature and the part load ratio (PLR) conditions (part load conditions refer to conditions in which the heating system is providing less heat than its nominal capacity). Assuming a constant water supply temperature from the boiler, its efficiency would only depend on its PLR conditions (Equation (11)). PLR is a coefficient calculated by dividing the heat provided by the maximum heat the boiler can provide in those conditions.

$$\text{CAPfText} = a + b \cdot T_{water} + c \cdot {T_{water}}^2 + d \cdot T_{air} + e \cdot {T_{air}}^2 + f \cdot T_{water} \cdot T_{air} \tag{9}$$

$$\text{COPfText} = a + b \cdot T_{water} + c \cdot {T_{water}}^2 + d \cdot T_{air} + e \cdot {T_{air}}^2 + f \cdot T_{water} \cdot T_{air} \tag{10}$$

$$\text{EfffPLR} = a + b \cdot PLR + c \cdot PLR^2 \tag{11}$$

where a, b, c, d, e and f are coefficients obtained from applying linear regression to manufacturers' data. T_{water} represents the water supply temperature and T_{air} the exterior air temperature in °C.

We calculate the maximum capacity of the heat pump in each condition taking into account Equation (9). The result of Equation (9) is a coefficient of around 1, and it multiplies the nominal capacity of the air/water heat pump. The nominal capacity of an air/water heat pump is obtained when the heat pump supplies water at 35 °C and the heat source, which is air in this case, is at 7 °C [19]. Since the actual working conditions can vary significantly, calculating the real capacity for more accuracy is advisable.

For both types of technologies, it is assumed that if the heating demand is lower than 10–15% of the nominal capacity, the heating system cannot deliver heat at that moment as there is a limit on the minimum heating demand it can provide.

Figure 3 shows the performance curves of the heating systems studied. This figure enables the comparison of the efficiencies of the different heat pumps considered for the study. It shows how the efficiency can vary from less than 2.5 to more than 3 in most exterior conditions. It can be noted that, at the same temperature level, a standard heat pump can have higher COPs in warmer conditions than a high-temperature heat pump. This is due to the configurations of the internal elements of the heat pump such as the compressor types used, the refrigerant, and how many refrigerant loops are included. At lower temperatures, this COP is better for high-temperature heat pumps. This is partly because they are designed to work when the temperatures of the heat sources and the temperature of the water supply have a greater difference.

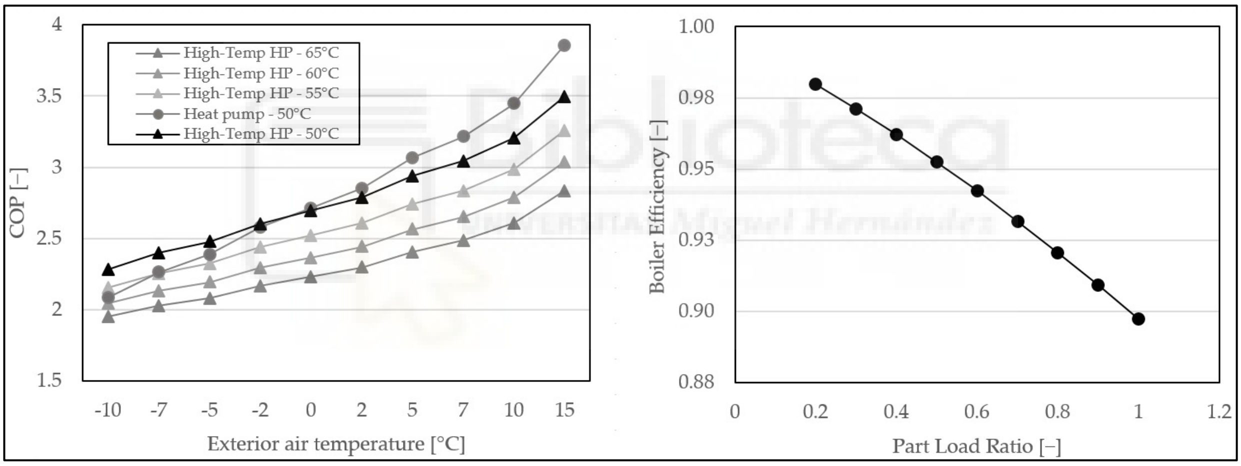

Figure 3. Performance curves used in the model.

When we model a hybrid heat pump, we must consider the performance curves and the control strategies. We modelled the hybrid heat pump based on three states: state 1 is when the heat pump cannot work, and only the boiler can provide the heating demand. This state occurs when the exterior temperature is lower than the minimum exterior temperature at which the heat pump can work. If we want the heat pump to work as much as possible without using gas, this temperature should be around the minimum temperature at which the heat pump (T_{off}) can operate, which usually could be −10 °C or −20 °C. In this study, we assume that only the boiler works if the exterior temperature is below −10 °C, only the boiler will work; the working system state is 1. In state 2, the heat pump and the gas boiler work together. In this state, the exterior temperature is higher than T_{off} but the radiators need a higher temperature than the heat pump can deliver. The maximum water temperature that we consider the heat pump to be able to deliver is 50 °C, so if the radiators demand 60 °C, the boiler should complement the heat pump; the working state is 2. In state 3, the heat pump provides all heating, and the boiler is not working. In state 3, the exterior temperature is above −10 °C and the required radiator temperature is below 50 °C. Figure 4 summarises this control.

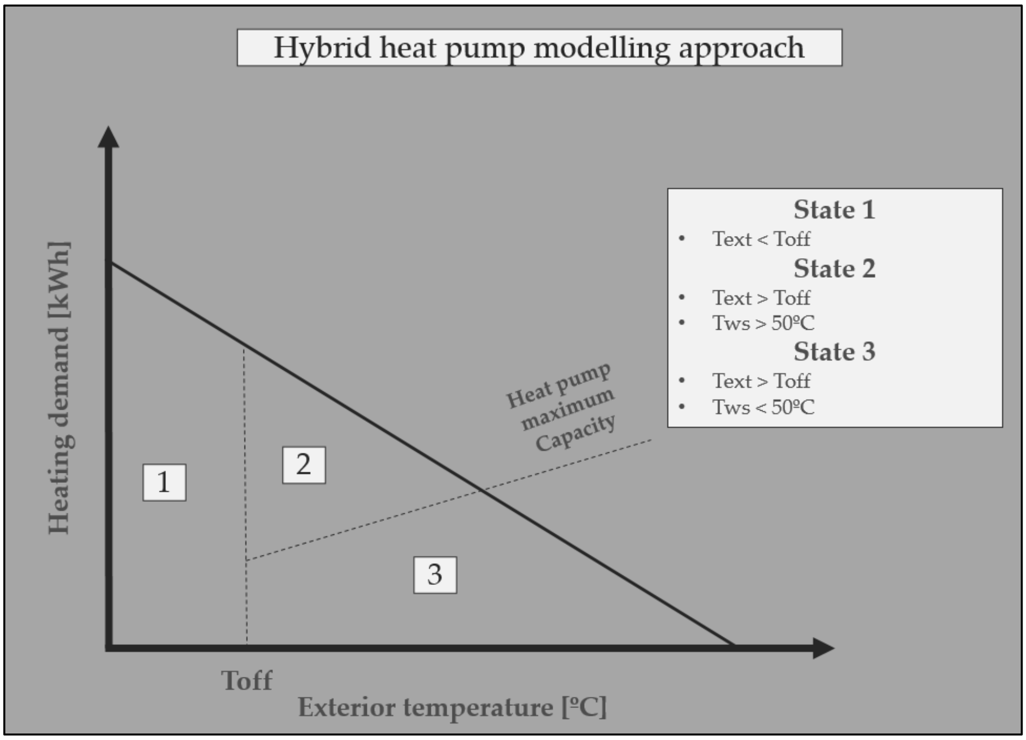

Figure 4. Modelling of a hybrid heat pump.

2.4. Hydronic Facility

We assume that the current hydronic facility was designed to provide the maximum heating demand at the temperature level of a condensing boiler. The working temperatures of the boiler are 65–55 °C, so the hydronic facility has a ΔT_{nom} of 10 °C in the coldest winter conditions, and it supplies the water to the radiators at 65 °C.

We assume that the boiler works with a constant water flow and always produces the water at 65 °C. This means the facility will work with a lower ΔT when the heating demand is lower than the maximum heating demand expected. In order to work out the new ΔT, we use Equation (12), assuming a constant mass flow and equations from EN 442 standard [20].

$$\dot{Q} = \dot{m} \cdot C_p \cdot \Delta T \tag{12}$$

$$\dot{Q} = K_m \cdot (T_{rad} - T_{room})^n \tag{13}$$

$$T_{rad} = \frac{T_{sup} + T_{ret}}{2} \tag{14}$$

where $\dot{Q}$ is the heat delivered in kWh, $\dot{m}$ is the water flow in kg/s, K_m and n are unitless factors that depend on the radiator, T_{sup} is the water supply temperature in °C, T_{ret} is the return water temperature in °C, and T_{rad} is the average temperature of the radiator. Assuming that the water flow is constant and the properties of the radiators do not change $(\dot{m} = cte,\ K_m = cte\ \&\ n = cte)$, we realise that the ΔT and the T_{sup} depend on the heating demand. Equations (15) and (16) show how to calculate the ΔT and the water supply temperature in different conditions than the nominal conditions:

$$\Delta T = \frac{\dot{Q}}{\dot{Q}_{nom}} \cdot \Delta T_{nom} \tag{15}$$

$$T_{sup} = \frac{\Delta T}{2} + T_{room} + \frac{T_{sup,nom} - \frac{\Delta T_{nom}}{2} - T_{room}}{\sqrt[n]{\frac{\dot{Q}_{nom}}{\dot{Q}}}} \tag{16}$$

This enables an estimation of the heat supplied by a heat pump if installed in a hydronic facility meant to work at higher temperatures. A regular air/water heat pump, as mentioned above, can deliver water at 45 °C or 50 °C at a wide range of exterior temperatures. In this study, the capacity of the heat pump is calculated using the exterior conditions that allow delivering heat at 50 °C in a hydronic facility designed to work at 65 °C. First, we assume the ΔT that allows it to operate at 50 °C, which will be lower than the nominal. With this ΔT, we can estimate the capacity ($\dot{Q}$) of the hydronic facility (Equation (12)). Knowing the new ΔT and $\dot{Q}$, we go to Equation (16) and verify the supply temperature that allows exchanging the same amount of heat. If we want to supply the heating demand at 50 °C with the same hydronic facility, the capacity will be 60% of the nominal capacity at 65 °C with ΔT of 10 °C. For instance, if the hydronic facility has been calculated to provide 20 kW, supplying the water at 65 °C with a ΔT of 10 °C, and we want to install a heat pump, which can only supply heat up to 50 °C, the capacity of the heat pump would be 12 kW. For heating demands higher than 12 kW, a water supply temperature higher than 50 °C is required; a boiler must supply the difference.

3. Results

In this section, we present the results of applying the methodology described above. First, we show an overview of the heating demand of all the houses selected and then the CO_2 emission results of applying different heating systems. This provides an understanding of the heating supply required by the buildings. Then, we show the results of energy use in the buildings selected by applying the heating systems explained above. Finally, we compare the CO_2 emissions obtained with the proposed systems and the impact on the annual running costs.

3.1. Heating Demand Results

The heating demand of the different houses was obtained by applying the energy balance described in Section 2. The houses selected have similar characteristics concerning the annual heating demand: they are higher than 150 kWh/m^2. We assume the hydronic facility is not oversized if the heating demand exceeds that value. As the heating systems proposed in this study work at the same level of temperatures as a condensing boiler, the hydronic facility is not considered an obstacle to the decarbonisation of the buildings selected. Figure 5 shows the heating demand for the different houses.

The results in Figure 5 show that the heating demand in the selected buildings is between 160 and more than 200 kWh/m^2 a year. The heating demand depends not only on the exterior conditions but also on the level of insulation of the building. The buildings from Spain and Sweden have similar heating demands even though the Swedish climate is much colder. On the other hand, the building from Sweden has a higher-quality envelope characteristic than the rest of the buildings.

The current heating system installed in the five houses is a condensing gas boiler with a capacity of 20 kW. The new heating systems were calculated using a percentile of 1% of exterior temperatures, meaning that the possibility of facing lower temperatures is 1%. Once the capacity in these conditions is calculated, it is corrected to nominal conditions by using Equation (9). This step is carried out because an air/water heat pump of 10 kW cannot provide 10 kW at, for example, −5 °C. The nominal capacity of 10 kW can be provided at an air temperature of 7 °C and at a supply water temperature of 35 °C, not in other conditions. Table 2 shows the results of the capacities of the heating systems selected.

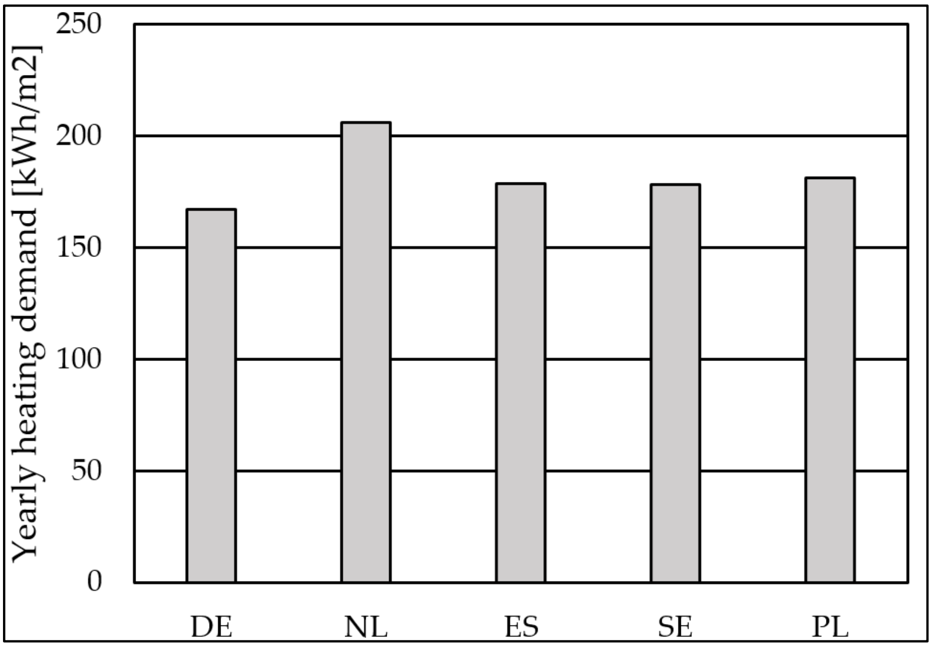

Figure 5. Heating demand of the different buildings.

Table 2. Capacities of the heating systems proposed.

	High-Temperature Heat Pump	**Hybrid Heat Pump** [1]
	kW	**kW**
DE	15	10
NL	12	8
ES	19	12
SE	10	7
PL	19	11

[1] Note that this capacity is boosted by a condensing boiler of 20 kW.

3.2. Energy Use Results

The energy used to supply the heating demand varies depending on the heating system selected. We performed the calculations for the five different buildings, applying a hybrid heat pump and a high-temperature heat pump to substitute the current gas condensing boiler of the houses. In this way, we can compare the initial gas consumption with the electricity consumption of the high-temperature heat pump, or with the gas and electricity consumption of the hybrid heat pump. Results are shown in Figure 6.

Applying the methodology of the hybrid heat pump explained in Section 2, we conclude that for the five houses, around 30% of the heating demand is supplied by the back-up system; see Figure 7.

We observe a higher contribution of the condensing boiler in the Netherlands and in Sweden. The condensing boiler only works if the exterior temperature is lower than −10 °C or if the hydronic facility needs more than 50 °C. The building envelope for the building located in the Netherlands has very low quality compared with the other buildings, and often, the hydronic facility connected to the radiators needs more than 50 °C. In Sweden, the exterior temperatures can be very low in winter, so the heat pump will be switched off for security reasons. Spain has the lowest boiler contribution, as the building has average U-values compared with the other buildings, and the climate is mild, which gives more opportunities to operate the heat pump.

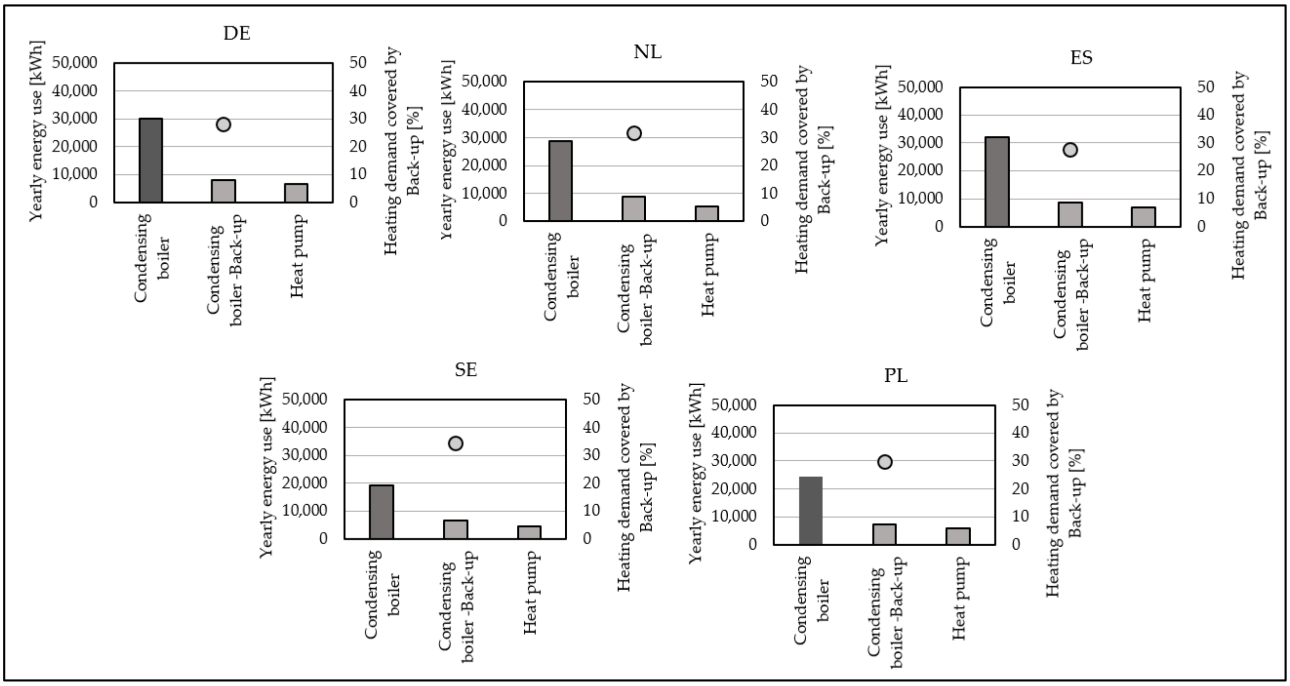

Figure 6. Final energy consumption of hybrid heat pumps in the buildings selected.

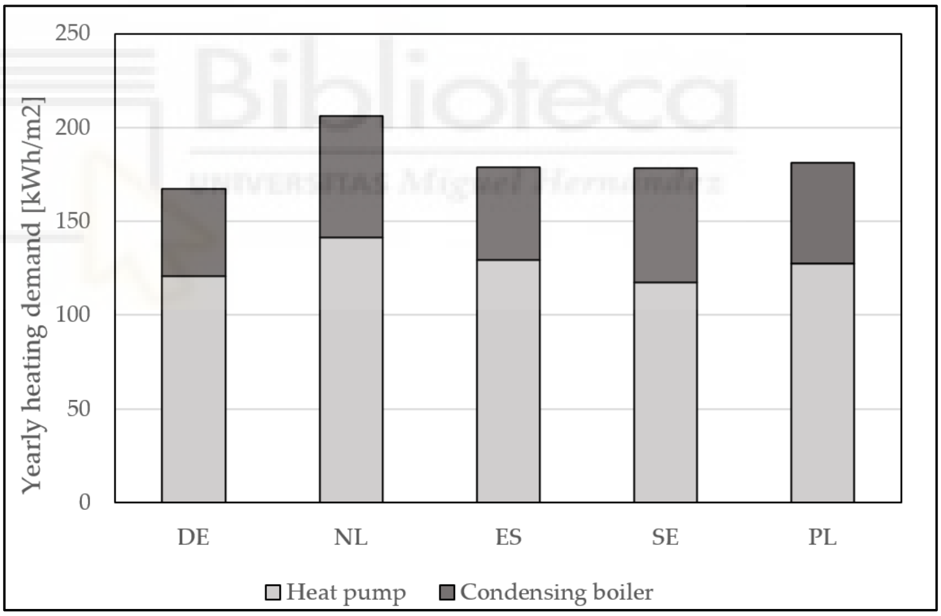

Figure 7. Heat pump and back-up contribution to the yearly heating demand.

Regarding use of the high-temperature heat pump, we only compare the electricity consumption of the heat pump with the gas consumption of the boiler. We see that in all the scenarios, the final energy consumption (FEC) is reduced by more than 60%. In terms of efficiency, this is positive, as we need much less energy to supply the same amount of heating. Figure 8 shows the results of FEC when a high-temperature heat pump is the heat generator.

However, even if we consume much less gas or if we consume electricity instead, the FEC reduction does not show how much we have decarbonised the building. We have to measure the decarbonisation of a building with the CO_2 emissions of the heating systems proposed. Once the FEC of the heating systems is known, we apply conversion factors of CO_2 to estimate how much CO_2 is emitted to cover the heating demand of the building. For gas, we assume 202 g/kWh. The factor for electricity varies per Member State. Table 3 shows the factors used.

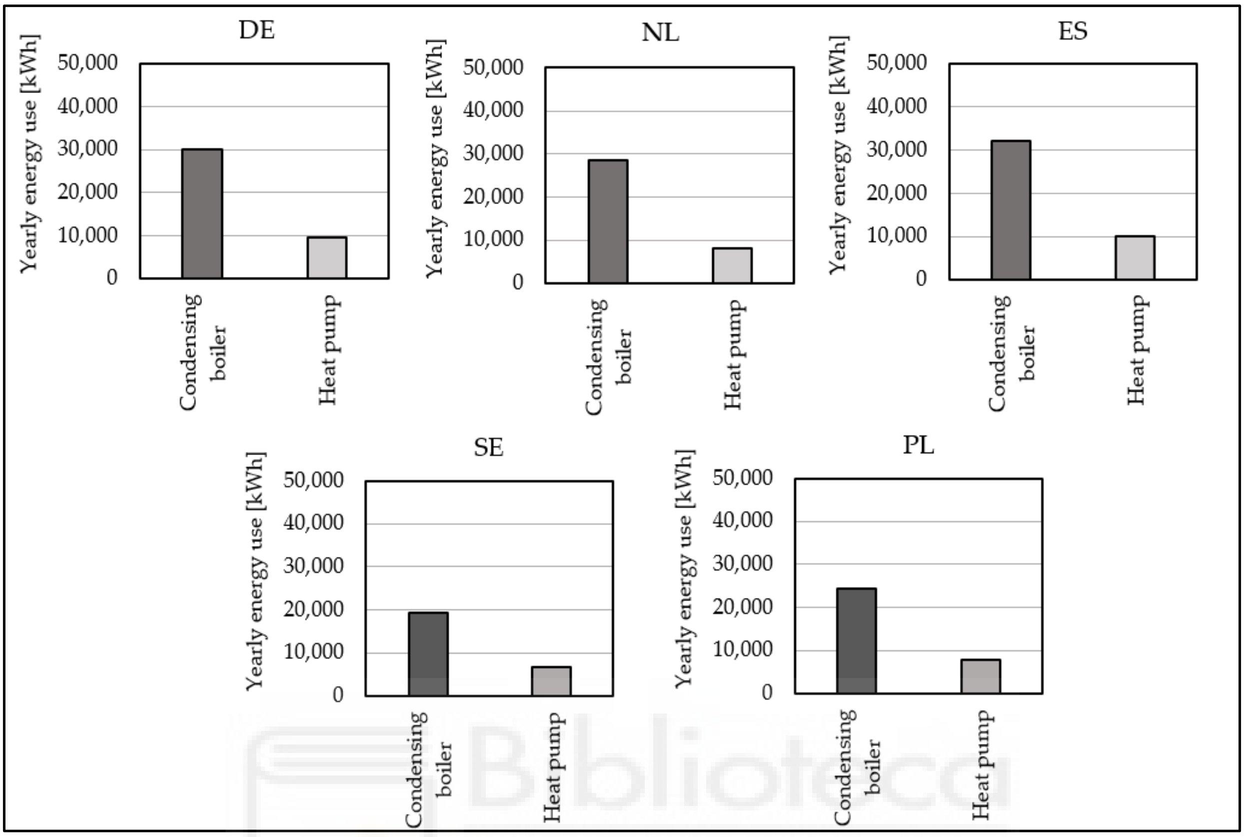

Figure 8. Final energy consumption of high-temperature heat pumps in the buildings selected.

Table 3. CO_2 emission factors for electricity [21].

	Sweden	Germany	Spain	Netherlands	Poland
gCO_2/kWh	8	314	177	333	710

Table 3 shows the CO_2 emissions produced on average for generating 1 kWh of electricity in each Member State. For example, Sweden has a high contribution of renewables and nuclear energy for electricity production, which means that the electricity grid is almost CO_2-free, as these technologies do not emit CO_2 to produce electricity. Poland, on the other hand, uses 70% solid fossil fuels to produce electricity.

3.3. CO_2 Emission Results

The decarbonisation of the buildings selected was carried out using different approaches depending on the building. As seen in Figure 9, the electrification of and reduction in gas consumption lead to lower CO_2 emissions in almost all the buildings.

For instance, Germany and the Netherlands have very close CO_2 emissions results when comparing hybrid and high-temperature heat pumps, which represent around 40% and 60% CO_2 emission reductions, respectively. The difference is more pronounced in Spain (50% reduction with a hybrid heat pump and 70% with a high-temperature heat pump) and much more so in Sweden, where the electrification of the heating generation produces a solution that is close to carbon-neutrality. In Poland, the electrification of heating with a hybrid heat pump results in increased CO_2 emissions due to its large share of electricity produced from coal.

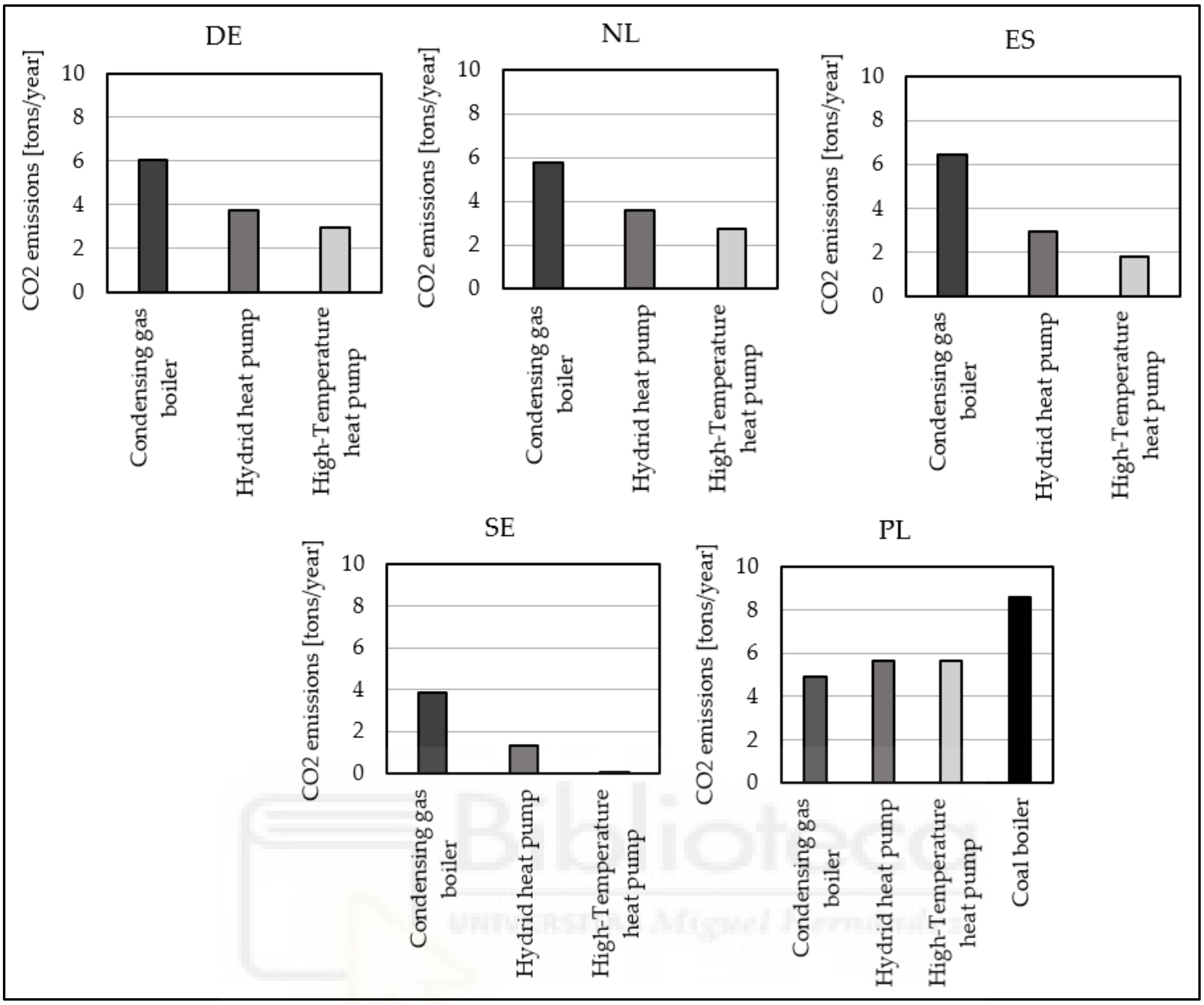

Figure 9. CO_2 emission results.

The decarbonisation results strongly depend on how much the electricity generation is decarbonised. For this reason, in Member States like Spain or Sweden with low CO_2 emission factors, if we electrify 100% of the heat using a high-temperature heat pump, the CO_2 emissions are lower than if we use a hybrid heat pump. Moreover, when the CO_2 emissions are at intermediate levels, as in Germany and the Netherlands, high-temperature heat pumps and hybrid heat pumps have similar amounts of CO_2 emissions (with the former being slightly lower). As mentioned above, Poland has a high CO_2 emission factor, which negatively impacts the electrification of the heating demand in buildings. For this specific case of Poland, we added a comparison with a coal boiler, due to the large share of this type of heating technology in Polish residential buildings [22]. The CO_2 emission factor assumed for coal is 354 g/kWh. We considered the same performance curve for the boiler but changed the energy carrier. So, the energy use is the same, but now, the energy carrier of the boiler is coal and not natural gas for this specific case. We can see in Figure 9 that even if the electrification of heating through heat pumps in Poland is not a decarbonisation option, it is still better than providing heating with coal boilers.

In terms of costs, the approach is different. In Table 4, we show the price of the energy carriers taken into account in the analysis. The prices come from VaasaETT [23], which provides monthly energy price information from the capital cities of EU Member States. The prices are the average from January 2022 to August 2023.

Table 4. Electricity and gas prices.

	Elec. Price	Gas. Price
	EUR/kWh	EUR/kWh
DE	0.4	0.13
NL	0.3	0.2
ES	0.3	0.12
SE	0.24	0.24
PL	0.2	0.05

We applied these prices to the energy use of the different heating solutions (reference and two alternative systems). Figure 10 shows the energy consumption costs of the current condensing gas boiler installed and the two high-temperature heating systems proposed. The approach has a different tendency depending on the Member State analysed.

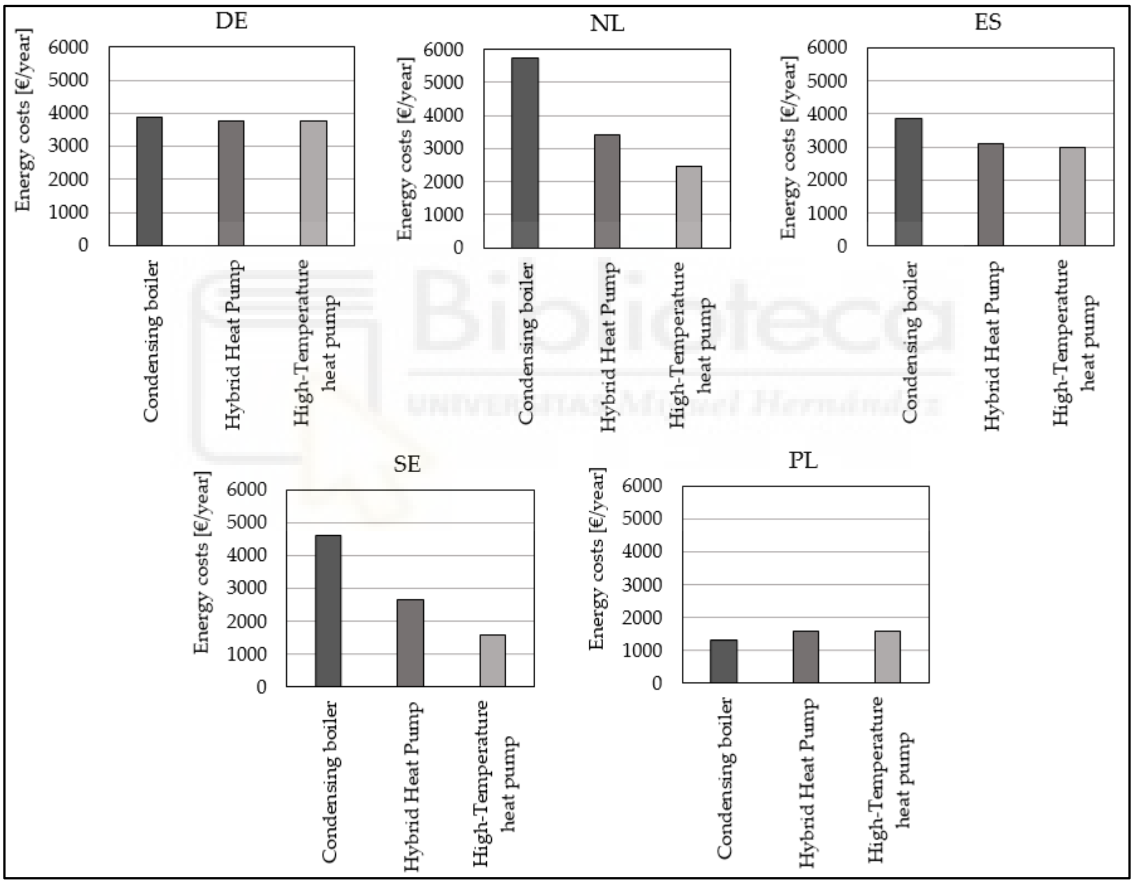

Figure 10. Energy costs of the different technologies proposed.

In Member States like Germany and Spain, even though the electricity consumption from the heat pump is much lower than the gas consumed by the gas boiler, the yearly energy costs are quite similar. This is because the difference in price between gas and electricity, with gas price being the lowest, is higher than the improvement in the efficiency of the system by using a heat pump. In countries like the Netherlands and Sweden, the situation is very different, as the consumption of electricity by a heat pump, hybrid or high-temperature, leads to cost savings of around 60–75% at the end of the year. However, in the case of Poland, the electrification of heating offers no economic benefit based on data used in this study and in the current context, as the yearly energy costs will increase.

4. Discussion

The results show that decarbonising the current building stock is possible through high-temperature heating systems like hybrid or high-temperature heat pumps.

The level of decarbonisation depends on how clean the electricity generation in each Member State is. Electricity has a higher CO_2 emission factor than gas in most Member States, but when we electrify the heating using heat pumps, we consume much less electricity than gas. This overcomes the effect of higher CO_2 emission factors with electricity. Despite that, as observed in Section 3 in the case of Poland, the electrification of the heat increases CO_2 emissions in countries with large shares of coal in power production. Hence, a threshold level can guide us in determining if it is possible to decarbonise buildings using high-temperature heat pumps.

According to the results, changing from a condensing gas boiler to a high-temperature heat pump reduces the FEC by around 2/3 in all the cases studied. As all these cases are from different climate regions in the EU, this approach can be extrapolated to all Member States. Figure 11 shows the relation between the electricity consumption of a high-temperature heat pump and the fuel consumption of a condensing boiler when they supply the same heating demand per country.

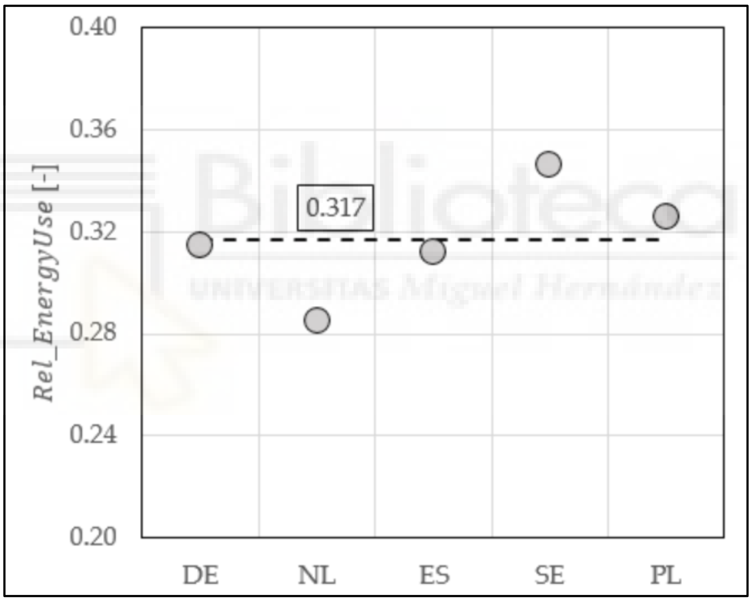

Figure 11. Energy use relationship—high-temperature heat pump and gas boiler.

The average reduction in FEC in the buildings selected is 0.317. Considering this and knowing that the CO_2 emission factor of gas for all the Member States is 202 gr/kWh, we can estimate when electricity is cleaner than gas in terms of CO_2 emissions. Equation (17) shows how to obtain it:

$$\mathrm{CO_2}factor_{gas} = Rel_{EnergyUse} \cdot \mathrm{CO_2}factor_{elec} \tag{17}$$

where $\mathrm{CO_2}factor_{gas}$ is the CO_2 emission factor of gas (202 gr/kWh), and $Rel_{EnergyUse}$ is the relation between the FEC of a high-temperature heat pump and a condensing gas boiler (0.317). The $\mathrm{CO_2}factor_{elec}$ represents the CO_2 emission factor that makes high-temperature heat pumps and condensing gas boilers have the same CO_2 emissions.

In addition, this relationship in energy use should only be applied when taking into account a heat pump and a boiler that operate at the same level of efficiency as the ones in Figure 3. This relationship in the FEC could vary for different efficiencies, as we are not comparing systems with the same efficiencies. Nevertheless, the order of magnitude should not change.

Solving Equation (17), we obtain the CO_2 emission factor at which high-temperature heat pumps emit more CO_2 than condensing boilers, which is 637.57 gr CO_2/kWh. Taking into account the CO_2 emission factors of all the Member States provided by [21], we can identify the Member States where a full electrification of the heating system is inadvisable in terms of CO_2 gas emissions.

According to Figure 12, the full electrification of heating through high-temperature heat pumps reduces CO_2 emissions in all Member States, with the exception of Poland. Estonia and Cyprus are borderline, and for Poland, using high-temperature heat pumps increases emissions until such time as power production is cleaner. Decarbonising buildings through electrification with high-temperature heat pumps would be more effective in Member States such as Austria, Finland, France, and Luxembourg, as their electricity grids have the lowest CO_2 emission factors.

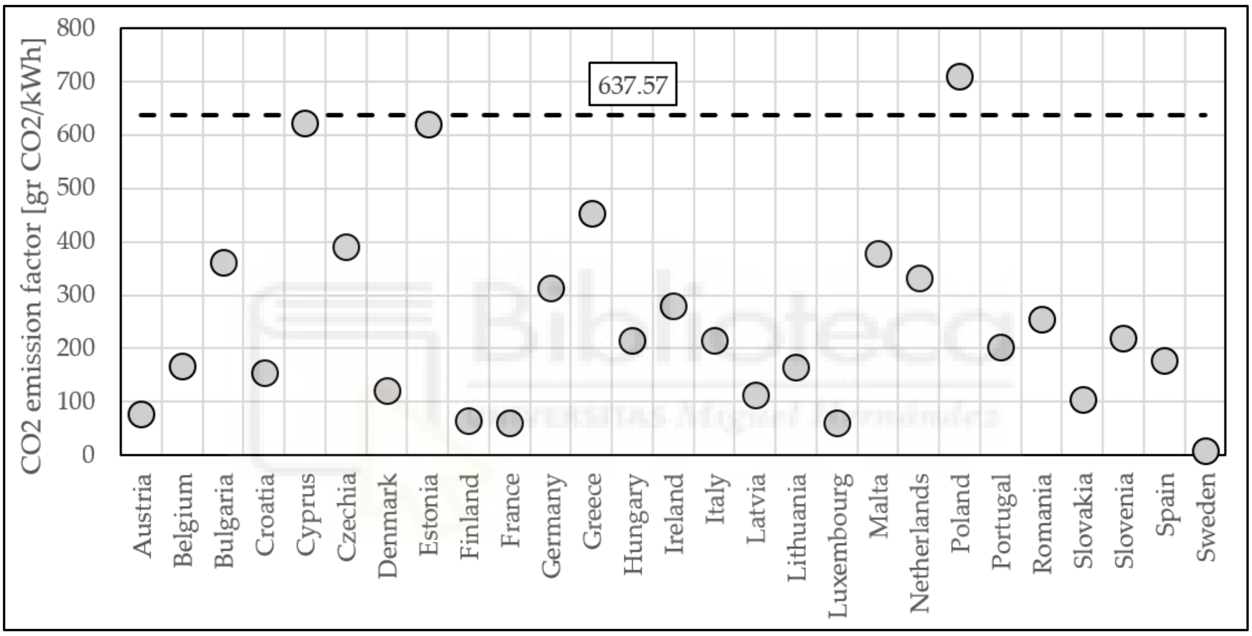

Figure 12. CO_2 emission factor of electricity from different Member States.

Even where full electrification is shown to be the best solution to decarbonise a building, bottlenecks such as grid overload can arise. Some buildings are not prepared to support this increase in the electricity demand as the installed electricity facility was not dimensioned for electric heating. For this reason, the full electrification of heating can lead to the replacement of the main electricity supply in the building. This can be achieved by changing the electrical cable section and protections and related distribution system elements including transformers. Whether this can be achieved depends on the applicable legislation. Although the EU can afford the installation of 30 million heat pumps at the Member State level as outlined in the REPowerEU Plan [12], all areas should be studied on a case-by-case basis, as some may present problems that need to be addressed if the power load increases [24,25]. The solutions depend on the region in which they appear. For instance, if only one user in a neighbourhood wants to change their power facility, it can be acceptable from the side of the grid owner. On the other hand, if there are several requests to increase the power capacity, the grid owner can ask for bigger cables, an additional transformation centre, etc.

The impact on the power system will be lower if the heating demand is reduced, for example by renovating the buildings. However, building renovations can be difficult for owners to realise and not economically viable in some cases [26]. Building renovations are not covered in this study, as we estimate the results only by applying energy efficiency measures on the heating systems.

Other types of air water heat pumps, which produce water at lower temperature levels, are not covered in this study as this work is focused on systems able to provide high-temperature heating. Low-temperature heat pumps also contribute to the decarbonisation of buildings, but more issues need to be taken into account. For example, it is not guaranteed that the current hydronic facility installed could work at lower temperatures, which implies changing radiators or pipes in the system, which sometimes can be an expensive upgrade depending on the geometry of the buildings. Our previous study [11] explains how these issues could be overcome and what type of opportunities low-temperature heating systems bring in the decarbonisation of buildings.

Air/air heat pumps are not categorised as high- or low-temperature. They can have the indoor units mounted on walls or a false roof with a duct system providing air at the desired indoor conditions. Sometimes, the lack of space in the roof of existing buildings to install long refrigerant pipes or duct systems can be an issue for their integration. However, this type of system can be considered an easy way to overcome failures in hydronic systems and prevent corrective maintenance operations.

The recommendations regarding the energy costs can be different, depending on the energy carrier selected and where the building is located. Electricity is usually more expensive than gas, but if heat pumps consume it, the electricity operating cost would be much lower than for gas consumption, which can bring lower final energy costs. If gas is much cheaper than electricity, the operating costs can be lower even though the heat pump is more efficient, as in the case of Germany and Poland.

Regarding the price of gas, as of 2027, the costs of gas boilers will be influenced by the new EU Emission Trading System (ETS) (https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/ets2-buildings-road-transport-and-additional-sectors_en) (accessed on 5 July 2024), which will cover the CO_2 emissions from fuel combustion in buildings. This means that the costs of gas could increase due to the addition of this levy. According to [27], for a house in Spain that has a yearly heating demand of 170 kWh/m^2 and a levy of 80 EUR /ton, the ETS impact could reach 4% of the house's income.

5. Conclusions

This paper analyses the decarbonisation potential of high-temperature heating systems. It presents findings on the impact of replacing condensing gas boilers with hybrid or high-temperature heat pumps in typical low-efficiency buildings located in the EU. The results show that these actions can yield significant CO_2 emission reductions without the need for building envelope renovations or upgrades to their hydronic facilities, actions that can be hard to perform in some buildings. Depending on the region within the EU, CO_2 reduction levels can reach between 40% and 70%.

These systems present a competitive alternative when renovating low-efficiency buildings is not possible, and provide a viable option to accelerate decarbonisation, particularly in low-efficiency buildings. These systems do not present the same efficiency levels as low-temperature heat pumps, but they side-step heat transfer issues and the need to renovate the hydronic facility of the building.

Taking into account the results obtained, they can be considered an alternative for decarbonising the building stock, helping to meet the targets set by the European Green Deal.

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