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Techno-economical analysis of different heat pump-based solutions for the energy retrofit of an existing residential building

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Summary

ABSTRACT

Nowadays, climate change and global warming are critical issues discussed worldwide. The global imperative to reduce emissions necessitates the adoption of sustainable technologies that aim to minimize or eliminate environmental impacts. In the building sector, particularly in heating systems, various technologies such as air-to-water heat pumps have become increasingly affordable and reliable. This technology utilizes external air to generate heat, which is then transferred to the indoor environment through different terminal units like radiators, underfloor heating and fan coils.

Since classical vapor compression heat pumps use electricity which can be produced with renewable energy, they reduce the needs for fossil fuels for space heating. Thus, they can be installed in new and existing buildings, replacing conventional gas boilers and thereby abating their direct emissions of carbon dioxide and of pollutants. The focus of this thesis is to assess the technical and economic aspects of retrofitting an old building using air-source heat pumps for space heating. The envelope of the case study building was recently retrofitted, by installing new windows and applying thermal insulation to the exterior walls. EnergyPlus software was used to simulate the energy demand for space heating before and after the retrofit. The simulation of the pre-retrofit case allowed to validate the building model based on natural gas bills collected by the building administrator.

Afterwards, an analysis of the heat pumps was conducted. Simplified models of heat pumps of different size were developed by making a regression of operating points declared by a heat pump manufacturer, and available in technical datasheet of commercial heat pumps for domestic application. The models were used to simulate and evaluate the long-term performance of different heat pump layouts based on weather data of the last ten years collected from an ARPAV weather station and assessing the economic and energy savings that such systems can provide. The analysis includes both heat pumps and hybrid systems made by the combination of heat pumps and gas boilers operated with different control logics depending on the considered heating capacity. Different techno-economical key performance indicators were used to assess heat-pump based retrofit solutions against a benchmark retrofit (centralized condensing gas boiler), such as the reduction of primary energy consumption and CO_2 emissions and the time needed to pay back the initial investment based on the cost savings given by the new configurations.

CHAPTER 1

INTRODUCTION

The European Union, increasingly aware of the urgency to address challenges related to climate change, has taken a prominent stance in promoting low-impact environmental solutions for building heating. This decision represents a significant step towards achieving sustainability goals and reducing greenhouse gas emissions. In a context where energy efficiency and environmental protection are central priorities, the adoption of innovative technologies in the building heating sector reflects Europe's commitment to pursuing solutions that strike a balance between residential comfort and environmental conservation. è

Climate change represents one of the most urgent and complex challenges of our time, with greenhouse gas emissions, particularly carbon dioxide, playing a significant role in global warming. The residential sector is one of the main contributors to CO_2 emissions, both directly through the use of fossil fuels for heating and cooling, and indirectly through the energy consumed for electricity and other household services. Given the current global demand to reduce carbon dioxide emissions, Europe is planning to replace boiler-based heating systems with less impactful technologies, such as heat pumps, by 2029. [1]

According to data from the World Meteorological Organization [2], global CO_2 concentration in 2021 was equal to 415.7 ppm, 149% the value of pre-industrial levels [3]. This worrying trend highlights the need for urgent and concrete actions to reduce CO_2 emissions and mitigate the effects of climate change.

The Paris Agreement, adopted in 2015 during the United Nations Climate Change Conference (COP21), sets the goal of limiting the increase in global average temperature well below 2°C above pre-industrial levels, with efforts to limit the increase to 1.5°C. To achieve this goal, signatory states have committed to reducing their CO_2 emissions and adopting measures to adapt to climate change.

Pollutant emissions primarily stem from three sectors: industry, transportation, and residential. While the share of emissions linked to transportation and industrial activities varies from city to city, that associated with buildings represents a key factor. In order to effectively manage and, particularly, reduce such emissions for both new and existing neighbourhoods, it is necessary to better understand not only which sectors and buildings currently cause these emissions but also what future effects both global energy retrofit programs and changes in energy supply infrastructure could have [4].

The European Recommendation 2016/1318 [5] identifies new construction buildings as a way to contain energy demand; these buildings should be characterized by very low energy consumption and, whenever possible, should generate energy locally through the use of renewable sources.

The concept of targeted tax incentives emerges as a key tool to promote the transition towards a low-carbon economy. In this context, the Superbonus at 110% represents a significant initiative introduced by the Italian government with the aim of stimulating investments in the energy efficiency and building renovation sector. This program, launched in response to the economic crisis caused by the COVID-19 pandemic, aims to promote the energy redevelopment of buildings, simultaneously reducing energy consumption and pollutant emissions.

Indeed, many old buildings have been renovated by implementing more efficient systems and thermal insulation. The building analysed was retrofitted thanks to Superbonus 110%. Currently, the Superbonus is no longer available, as this incentive was discontinued at the end of 2023. The redevelopment of buildings through the implementation of more efficient systems and thermal insulation is crucial for reducing energy consumption and mitigating the environmental impact associated with their management, reducing greenhouse gas emissions and natural resource consumption.

To effectively intervene in the building sector in order to reduce energy consumption, it is essential to be able to model the thermal behaviour of a building accurately. Over the past few decades, numerous tools have been developed for energy modelling of buildings in urban contexts. In general, the thermal dynamics of a building can be modelled following two different approaches. The first involves explicitly modelling the physical phenomena that occur within the building, namely all the physical processes that significantly influence the energy balance of the considered thermal zones. The models following this logic are defined as white box models.

The second approach is based on statistical methods applied to available data (energy consumption, temperature values, and relative humidity recorded in the environment) without any explicit reference to the equations governing their energy balance, and are therefore called black box models [6]. In most cases, data are either unavailable, for example, during the design phase, or incomplete. In these cases, we are forced to use the first type of model.

Buildings are highly complex energy systems (dynamic systems) because they are affected by various overlapping physical processes, such as heat exchange by convection and radiation between internal wall surfaces, internal heat and vapour generation, absorption of solar radiation, and many others. Additionally, they are composed of complex structures (three-dimensionality, multi-layered envelope consisting of opaque and glazed components, multiplicity of thermal zones). Therefore, the energy requirement for heating or cooling can be calculated in various ways, more or less detailed depending on the objective of the analysis.

To analyse the case study presented in this work, dynamic models are used thanks to the use of the EnergyPlus software [7]. The necessary steps for modelling the building under analysis is explained later on, followed by a subsequent analysis including the retrofit, in order to visualize the reduction in primary energy and carbon dioxide emissions as dictated by the global need considering the same thermal plant.

Subsequently, the coupling of air-to-water heat pump systems is analysed to produce the required heat for the building. Specifically, the results derived from the simulation are considered and analysed to align this need with the heat production of the heat pump. Various configurations are examined, highlighting the performance of the heat pumps, as well as primary energy consumption and carbon dioxide emissions. Finally, they are compared to determine which configuration is best suited to meet the building's thermal demand based on the overall energy cost. Additionally, the configuration with radiant floor heating is considered to assess further savings compared to configurations with radiators.

CHAPTER 2

DESCRIPTION OF THE CASE STUDY

In this section, the case study under examination is presented. The characteristics of the analysed building will be outlined, both in the pre-retrofit and post-retrofit scenarios. The existing systems will be described, namely the installed thermal plant and the method of hot water generation along with their respective characteristics.

2.1. The building

The condominium is a residential building built in 1964 composed of twelve units; six apartments and six garages. The building is located in the municipality of Padua (climatic zone E).
Previously, refurbishment works were carried out which involved the replacement of the windows for only one apartment (winter 2018/2019) and the insulation of the roof (summer 2019).

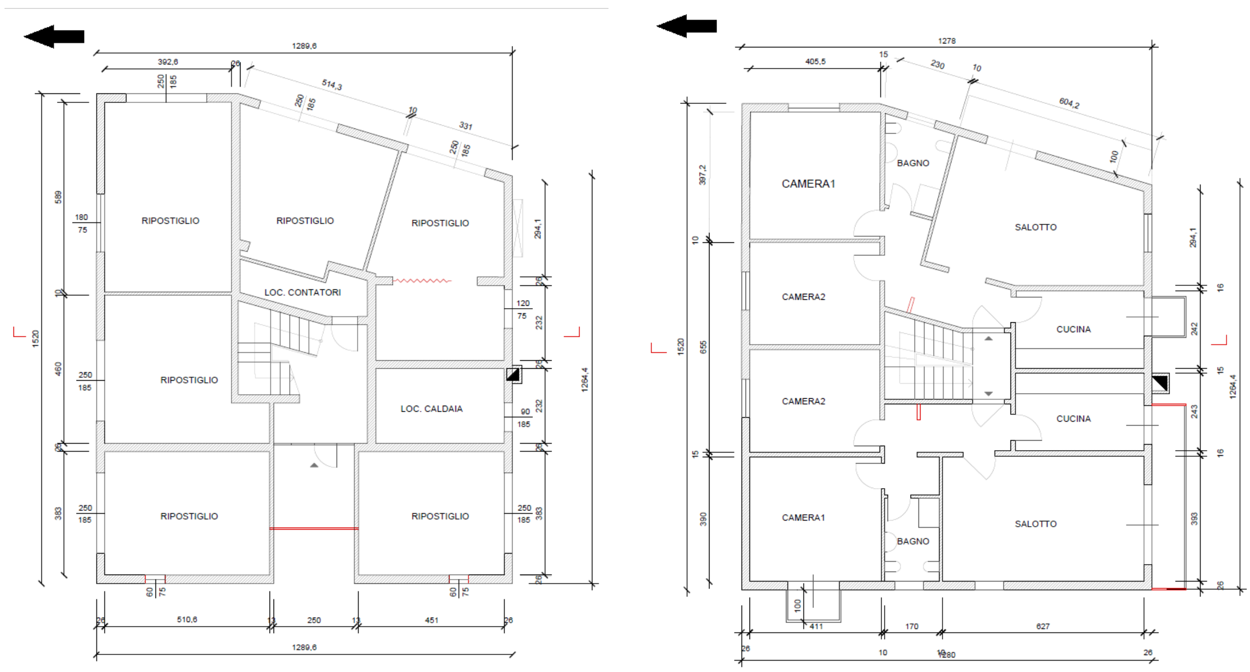
Figure 1. Building elevation.

The main purpose of this analysis is to study the energy need of the building before and after the retrofit, useful to identify the economic and energy saving related to the intervention.
To simulate the thermal behaviour and the energy need of the building, it is necessary to know the stratigraphy of the walls, of the windows and the planimetry of the building.

The latter highlights the composition of the apartments: in particular, the first and second floor have the same planimetry while the third one is different because of a bigger terrace leading to smaller apartment (Figure 1).
Every single floor is composed of two apartments: both are composed of a kitchen, a living room, a bathroom and two bedrooms. What is different is the dimension of the apartments, in particular: the apartments of the first and second floor are 83 m^2 while the apartments of the third floor are 75 m^2.
Table 1 collects the general dimensions of the condominium, while Figure 2 collects the planimetry of the building.

Net surface	482.6 m^2
Gross volume	1400 m^3
Shape factor S/V	0.345

Table 1. General dimension of the condominium.



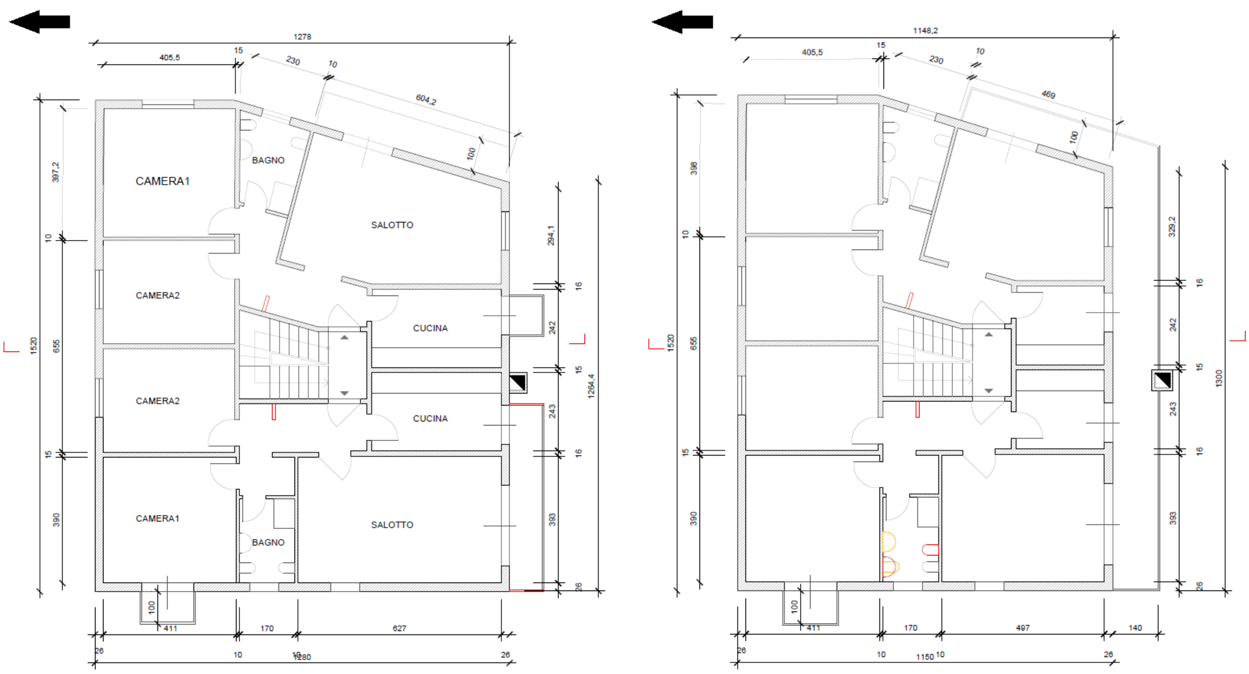


Figure 2. Planimetry floor by floor. First row of the table: garages on the left and first floor on the right. Second row of the table: second floor on the left and third floor on the right. The black arrow points the North. The apartments facing East are the "A".

2.1.1. Building envelope before retrofit

The building, being built in the 70s, presents a poor thermal insulation. In fact, the thermal conductivities of the components of the envelope are very high.

Subsequently, only the total conductivities of the individual opaque components are reported. For a complete view of the stratigraphy of each individual component, refer to Annex A.

	Total thermal conductivity [W/(m^2*K)]
External wall	1.85
Load-bearing inner wall	2.18
Internal partition	2.06
Attic floor	0.20
inter-storey slab	1.38
Floor against the ground	1.27

Table 3. Total thermal conductivity of the opaque components.

In this condominium two types of windows are installed. Five apartments out of six present double windows with the inner frame made of wood and the outer frame made of anodized aluminium. The remaining apartments, due to renewal, install double-glazed windows with the frame made of PVC.

In Table 4 the total thermal transmittances of the transparent surfaces are reported: in Annex A also the characteristics related to the frame are reported.

Component	Total thermal transmittance [W/(m²*K)]
Double window in anodized aluminium 120x150 cm	2.7
Double window in anodized aluminium 240x240 cm	2.78
Double window in anodized aluminium 120x240 cm	2.69
Double window in anodized aluminium 90x150 cm	2.62
Double window in anodized aluminium 160x240 cm	2.73
Double window in anodized aluminium 160x150 cm	2.71
Double-glazed window in PVC 120x150 cm	1.51
Double-glazed window in PVC 120x240 cm	1.48
Double-glazed window in PVC 90x150 cm	1.61
Double-glazed window in PVC 160x240 cm	1.4
Double-glazed window in PVC 160x150 cm	1.44

Table 4. Total thermal conductivity of the transparent surfaces.

Tables A3 collects all the components of the building envelope, subdivided by apartment. Every single apartment is heated up, and it confines with other apartments or with unheated spaces such as the external environment or inner unheated spaces. These pieces of information are very important since they affect directly the energy need of the whole condominium. In Tables A3 these external boundaries conditions are expressed with different letters:

(E) for spaces confining with the external environment,

(A) for spaces confining with heated spaces (apartments)

(U) for spaces confining with unheated spaces (garages, stairwell and roof).

Another important parameter useful for the simulation is the orientation of the surfaces, properly highlighted in the same Table.

The surfaces considered and analysed are then subdivided into opaque (OP) and transparent (TR).

Besides the apartments, in this building there are unheated zones. These zones are listed in Tables A4 in Annex A, which contain the areas and thermal transmittances of the zones mentioned above.

2.1.2. Building envelope post-retrofit

The main retrofit interventions are three. The first one refers to all the facades of the building except for the facades of the garages and the terraces: In this case, the intervention involves adding a 12 cm layer of EPS to the affected walls, translated in a thermal resistance of 3.429 (m^2*K)/W. The second intervention refers to the facades of the terraces. For this intervention, different thicknesses were used compared to the first one. This was done to reduce the insulation clutter: in fact, having a limited space dictated by the terrace constraints, having a thick insulation layer would have led to a reduction in usable space. Therefore, a 5 cm layer of EPS coupled with a 1 cm layer of aerogel was installed. The total thermal conductivities of the opaque component are listed in the following Table, while for the details refer to the Annex A.

External wall: no terraces	
	Thermal resistance [(m²*K)/W]
Internal plaster	0.029
Brick	0.321
External cement mortar	0.022
EPS	3.429
Total thermal conductivity [W/(m²*K)]	0.252
External wall: terraces	
	Thermal resistance [(m²*K)/W]
Internal plaster	0.029
Brick	0.321
External cement mortar	0.022
Aerogel	0.69
EPS	3.429
Total thermal conductivity [W/(m²*K)]	0.215

Table 5. Total thermal resistance of the opaque components post retrofit.

The new windows installed present a frame made of PVC and a thermal transmittance of 1.1 W/(m²*K), lower than the limit imposed by the climatic zone E in which the building is located [8].

The new windows were installed in all the apartments except for apartment 2A, because it already had PVC windows.

2.2. Heating system pre-retrofit

Space heating is provided through a centralized condensation gas boiler with maximum rated power equal to 53.6 kW considering 80–60 °C as temperatures for the generated hot water (supply – return), while, if the boiler supplies water at lower temperature (50 – 30 °C), the maximum rated power is equal to 59.3 kW.
The efficiencies declared by the manufacturer are 87.7% for high temperature water production and 98.9% for low temperature water production. These two efficiencies are based on the high heating value (HHV) of the gas methane.
The distribution system is a centralized riser system with non-insulated horizontal distribution in the cellar. The heat is then exchanged with radiators positioned on external walls without insulation. The regulation of the temperature inside the rooms is performed thanks to thermostatic valves installed on the radiators.

2.2.1. Heating system post-retrofit

The heat generation system selected for the post-retrofit is the heat pump. This solution fits with the already existing plant. Regarding the distribution and emission system, there will not be any modification. A further analysis is to verify if the already installed radiators are sufficient to fulfil the power needed by every single apartment since the water produced by the heat pump will not be higher than 50 °C (instead, with the boiler, the water could be heated up to 80 °C). Different solutions will be analysed later in this work.

2.3. Domestic hot water

Domestic hot water production is provided with autonomous gas boilers installed for each apartment. The production is instantaneous and hot water is produced between 40 and 45 °C

CHAPTER 3

METHOD: APPLICATIONS AND IMPLEMENTATIONS

In this section, the method employed for analyzing the integration of the heat pump as a heating system in the case study will be illustrated. Firstly, the OpenStudio and EnergyPlus software will be introduced, which are used to model the building and evaluate its energy requirements.
Subsequently, the thermal performance analysis of the radiators in each apartment will be conducted to verify whether they can meet the required peak heat demand when using the heat pump as the heat source.
Once this phase is completed, the model applied to the heat pump will be presented, evaluating its operation under the real climate conditions over 10 years.

3.1. BUILDING ENERGY MODEL

EnergyPlus is a building energy simulation software that plays a key role in the analysis and design of high-performance energy buildings.
EnergyPlus was developed by the U.S. Department of Energy (DOE), specifically by the staff of the "Building Technologies Office" program within the Office of Energy Efficiency and Renewable Energy (EERE). The project began in 1997 with the goal of providing an advanced simulation tool for assessing the energy performance of buildings [9].
The full name of the program is "EnergyPlus: Energy Simulation Program," and it was designed to be a successor to the set of programs BLAST and DOE-2, also developed by the DOE. EnergyPlus was created to overcome some limitations of its predecessors, offering greater flexibility, detailed modelling, and increased precision in simulating the energy performance of buildings [10]. The approach of EnergyPlus is based on detailed modelling, considering a wide range of variables to provide an accurate representation of the thermal and energy performance of a building over time.
To begin, users provide detailed data about the geometric characteristics of the building, such as shape and size, as well as information about the materials used for walls, floors, and roofs, including insulation properties and thermal mass. These details are essential for the accuracy of the simulation as they directly influence how the building interacts with the surrounding environment.
An important aspect of EnergyPlus involves HVAC systems, including heating, cooling, ventilation, and air conditioning. Users define the parameters of these systems, along with control strategies and set points, to model the internal thermal behaviour of the building in response to external conditions.

Building occupancy, lighting systems, and other internal loads are also integrated into the model, allowing for a comprehensive assessment of energy efficiency.
The heart of EnergyPlus is its advanced simulation engine, which performs complex calculations to predict the energy consumption and thermal behaviour of the building on an hourly basis. This detailed approach provides accurate results that enable users to identify areas for improvement and optimize the overall energy performance of the building.
The procedure performed by EnergyPlus to obtain the desired results consists into three main phases preceded and based on the reading of the input file (in.idf) and the data dictionary (Energy+.idd).
The input file (in.idf) contains all the information necessaries to perform the simulation: the geometry of the building, the location of the building and its orientation, the stratigraphy of the walls and the windows, the schedules for the internal heat gains and the schedules for the heating and cooling season and the boundary condition for each surface composing the building.
In this file are also reported the output that the program supplies, with the related settings.
Besides these two files must be present also the “Weather file”, called EPW: it is a crucial element to ensure the accuracy and validity of simulations as it provides essential meteorological data to model the thermal and energy behaviour of a building in a specific location.
For the energy simulation of buildings using EnergyPlus, the set of climatic data employed is referred to as "TRY" (Test Reference Year), constituting a collection of files containing reference climatic data. These files, derived from various sources, include measurements from actual meteorological stations, though comprehensive coverage for all locations is not guaranteed. For specific climatic data for Europe, including the EPW files used by EnergyPlus, it is advisable to refer to official resources provided by national or international meteorological services. For instance, CIBSE (Chartered Institution of Building Services Engineers) provides climatic data for various European locations, including EPW data [11]. Additionally, the IWEC archive (International Weather for Energy Calculations) offers EPW files based on measured climatic data from various stations across Europe and the world [12].
The EPW file structure begins with a header containing key information about the location, reference year, and other relevant specifications. The main section of the file is dedicated to hourly data, including climatic parameters such as temperature, humidity, wind speed, and solar radiation. This data is segmented for each hour of the year, allowing for a detailed representation of climatic conditions.
EnergyPlus fully utilizes the data within EPW files to perform detailed energy simulations. The accuracy of simulations is directly linked to the quality of meteorological data provided by the EPW file.
EPW files can be obtained from official sources such as national or international meteorological agencies. Proper selection of a representative EPW file for the specific location of interest is a critical step to ensure realistic and relevant simulations in the realm of building energy analyses.

These preliminary phases are useful for the simulation, since they permit to process the data giving the desired results. Once the data are elaborated, EnergyPlus generates a report which contains all the results and all the summaries of the data used and elaborated by EnergyPlus itself. In this report, in fact, is possible to check all the consequences of the input data like the overall thermal conductivity of the walls or of the windows. This control could be very helpful since it is possible to verify if the input data elaboration is correct, giving consistent results with the real case.

If the input data are not correct, it is generated a file containing all the error. In this file, called eplusout.err, can be found two types of errors depending on them severity.

A further analysis consists into the simulation of the energy need of the building along ten years, modifying properly the EPW and considering the necessary data of the real location of the building.

3.1.1. Geometry of the building

The geometry of the building is the first step that must be accomplished for the energy analysis of the building. OpenStudio is used as the EnergyPlus interface : it is a cross-platform collection of software tools to support whole building energy modelling [13]. Moreover, it is compatible with SketchUp, a support software used to create also complex surfaces and facilitate the modelling.

The building was implemented following the planimetry represented in Table 2. This allowed to subdivide every single floor room by room considering, thus, the thermal inertia of the separating walls obtaining a more precise simulation.

In this model, however, it was considered a simplification regarding the garages. Since they are not heated up, they were considered without any separating wall, omitting the thermal inertia of the separating walls, behaving like a single unheated room.

Performing the modelling of the building in OpenStudio, it will automatically assign the outside boundary condition to the generated surfaces, subdividing them in adiabatic, facing outside or facing the ground.

Every single boundary condition can be modified later inside a specific tab in the software if the automatic assignment is not correct. In addition, different outside boundary conditions can be defined in EnergyPlus.

Later, the windows are created. The shading coefficient of the windows is fixed to 0.6: it is a measure of the thermal performance of a glass unit (panel or window) in a building.

It is the ratio of solar gain (due to direct sunlight) passing through a glass unit to the solar energy which passes through 3mm Clear Float Glass. It is an indicator of how well the glass is thermally insulating the interior when there is direct sunlight on the panel or window.

Following these steps, the whole building was divided into different Thermal Zones (TZ).

A Thermal Zone represents an isothermal volume of air that may have only one thermostat. The Thermal Zone forms the connection point between the air-conditioned space and the HVAC equipment [14].

Every single Thermal Zone has been chosen based on the behaviour of the people or based on the spaces themselves, like the garages, the attic and the stairwell where the people are not used to live there. In addition, these three spaces are not heated up.

Based on this concept, for each apartment have been defined two Thermal Zone: the first one includes the corridor, the kitchen, the bathroom and the living room, called "Zona Giorno (ZG)", while the second Thermal Zone includes the two bedrooms, and it is called "Zona Notte (ZN)".

This subdivision of the apartment (AP) is performed for each floor (F) and, based on the classification expressed in Table 2, the apartments are also represented with the letter A or B.

An example of Thermal Zone is TZ_ZG_APA_1F, representing the Thermal Zone "Zona Giorno", Apartment A, first floor.

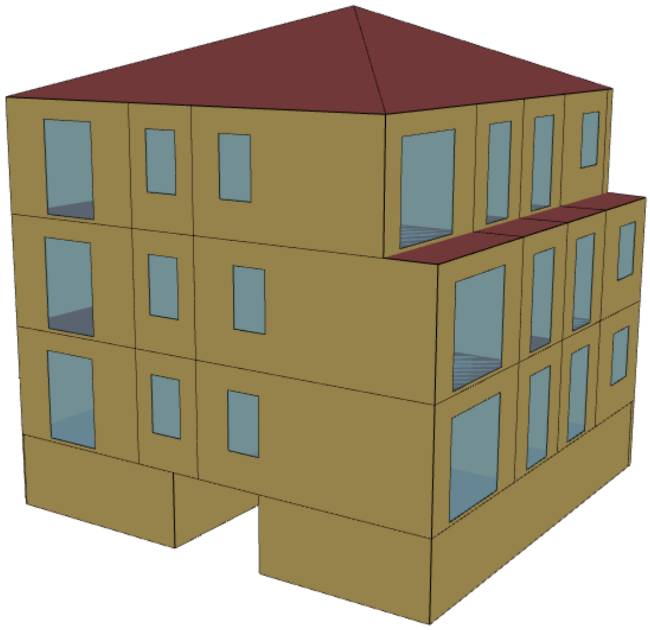


Figure 3. Building model from OpenStudio.

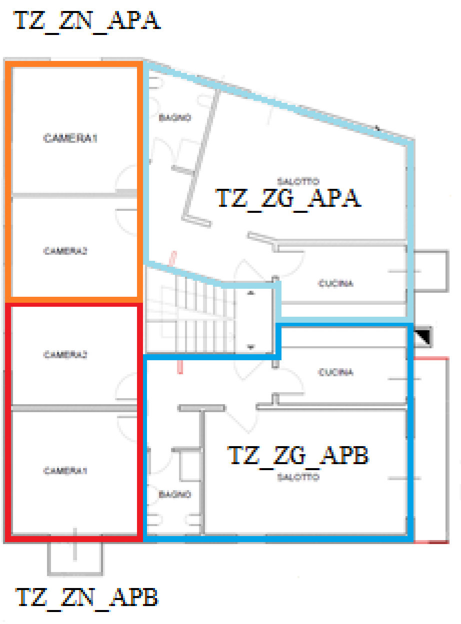


Figure 4a. Thermal zone subdivision for the first and second floor.

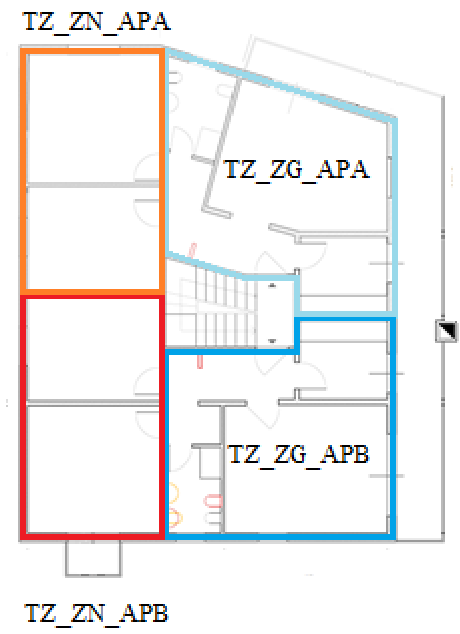


Figure 4b. Thermal zone subdivision for the third floor.

3.1.2. Building envelope

Once completed the modelling of the building in OpenStudio, the following step consists into the definition of the material composing the whole building. In this phase, the materials' characteristics are defined in the software.

Since the boundary conditions have been already defined in the previous phase, in this phase the opaque and transparent surfaces are defined in terms of stratigraphy.

This is possible in the tab "Construction" and section "Materials", which permits to create all the material composing every single surface.

For the material composing the opaque surfaces, it is necessary to define its thermal and mechanical characteristics like the roughness, the thermal conductivity, the density, the thickness and the specific heat. Regarding the transparent materials, it has been used the simplified way which permits to define the overall thermal transmittance of the windows. This choice has been taken based on the available data; in fact, many manufacturers don't provide separately the thermal transmittances values of the glass part and the frame.

3.1.3. Weather data

The weather file used for the first simulation is the Test Reference Year (TRY) for the location of Venice, in Italy, close to the location of the case study.

The mean monthly temperatures considered in the simulation are expressed in Table 6 and Figure 5

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2.3°C	4.5°C	7.4°C	12.5°C	17.8°C	21.4°C	24.4°C	23.0°C	18.7°C	14.0°C	7.9°C	4.4°C

Table 6. Mean monthly temperatures for the test reference year

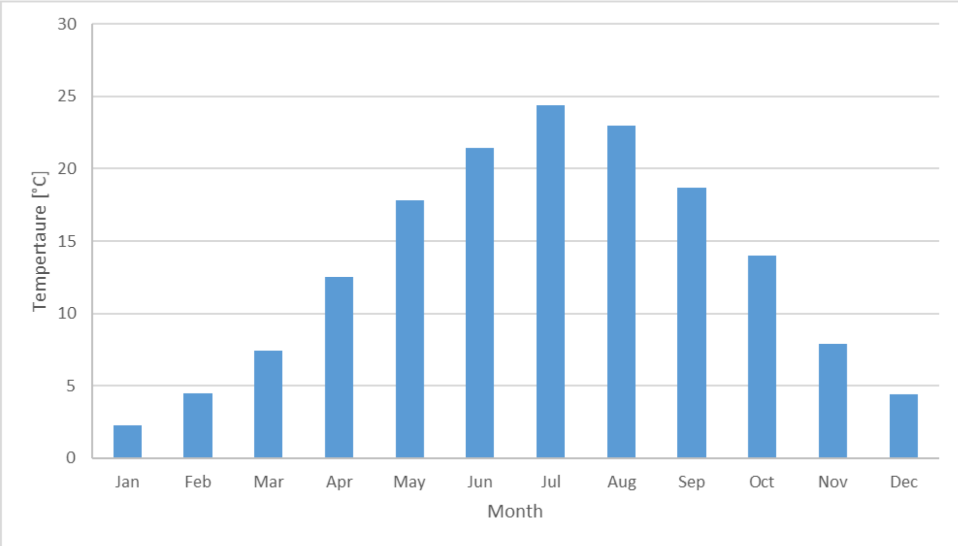


Figure 5. Mean monthly temperature from TRY in Venice.

In addition to the external average temperatures, other information such as the global horizontal solar irradiation, wind speed, and humidity are present within the weather file. In particular, data related to global horizontal irradiation (GHI) are reported.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean monthly GHI [kWh/m^2]	31.9	51.8	91.9	121.8	143.8	167.1	187.4	152.8	99.5	61.9	38.7	23.6

Table 7. Mean monthly GHI of the TRY.

In Figure 6, the same data are represented in a graph, useful to visualize the trend along the reference year.

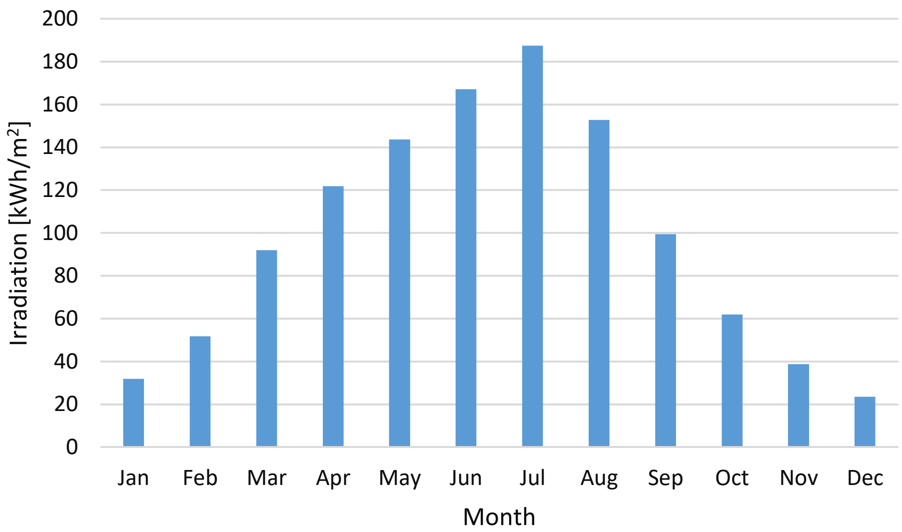


Figure 6. Mean monthly GHI along the TRY.

The simulations used to verify the operation of the heat pump and to validate the model utilize a properly modified EPW file containing real data from the years 2013 to 2022. These data have been collected and made available by ARPAV (Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto) [15]. In particular, these data have been collected from station number 234, located in Padua. Similarly to what was reported for the TRY, for this EPW file, data regarding the average monthly temperature and global horizontal irradiation will also be included.

In the following Table, monthly average temperatures based on a 10-year period are reported along with their graphical representation.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
3.6°C	6.2°C	9.2°C	13.6°C	17.6°C	22.9°C	24.7°C	24.0°C	19.6°C	14.7°C	9.6°C	4.5°C

Table 8. Mean monthly temperature based on the 10-year period.

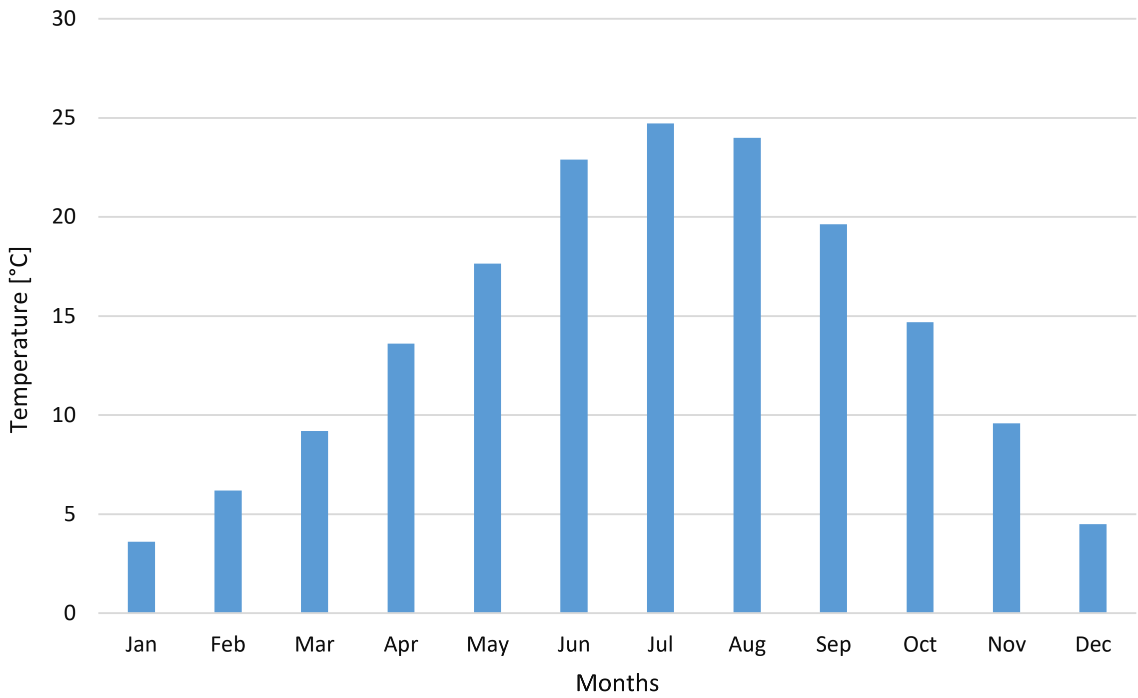


Figure 7. Mean monthly temperature based on the 10-year period.

As can be seen, the minimum temperature is registered in the month of January. In the following Table the mean monthly temperatures will be reported for each year considered in the modified EPW. The same data are expressed in Figure 8.

Mean temperatures [°C]	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
January	3.9	6.8	4.1	3.1	0.9	5.5	2.2	3.3	3.1	3.0
February	4.0	8.3	5.7	7.5	6.1	3.8	6.0	7.3	7.1	6.2
March	7.8	10.9	9.5	9.7	11.1	7.1	9.8	9.2	8.4	8.2
April	13.8	14.8	13.5	14.0	13.8	15.8	13.1	13.9	11.5	12.0
May	16.6	17.4	18.6	17.0	18.3	19.8	14.8	18.0	16.0	20.0
June	21.7	22.0	22.4	21.6	23.7	22.9	25.0	21.2	23.7	24.5
July	25.0	22.7	26.4	24.8	24.6	24.6	24.5	23.9	24.3	26.2
August	23.5	21.8	24.3	23.1	25.3	25.2	24.5	24.2	23.3	24.6
September	19.4	18.8	19.6	20.7	17.8	20.7	19.6	20.4	20.0	19.3
October	15.1	16.0	14.0	13.3	13.7	15.6	15.7	13.3	13.3	16.9
November	10.0	11.6	8.1	9.2	8.1	10.3	10.6	8.4	9.4	10.2
December	4.4	6.2	3.3	3.0	2.8	3.1	5.8	5.8	4.0	6.5
Heating Degree Days	2109	1697	2093	2044	2146	2114	1981	1997	2317	1991

Table 9. Mean monthly temperatures along the years of the simulation.

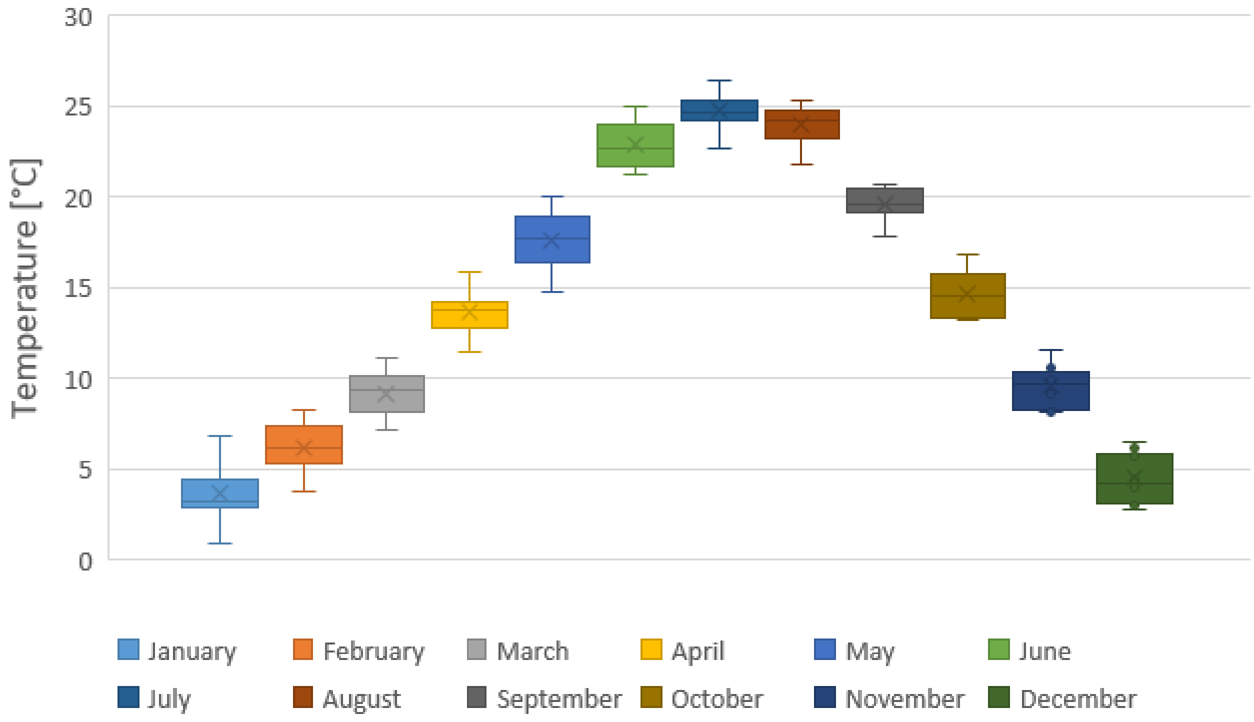


Figure 8. Mean monthly temperature for each month and year.

What is interesting to evaluate is the degree days associated with each year. They inherently reflect the temperature trends throughout the year. In fact, the higher the number of degree days, the greater the need for heating in the given year.

From the analysis of degree days (Table 9), the coldest year appears to be 2021 due to the higher number of degree days. On the other hand, the warmest year seems to be 2014, showing a reduced number of degree days. Given the need to validate the model, data relating to the period used for this verification will be presented subsequently. The analysed period is the heating period between the years 2019 and 2020.

Likewise for the TRY data, the real mean monthly temperature along the heating period as well as the GHI are presented.

Month	Mean monthly temperature [°C]
October 2019	15.7
November 2019	10.6
December 2019	5.8
January 2020	3.3
February 2020	7.3
March 2020	9.2
April 2020	13.9

Table 10. Mean monthly outdoor temperature for the heating period 2019/2020.

The same data are reported in the Figure below.

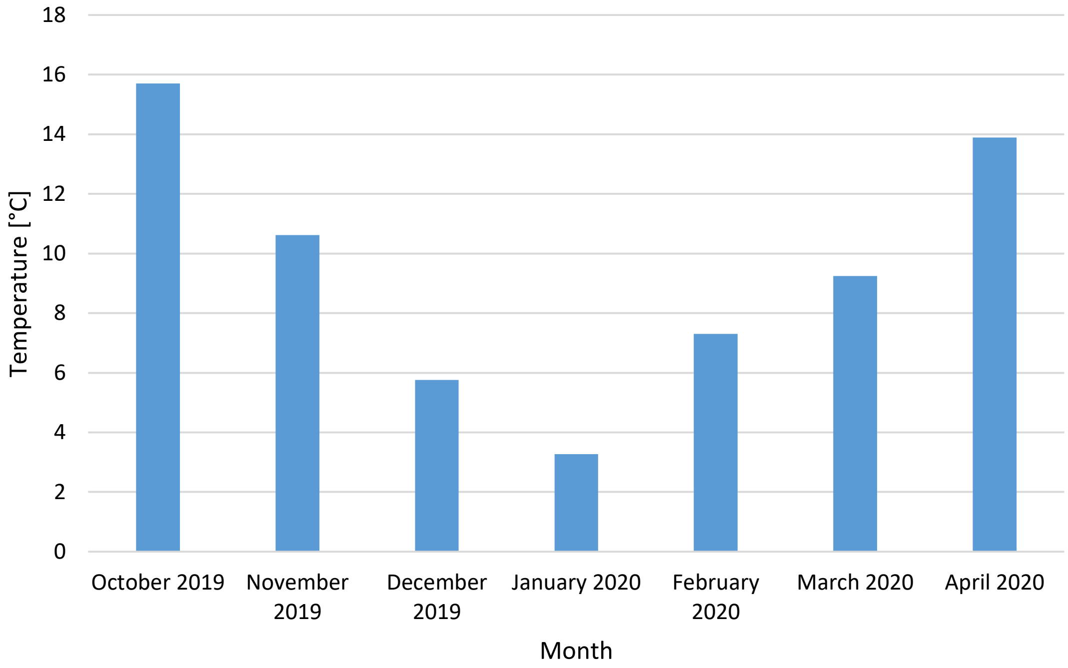


Figure 9. Mean monthly temperature for the heating period 2019/2020.

Besides the external temperature, the GHI plays an important role in the model. Thus, particular attention must be paid for these data. In particular, they are equal to:

Month	Mean monthly GHI [kWh/m^2]
October 2019	80.0
November 2019	37.4
December 2019	37.4
January 2020	48.5
February 2020	71.5
March 2020	114.3
April 2020	175.6

Table 11. Mean monthly GHI for the heating period 2019/2020.

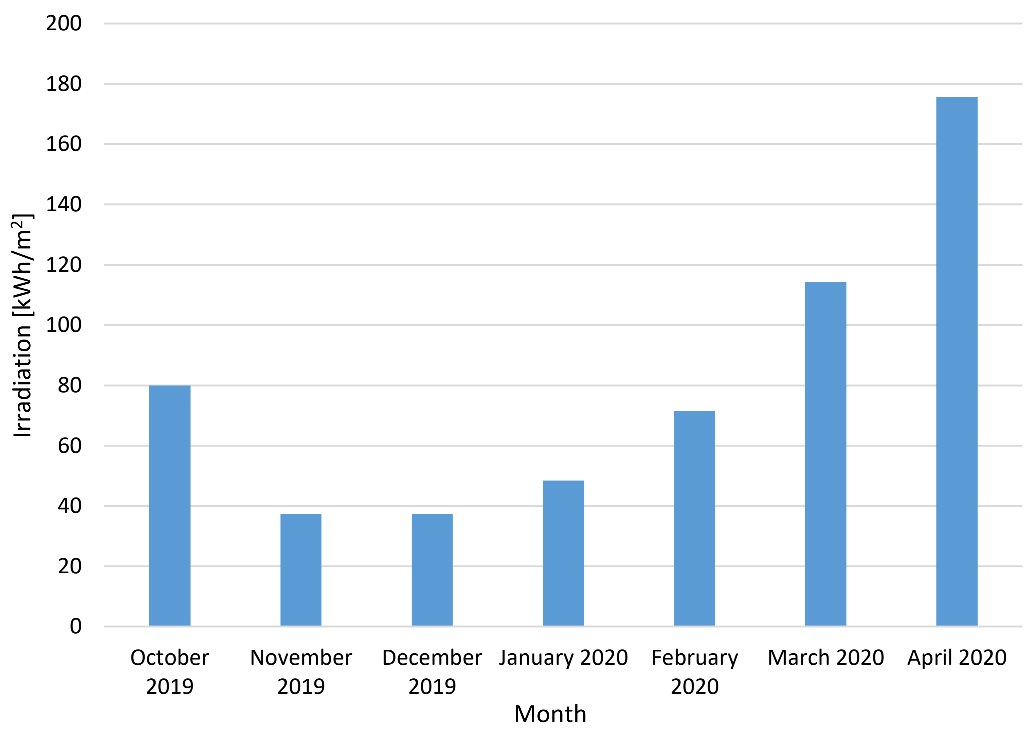


Figure 10. Mean monthly GHI for the heating period 2019/2020.

What can be observed both from the TRY and the modified EPW file is that January is consistently the coldest month on average. Therefore, it has been decided to analyse its behaviour over the years, always considering the same characteristics, such as temperature and GHI.

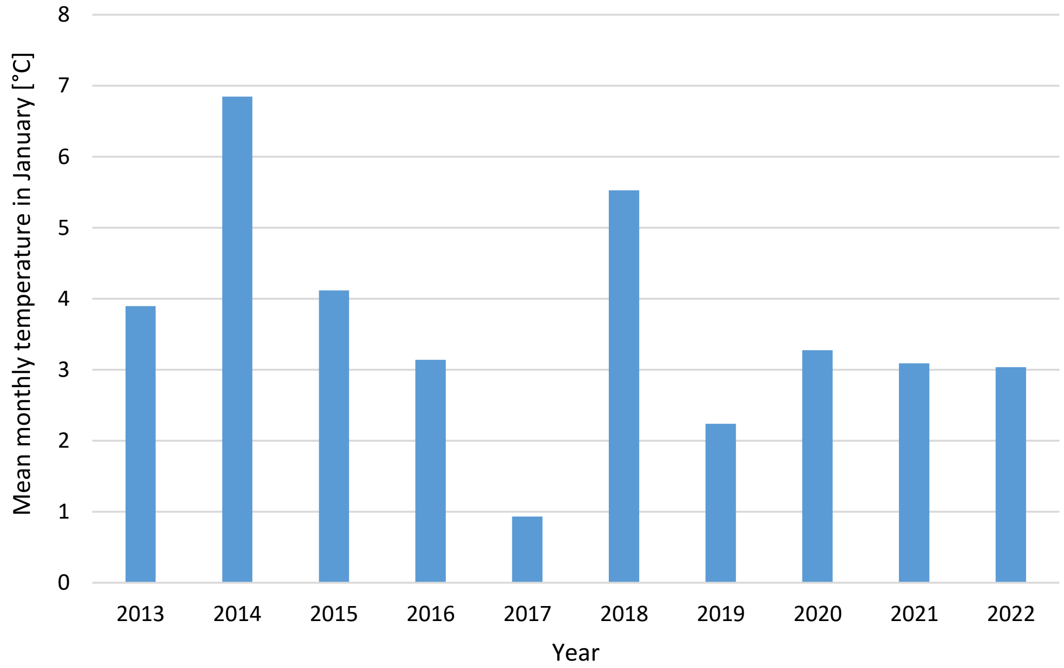


Figure 11. January's monthly temperature year by year.

As highlighted by the graph above, a significant variation in temperatures is observed over the course of 10 years. The year with the highest temperature is 2014, recording a temperature of 6.8 °C, while the minimum temperature was recorded in 2017, at 0.9 °C. Indeed, there is a notable variation in these two extreme cases, despite minor variations in temperature observed in other years.

This variation can also be observed through the degree days of the various years, which indirectly reflect the average temperature during the heating period. In fact, the higher the number of degree days, the lower the average temperature during the heating period. Generally, it's not enough to have the temperature data for a single month to conduct this analysis. Indeed, in Table 9, it's noted that the year with the highest number of degree days is 2021, not 2017. However, 2017 is the second year with the highest number of degree days, while 2014 has the lowest number, which aligns with the higher temperature recorded in 2014.

The irradiance of January along the years is

January	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Monthly irradiation [kWh/m^2]	33.1	25.2	44.8	39.9	54.5	38.7	46.7	48.5	38.5	51.7

Table 12. January monthly irradiation by year.

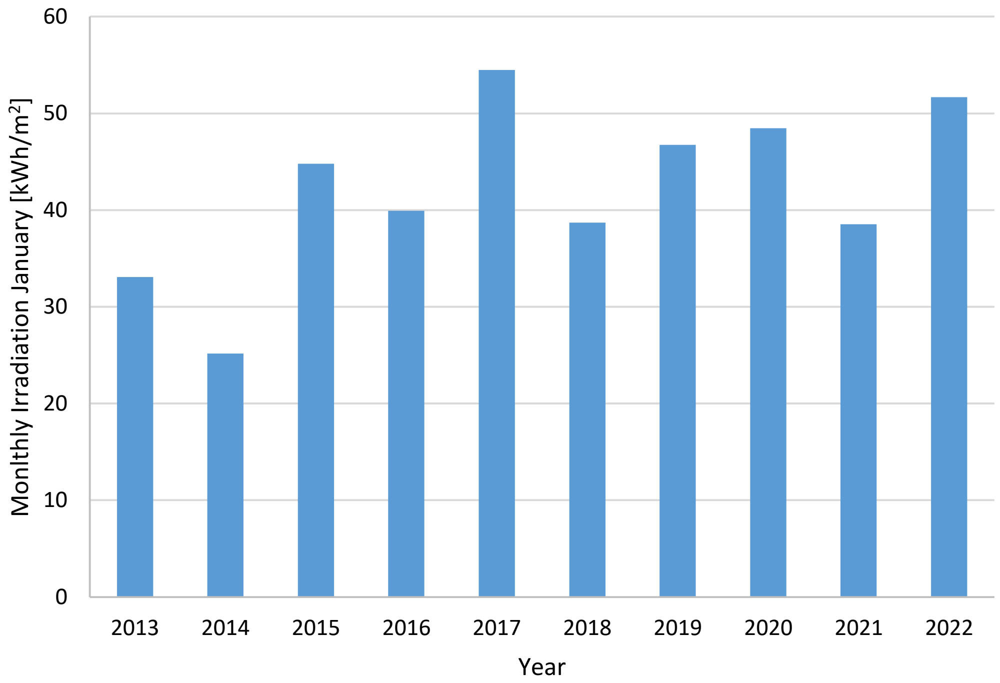


Figure 12. January mean monthly GHI by year.

3.1.4. Comparison between TRY's weather data and real weather data

For a better understanding of the differences between the TRY file and the real weather data (modified EPW) file, this paragraph will present the same types of graphs analysed so far, directly comparing the values of the two files. This will allow for a direct comparison between the previously described data.

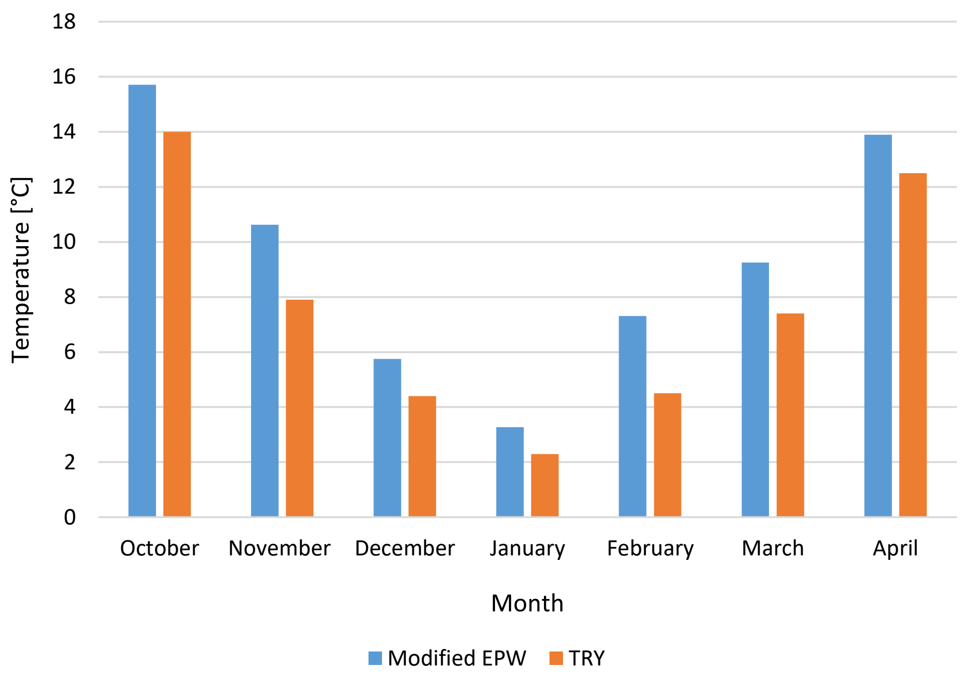


Figure 13. Temperature comparison between the TRY and the modified EPW, in particular for the heating period 2019/2020.

As observed, the TRY displays monthly average temperatures overall lower than the actual data for the heating season of 2019/2020. The same trend is observable in the mean monthly irradiation throughout the same period.

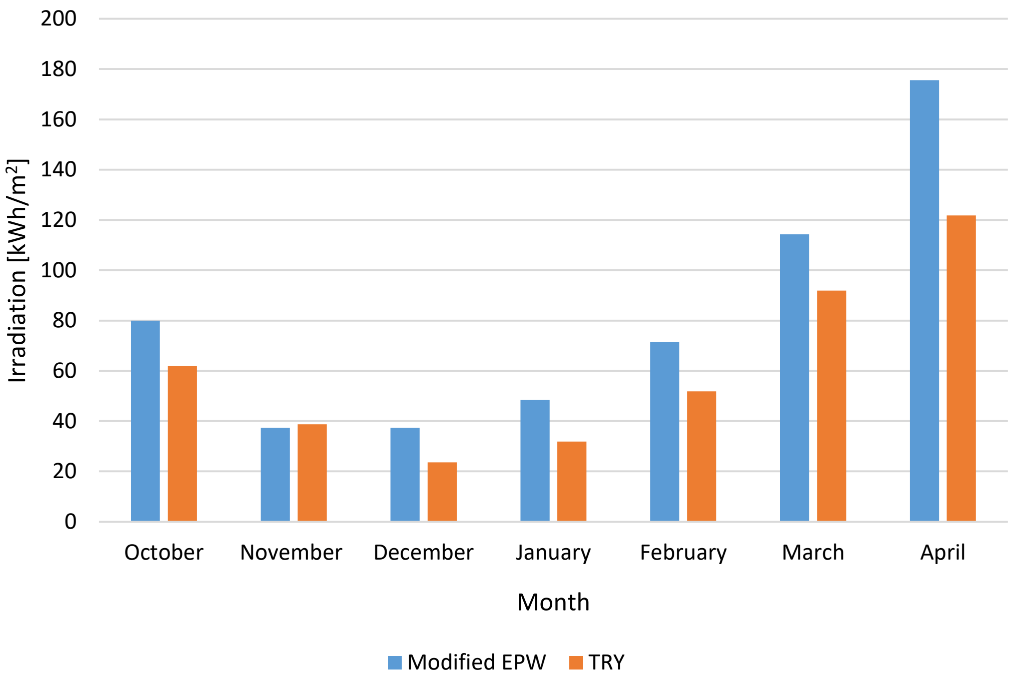


Figure 14. Irradiation comparison between the TRY and the modified EPW for the heating period 2019/2020.

Moving to the analysis concerning the month of January, it can be observed that once again the TRY exhibits values that are generally lower compared to the period under consideration.

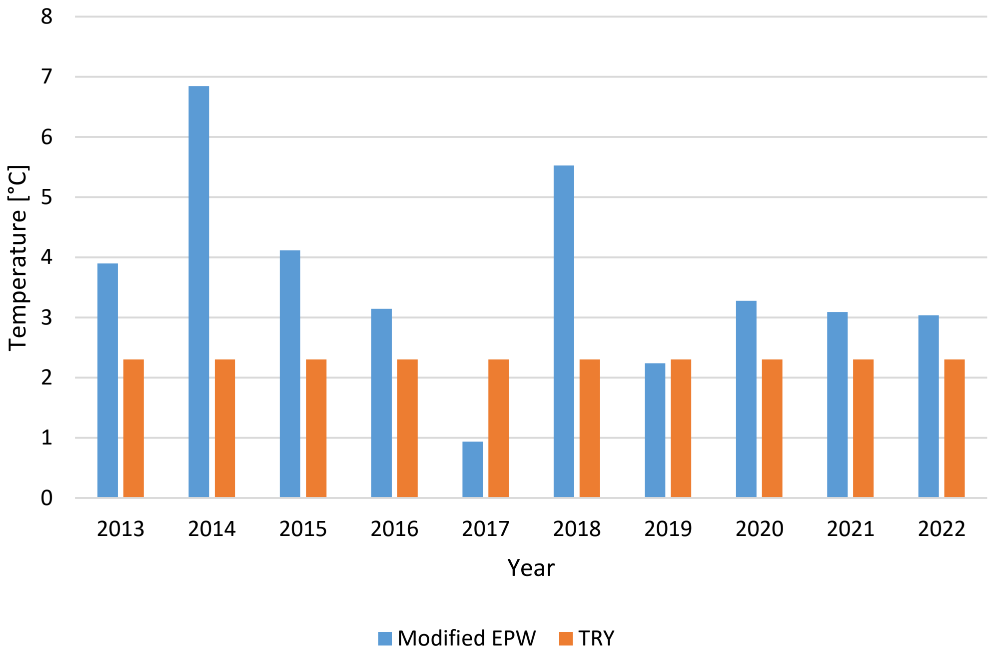


Figure 15. January temperature by year compared with the January temperature of the TRY.

As anticipated, the values from the TRY are generally lower compared to the values of individual years. However, there are some exceptions: indeed, the value from the TRY is significantly higher compared to that of the year 2017 and slightly higher than that of 2019.

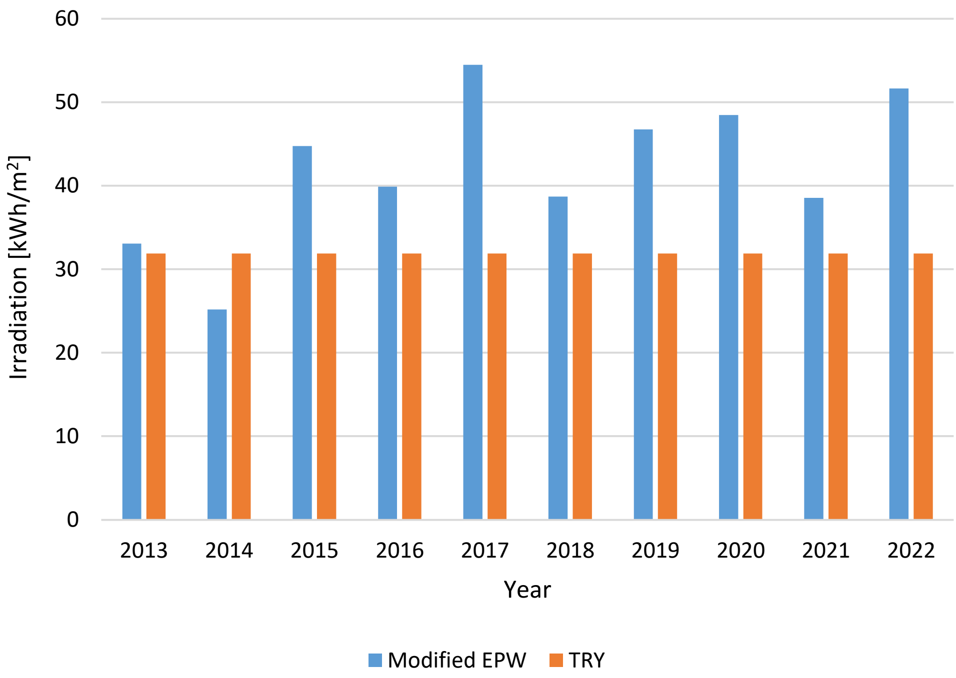


Figure 16. January mean irradiation by year compared with the January mean irradiation of TRY.

In this case as well, the monthly average irradiation from the TRY is lower compared to the year-by-year irradiation values, with the exception of the year 2014.

3.1.5. Internal loads and schedules

The internal loads are heat gains generated inside the building, and they refer, in general, to heat gains due to people, internal lighting and other electrical appliances.

The definition of these heat gains is very important since they can affect the total energy demand of the building.

The internal loads are defined in the Openstudio's tab "Loads", selecting the required section depending on the type of heat gain that must be implemented in the software.

For this case study, it was possible to implement realistic schedules for the occupants' behaviour, as the exact number of people living in the apartments was known.

This procedure was used for the Thermal Zones "Zona Giorno", while the occupancy of the Thermal Zones "Zone Notte" was set constant for each apartment. The number of people living in each apartment is than expressed in Table 13.

Apartment	Number of people
Apartment 1A	2
Apartment 1B	2
Apartment 2A	2
Apartment 2B	3
Apartment 3A	1
Apartment 3B	3

Table 13. Number of people living inside each apartment.

The number of people has been implemented considering specific values for the sensible heat fraction and radiant heat fraction. In particular, these values are respectively equal to 0.5 and 0.3.

For every occupancy schedule, the software requires also the activity rate of the people. This value expresses the total thermal power generated by the people and depends on the activity carried out by the people themselves. The activity rate considered is 120 W/person.

The occupancy schedules used are expressed in relative terms and reported below subdivided in each apartment. It means that the people inside the apartments, hour by hour, are equal to the product between the maximum number of people living in the apartment (Table 13) and the relative number expressed in the schedule (Table 14)

Hour of the day	Apartment 1A	Apartment 1B	Apartment 2A	Apartment 2B	Apartment 3A	Apartment 3B
1	1	1	1	1	1	1
2	1	1	1	1	1	1
3	1	1	1	1	1	1
4	1	1	1	1	1	1
5	1	1	1	1	1	1
6	1	1	1	1	1	1
7	1	0.5	0	0.3	1	0.6
8	1	0.5	0	0.3	1	0.6
9	1	0.5	0	0.3	1	0.6
10	1	0.5	0	0.3	1	0.6
11	1	0.5	0	0.3	1	0.6
12	1	0.5	0	0.3	1	0.6
13	1	0.5	0	0.3	1	0.6
14	1	0.5	0	0.3	1	0.6
15	1	0.5	0	0.3	1	0.6
16	1	0.5	0	0.3	1	0.6

17	1	0.5	0	0.3	1	0.6
18	1	0.5	0	0.6	1	0.6
19	1	1	1	0.6	1	1
20	1	1	1	1	1	1
21	1	1	1	1	1	1
22	1	1	1	1	1	1
23	1	1	1	1	1	1
24	1	1	1	1	1	1

Table 14. Occupancy's schedules for each apartment.

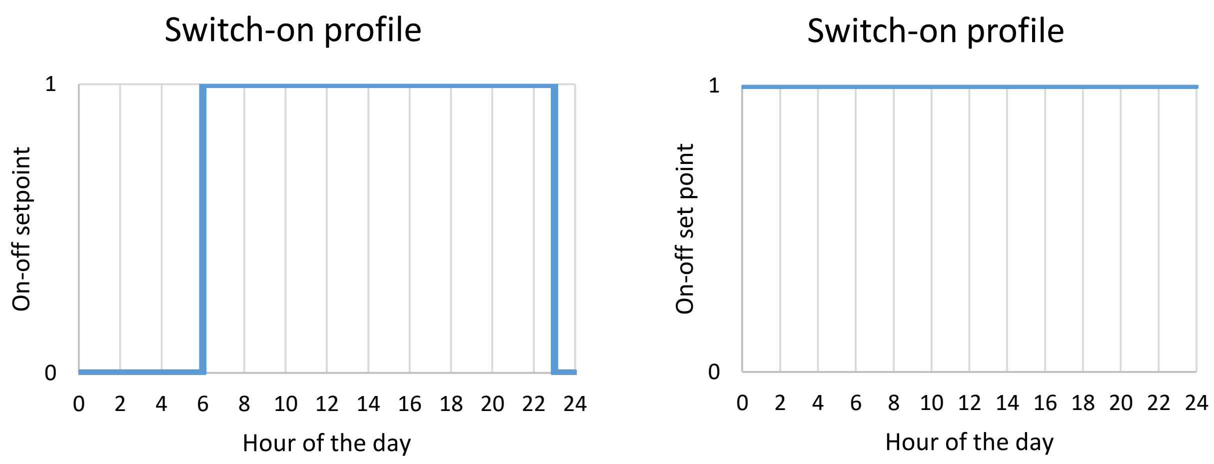
As mentioned at the beginning of this paragraph, also the electrical appliances and lighting are internal heat gains: to represent them it is necessary to repeat the same procedure performed for the people, considering the appropriate section in the software.

For this case, the electrical appliances and lighting have been considered as a unique internal heat gain.

The power associated to the appliances has been considered constant all over the day and equal to 150 W for the "Zona Giorno" and 100 W for the "Zona Notte". This is translated in 3.26 W/m^2 for the "Zona Giorno" and 2.65 W/m^2 for the "Zona Notte" as average between the floors.

Besides the internal load, in the section "Schedules" can be defined: the operation of the heating and cooling systems, the set point temperatures, infiltrations and natural ventilation, where present. As regards the operation of the air conditioning system, the following graphs describe the switch-on profiles for the winter and summer seasons.

Two distinctions need to be made: the pre-retrofit heating hours are not 14 but rather 16. Therefore, the heating schedules differ between the two scenarios.



Figures 17. Heating system on/off (left) and cooling system on/off (right).

the set point temperature for the winter season is 20 °C when turned on, while for the summer season it has been set to a constant temperature equal to 26 °C from 15/06 to 15/09.

The ventilation of the living areas is provided simply by opening the windows since the mechanical ventilation is not installed in this building. This action was implemented by creating an appropriate schedule which simulates the opening and closing of the windows.

The infiltrations were set to 0.3 ach for the apartments during the heating season. Different infiltrations have been considered for the months in between the heating and cooling period. In those periods, the infiltrations have been set equal to 1 ach. Infiltrations were considered also for the stairs and the garages because these Thermal Zones present windows or openings. The value for these Thermal Zones is different from the living areas, assumed 1 ach. The set point temperatures are then associated to each thermal zone in the tab “Thermal Zones”: it is necessary to check the box “Turn on ideal load” to calculate the energy need of the building neglecting the type of conditioning system installed.

3.1.6. Simulation’s settings and model validation

After having modified the settings as desired, the simulation can start. Later, it is necessary to validate it. This step is crucial because it allows for checking the accuracy of the results by comparing them with real data. The comparison was carried out by matching the simulation results with the actual data from the building, specifically focusing on the gas consumption during the 2019/2020 heating period.

In order to carry out this operation, it was necessary to use the modified EPW file properly created, in particular considering the data from the heating period 2019/2020. Subsequently, it was also necessary to adjust the simulation period in EnergyPlus to obtain the results needed for this assessment.

By checking the building’s consumption data, a gas consumption of 4080 Sm^3 was identified, equivalent to a total of 45165 kWh. This value was obtained by considering the methane’s high heating value of 11.07 kWh/Sm^3.

This energy and gas value refers to the so-called final energy, which is the energy associated with the quantity of gas entering the boiler. Therefore, it is necessary to determine this value for the simulation. To do this, the "Efficiency method" [16] is used, which assigns coefficients to the system components to trace back to the final energy starting from the energy value obtained from the simulation (net energy).

The overall efficiency is the product of four efficiencies:

- The emission losses efficiency;
- The distribution losses efficiency;
- The regulation efficiency;
- The generation losses efficiency.

$$\eta_{tot} = \eta_{em} * \eta_{dist} * \eta_{reg} * \eta_{gen} \tag{3.1}$$

By comparing the values associated with the system components, it was possible to assign a value to each factor in this Formula.

The efficiencies are: $\eta_{em} = 0.95$, $\eta_{dist} = 0.95$, $\eta_{reg} = 0.88$ and $\eta_{gen} = 0.9$, leading to an overall efficiency of $\eta_{tot} = 0.71$. Without the generation efficiency, the overall efficiency is equal to $\eta_{tot,nogen} = 0.79$.

3.2. RADIATORS: ANALYSIS OF THE THERMAL OUTPUT

The application of insulation on the building envelope allows for a reduction in the overall thermal demand. This reduction not only impacts the building's thermal requirements but also has a significant effect on the peak power required for heating. The decrease in both these factors enables the use of low-temperature heating technologies. Considering that the study focuses on retrofitting, it is essential to adapt the modifications to the existing components, especially the central heating and its related systems. The main purpose of the study is to evaluate, from an economic and environmental point of view, the replacement of the gas boiler with a heat pump system. Both the use of conventional heat pump and hybrid heat pump were analysed in this study. The distribution system using radiators in the apartments remains unchanged. Unlike the boiler, the heat pump is not capable of producing hot water at temperatures exceeding 50 °C. Therefore, it is necessary to verify whether the radiators can meet the peak power requirements for each apartment with a maximum temperature of 50°C. Conducting this analysis requires a thorough understanding of the types of radiators present in the apartments.

This preliminary analysis is necessary to verify if the installation of the heat pump is sufficient to fulfil the energy need of the building.

3.2.1. Radiators' characteristics

First, it's important to assess the type of radiators installed in the apartments. Access to the technical specifications of the radiators is necessary to easily identify their key characteristics. However, since the technical specifications were not available, it was necessary to gather information about the radiators' features, such as height, depth, material, number of columns, number of elements and shape in order to obtain their associated technical data sheet.

In Appendix B, Table 1B, all the radiators installed in each individual apartment are listed along with their respective characteristics.

With the specific model of the radiators it is possible to select the associated technical data sheet.

The obtaining of these data sheets is crucial for determining the thermal output of the radiators, important to verify the operation of the latter combined with the heat pump.

Inside them, there are the characteristic values of thermal output under standard conditions i.e.

$$T_{w,mean,radiator} - T_{air,environment} = 50\ K \quad (3.2)$$

accompanied by the characteristic coefficients of the radiator elements.

A high thermal output indicates that the radiator can effectively transfer heat to the surrounding environment, thereby contributing to space heating. Conversely, a low thermal output may indicate that the radiator cannot emit enough heat to adequately warm the environment, requiring a higher energy consumption to maintain a comfortable temperature.

The characteristic coefficients allow verifying the thermal output under conditions different from the standard ones, as is the case for this scenario, where the higher temperature has been set at 50°C.

Generally, in catalogues, the thermal output is expressed for a single element. Therefore, to find the overall thermal output of the radiator, it is necessary to multiply the output of one element by the number of elements that make up the radiator itself.

In particular, the equation of the thermal output of the radiator is

$$q_R = K_m\left(T_{w,average} - T_{air}\right)^n \quad (3.3)$$

Where:

- K_m is the radiator model's constant;
- $T_{w,average}$ is the average water temperature inside the radiator $(T_{w,in} + T_{w,out})/2$,
- T_{air} is the air temperature in the room;
- n is the radiator characteristic coefficient.

As mentioned earlier, this relationship refers to standard conditions, namely when the term inside the parentheses is equal to 50 K. This occurs when the average radiator water temperature is 70°C, achievable with a maximum production temperature of 80°C from the thermal power plant, with a return temperature of 60°C. However, since it's not possible to reach such temperatures with the heat pump with acceptable performances, it's necessary to recalculate the thermal output of the radiators. This is done by considering a temperature difference between supply and return of 10°C and, considering the supply temperature of 50 °C, this results in an average water temperature inside the radiator of 45°C. Subsequently, the formulation of the thermal output for off-design conditions is provided.

$$q_{actual} = q_{nominal}\left(\frac{T_{w,average} - T_{air}}{50}\right)^n \quad (3.4)$$

Where the number 50 in the denominator represents the standard difference between $T_{w,average} - T_{air}$, difference used in the catalogue to calculate the standard thermal output $q_{nominal}$.

Once the thermal output per element is obtained, it is sufficient to multiply this value by the number of elements to obtain the overall thermal output, necessary to evaluate the proper operation of the heat pump. The characteristic coefficient of every single radiator is expressed in the Appendix B, including also the thermal output per element in design and off-design conditions (Table 2B, Table 3B).

3.3. HEAT PUMP SIMULATION

In the context of this case study, the considered technology involves the use of air-to-water heat pumps, deemed more suitable for this scenario as they do not require extensive modifications to the building's terminal units and distribution system. However, the application of this technology proves to be more complex compared to the use of boilers. This is because the performance of the heat pump is strongly dependent on the external temperature and the temperature of the heating water production. Given this significant dependency, it is necessary to apply models to verify the operation of the heat pump in relation to these factors. This study allows for adjustments to be made to the operation of the heat pump to optimize its performance.

3.3.1. Mathematical model

The base concept of the method, the "Equation-fit model," is built upon catalogue data interpolation to find coefficients to apply to the simulation's data, in order to derive, eventually, the thermal power and the COP. It requires minimal computational time and is well-suited for cases where there is not a high quantity of additional data beyond the catalogue data.

Indeed, this type of function allows for optimal interpolation of catalogue data even when they are noisy, minimizing errors between the function itself and the catalogue data: in this work, the generalized least square method was used for this purpose [17], according to the methodology proposed in Bordignon et al. [].

It doesn't necessarily require a polynomial form, but it demands a linear combination of the functions, in particular:

- n functions
- m data points

$$y = c_1 f_1(x) + c_2 f_2(x) + c_3 f_3(x) + \cdots + c_n f_n(x) \tag{3.5}$$

Where x are the input catalogue data, $f_i(x)$ represents the combination of the different input catalogue data used for the interpolation and **F** is the matrix including all the functions $f_i(x)$ and $\boldsymbol{y}$ represents the known value from the catalogue.

3.3.2. Choice of the heat pump and model application

Before proceeding with the calculation, there is a need to define the heat pump. Given the wide variety of heat pump manufacturers, the research has been based exclusively on the thermal power it can develop and the data provided by the catalogue. Regarding the power of the heat pump, it must be close to the final peak power, namely 21.35 kW, under the design conditions for the climatic zone, i.e., at -6.8 °C external

temperature and 50 °C water temperature production. The choice fell on the manufacturer Galletti, which provides various data even under different load conditions. The model chosen is the MDI DC 29 H (Unit 29 later on), which has a rated power equal to 33.8 kW (external air 7°C, water production 40-45 °C).
As can be noticed, the thermal power of the heat pump is much higher than the power required by the building. This is because a heat pump was chosen to meet the building's demand at the design temperature, namely -6.8 °C. By analysing the catalogue of this heat pump, it was found that it delivers 25.6 kW with an external temperature of -5 °C. A preliminary interpolation was used to verify the feasibility to fulfil this power under the required temperature: confirmed this feasibility, this heat pump was chosen.
At this stage, there is a need to choose which values to consider in matrix **F**. The selection of these values depends on the availability of data resulting from the simulation, namely the external temperature and hourly thermal demand. As a first attempt, it was decided to opt for a constant production of hot water at 50 °C, allowing the setting of a variable useful for the model.
Firstly, there is a need to verify the thermal power that the heat pump can deliver in relation to external conditions and water production temperature.
Regarding the Unit 29 heat pump, the thermal power it must generate has been set equal to the building's thermal demand. This assumption is possible because the maximum thermal power it can generate at the worst condition, i.e., the lowest external temperature, is equal to the building's demand. Therefore, the model application is not required for this point of the analysis.
The following steps are provided for a better understanding.

MPI DC 029 H	**Dati nominali a frequenza massima**											
	25	30	27,20	9,73	29,60	9,67	34,90	9,62	36,90	9,60	46,50	9,51
	30	35	26,40	10,22	29,80	10,32	34,40	10,36	40,70	12,87	45,90	10,43
	35	40	26,00	10,97	29,40	11,07	33,90	11,27	41,70	11,37	45,30	11,47
	40	45	25,60	11,87	29,00	12,07	33,40	12,27	40,70	12,87	44,40	12,57
	45	50	25,60	13,07	28,80	13,27	33,00	13,47	40,20	13,67	43,80	13,77
MPI DC 029 H	**Dati nominali a frequenza intermedia**											
	25	30	16,80	5,62	18,70	5,58	22,20	5,52	26,90	5,45	29,70	5,41
	30	35	16,30	5,89	18,30	5,92	21,80	5,93	26,50	5,91	29,10	5,90
	35	40	15,90	6,28	17,90	6,35	21,40	6,42	25,90	6,45	28,50	6,45
	40	45	15,50	6,77	17,60	6,86	21,00	6,96	25,30	7,03	27,80	7,05
	45	50	15,30	7,37	17,30	7,47	20,60	7,59	24,80	7,68	27,30	7,72
MPI DC 029 H	**Dati nominali a frequenza minima**											
	25	30	4,72	2,40	5,33	2,38	6,39	2,34	7,75	2,30	9,02	2,27
	30	35	4,60	2,48	5,21	2,48	6,25	2,47	7,60	2,44	8,32	2,94
	35	40	4,49	2,59	5,11	2,60	6,12	2,61	7,46	2,60	8,19	3,04
	40	45	4,40	2,74	5,01	2,75	6,00	2,77	7,29	2,77	8,06	3,15
	45	50	4,33	2,91	4,93	2,93	5,89	2,95	7,12	2,96	7,93	3,26

Table 15. Example of the catalogue data. [18]

As previously stated, this manufacturer provides data for various operating conditions, particularly concerning the rotation frequency of the compressor. Analysing the catalogue, the compressor's operating range is specified: from 110 Hz to 30 Hz. Therefore, these two values have been associated with the labels "Nominal data at maximum frequency" and "Nominal data at minimum frequency." Regarding "Nominal data at intermediate frequency," a frequency of 70 Hz was chosen, equivalent to the average of the two limit frequencies.

For the COP calculation, specifically, the decision was made to incorporate the external temperature along with the thermal power generated by the heat pump and its nominal value.

In particular, for the COP case the vector **x** is composed of different columns characterized by intrinsic values. These values are:

- 1: column composed of ones;
- T_{air}: external air temperature;
- $T_{w,out}$: outlet water temperature;
- P_t: thermal power generated by the heat pump;
- $P_{t,N}$: rated thermal power.

Once this vector is defined, it is possible to define the matrix **F** containing combinations of the values within vector **x**, specifically:

$$F_{COP} = \left[1_i;\ T_{air,i};\ T_{w,out,i} - t_{air,i};\ \left(T_{w,out} - t_{air}\right)_i^{\ 2};\ \left(\frac{P_t}{P_{t,N}}\right)_i^2;\left(\frac{P_t}{P_{t,N}}\right)_i \right] \quad (3.6)$$

In particular:

$$\frac{P_t}{P_{t,N}} \quad (3.7)$$

- P_t represents the thermal power supplied by the heat pump (column PT in Table 6)
- $P_{t,N}$ represents the nominal thermal power of the heat pump, 33.8 kW.

Moreover,

$$T_{w.out} - T_{air} \quad (3.8)$$

Obtaining:

$$y = c_1 \cdot 1 + c_2 \cdot T_{air} + c_3 \cdot \left(T_{w,out} - T_{air}\right) + c_4 \cdot \left(T_{w,out} - T_{air}\right)^2 + c_5 \cdot \left(\frac{P_t}{P_{t,N}}\right)^2 + c_6 \cdot \frac{P_t}{P_{t,N}} \quad (3.9$$

Represents the difference between the outlet water temperature and the external air temperature.

The vector **y** is composed by the catalogue COP values.

Following the steps of the generalized least square method, it was possible to calculate the vector **c** containing the various numerical values of the model coefficients, resulting in

$$y_{COP} = 4.33 \cdot 1 + 0.0052 \cdot T_{air} - 0.108 \cdot \left(T_{w,out} - T_{air}\right) + 0.00083 \cdot \left(T_{w,out} - T_{air}\right)^2 + \\ -1.956 \cdot \left(\frac{P_t}{P_{t,N}}\right)^2 + 3.446 \cdot \frac{P_t}{P_{t,N}} \quad (3.10)$$

3.3.3. Model's accuracy

Before applying the model to the real case, it is necessary to verify the results of the model against catalog data. To do so, the thermal power and COP values obtained from the model are compared with catalogue values, checking the root mean square error, relative error, and the graphical trend of them.
The root mean square error is expressed as:

$$RMSE = 100 \cdot \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{y_{c,i} - y_{m,i}}{y_{c,i}}\right)^2} \quad (3.11)$$

In particular:

- N represent the number of the row for the matrix **F**
- y_c represents the catalogue COP value,
- y_m represents the model COP value.

The relative error is equal to

$$err_{rel} = \frac{y_c - y_m}{y_c} \quad (3.12)$$

And it is calculated for each row of the matrix **F.**
For a better understanding of the error, the COP obtained from the model is compared with the catalogue COP. In the graph the yellow line represents the catalogue value, the blue lines indicate the COP error range of +10% and -10%.

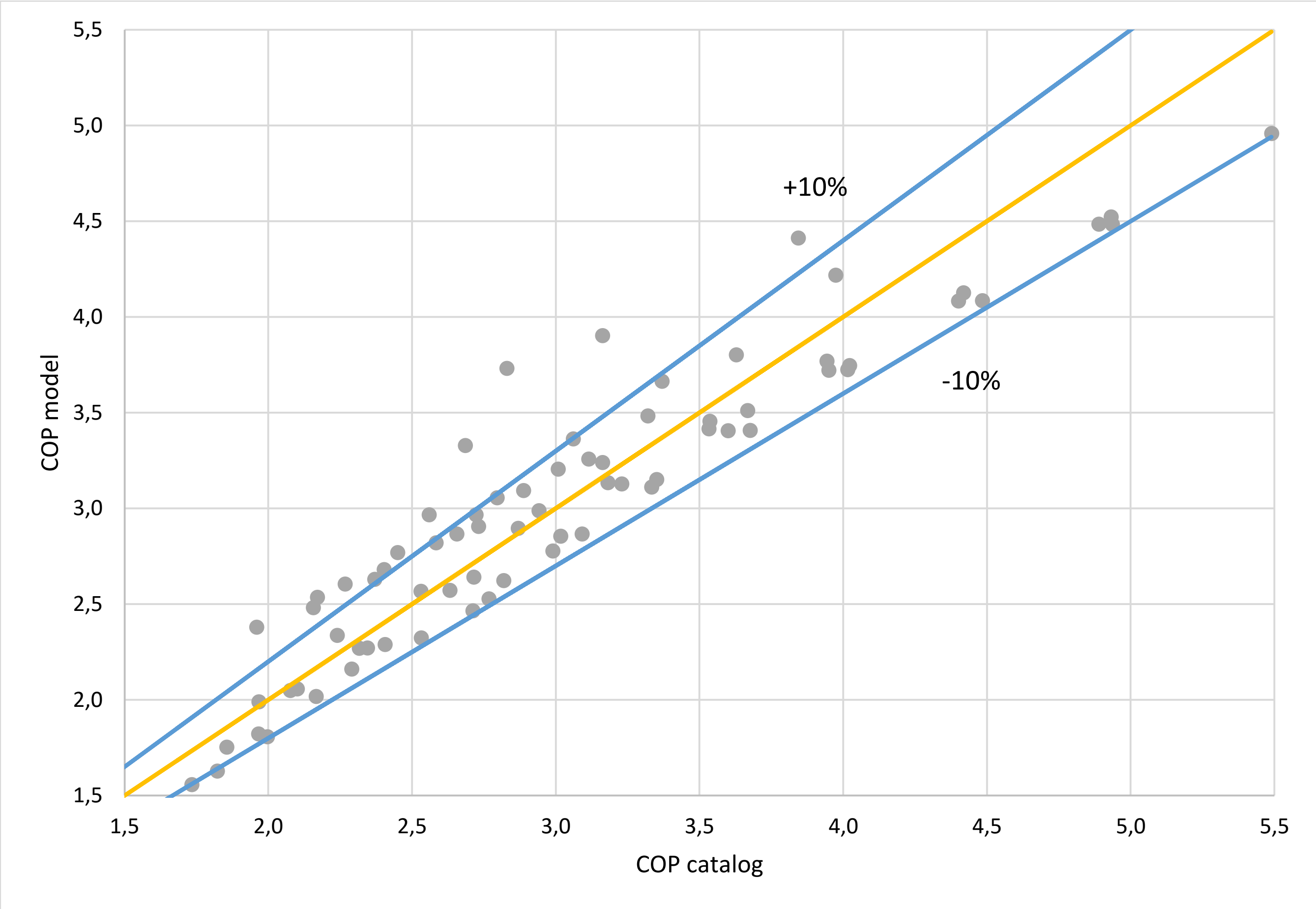


Figure 18. Relative error for the COP model of Unit 29.

The RMSE related to this model is equal to 9.8%.

As can be observed from the graph, there are some values that fall outside the 10% threshold. However, given the limited amount of data, the obtained result is considered acceptable.

3.3.4. Weather compensated curve and hybrid systems

Considering the trend of energy prices over the past few years, it was decided to analyse hybrid solutions to reduce the installed electrical power and to increase the overall performances of the heat pump.A hybrid heat pump system combines the use of a heat pump with other heating or cooling technologies to optimize energy efficiency under different operating conditions. Typically, the hybrid system may involve a heat pump coupled with a traditional heating system, such as a gas boiler or a fossil fuel-based heating system. The heat pump operates efficiently at moderate temperatures, while the traditional heating system can come into play when weather conditions are extreme or when there is high energy demand. This hybrid approach aims to maximize the overall system efficiency and reduce energy costs by adapting to variations in weather conditions and thermal loadTo increase the efficiency of the energy system, is it possible to modulate the compressor rotation speed through frequency variation (variable-speed heat pumps), as well as to modulate the water supply temperature at the load side. Specifically, temperature variation is implemented to best match the building's thermal requirements. Therefore, when the building's thermal demand is low, the outlet temperature needs to be lower.

This operation is achievable by applying the so-called weather compensated curve, which allows adjusting the hot water production temperature based on the external temperature. Given the presence of radiators in the apartments, it is necessary to maintain a relatively high-water temperature. Specifically, it has been decided to have hot water production at 50 °C for external temperatures below 0 °C and a water temperature of 40 °C for external temperatures above 10 °C. In between, the water temperature varies linearly.

This relation is then applied in the appropriate column and subsequently processed by the model to find the COP of the heat pump.

Subsequently, it was decided to study the influence of the cut-off [19] on the plant.

The cut-off in hybrid systems represents a relevant control strategy, crucial for the optimal operation of heating systems composed of multiple heat sources, such as this case study. This strategy is adopted to regulate the activation or deactivation of specific system components in response to environmental conditions and the thermal demands of the building.

In the context of hybrid heating systems, the cut-off assumes particular significance as it allows for the optimization of overall energy efficiency and reduction of consumption. In practice, this means that in certain situations, such as when outdoor conditions are mild and the heat pump can efficiently meet the building's thermal demand, it is possible to deactivate the boiler or put it on standby. This way, the use of an auxiliary heat source, which may be less efficient or more expensive, is avoided when not strictly necessary.

3.3.5 Underfloor heating system

In addition to the analysis described previously, the use of a heat pump combined with an underfloor heating system was analysed. Radiant floor systems allow to lower the supply water temperature, leading to higher heat pump performance compared to traditional radiators. Indeed, the lower the outlet water temperature, the higher the SCOP. The method of applying the model remains unchanged; what changes is the value of the produced water temperature, which has been set at a constant 35°C throughout the heating period. The energy system has been coupled with a low-thickness underfloor heating system, which is particularly suitable for retrofit projects. This analysis allowed to evaluate the performance of the heat pump coupled with low-temperature terminal units.

3.4. HEAT PUMP FOR THE DOMESTIC HOT WATER

After evaluating the operation of the heat pump for heating, it was decided to apply the same technology to produce the domestic hot water (DHW). The heat pump is used both to produce domestic hot water and to produce heat for space heating. Currently, for the DHW, gas boilers are installed for each individual apartment, providing hot water instantly when requested. In general, the heat pump for DHW production is coupled to a thermal storage. The study conducted in this paragraph focuses on the sizing of the heat pump power as well as the sizing of the storage tank required to meet the demand for domestic hot water for the entire condominium. This analysis was made possible thanks to the use of an Excel spreadsheet appropriately modified and provided by Aicarr [20].

The method proposed by the Aicarr spreadsheet appears to be different from the UNI 9182 [21] standard simply because it is more dynamic, allowing control with different consumption profiles. The results are more precise.

This study focuses exclusively on the production of domestic hot water since the space heating has already been conducted in the previous sections. It is noteworthy that the heat pump always prioritizes the production of hot water when requested. In fact, during the heating of the building, it directs all power to the production of DHW, reducing the power used for heating the building. Therefore, it is necessary to include this consideration in the sizing of the heat pump.

The heat pump, along with its storage tank, is sized to provide the maximum flow rate of domestic hot water for a specific period. Typically, the maximum water flow is required during shower usage, so this parameter has been chosen for sizing the maximum flow rate that needs to be met. Since it's a building with six residential units, the entire overall demand must be considered. The nominal flow rate per unit used for sizing is 20 litres per minute. For this sizing, it's necessary to consider the so-called "simultaneity factor," which indicates how many devices are being used simultaneously. This value is defined based on the number of residential units (n°6) and the water flow rate required. This Table is always provided within the Excel spreadsheet, and considering the data from the case study, a simultaneity factor of 50% is obtained.

NUMBER OF BATHROOM FACILITIES	SUGGESTED PERCENTAGE OF SIMULTANEITY BASED ON THE MAXIMUM WATER FLOW RATE FOR THE BATHROOM FACILITIES												
	8 [liters/minute]	9 [liters/minute]	10 [liters/minute]	11 [liters/minute]	12 [liters/minute]	13 [liters/minute]	14 [liters/minute]	15 [liters/minute]	16 [liters/minute]	17 [liters/minute]	18 [liters/minute]	19 [liters/minute]	20 or more [liters/minute]
1	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
2	100%	100%	100%	100%	100%	100%	99%	92%	87%	82%	77%	73%	69%
3	100%	100%	100%	100%	100%	94%	88%	82%	77%	72%	68%	65%	61%
4	100%	100%	100%	100%	94%	86%	80%	75%	70%	66%	62%	59%	56%
5	100%	100%	100%	95%	87%	81%	75%	70%	66%	62%	58%	55%	52%
6	100%	100%	99%	90%	83%	76%	71%	66%	62%	58%	55%	52%	50%
7	100%	100%	95%	86%	79%	73%	68%	63%	59%	56%	53%	50%	47%
8	100%	100%	91%	83%	76%	70%	65%	61%	57%	53%	51%	48%	45%
9	100%	97%	88%	80%	73%	67%	63%	58%	55%	52%	49%	46%	44%
10	100%	94%	85%	77%	71%	65%	61%	57%	53%	50%	47%	45%	42%
15	94%	83%	75%	68%	63%	58%	54%	50%	47%	44%	42%	40%	38%
20	86%	76%	69%	63%	57%	53%	49%	46%	43%	40%	38%	36%	34%
30	76%	68%	61%	55%	51%	47%	43%	41%	38%	36%	34%	32%	30%
40	70%	62%	56%	51%	46%	43%	40%	37%	35%	33%	31%	29%	28%
50	65%	58%	52%	47%	43%	40%	37%	35%	33%	31%	29%	27%	26%
60	62%	55%	49%	45%	41%	38%	35%	33%	31%	29%	27%	26%	25%
80	56%	50%	45%	41%	38%	35%	32%	30%	28%	27%	25%	24%	23%
100	53%	47%	42%	38%	35%	32%	30%	28%	26%	25%	23%	22%	21%
120	50%	44%	40%	36%	33%	31%	29%	27%	25%	23%	22%	21%	20%
140	48%	42%	38%	35%	32%	29%	27%	25%	24%	22%	21%	20%	19%
160	46%	41%	37%	33%	30%	28%	26%	24%	23%	22%	20%	19%	18%
180	44%	39%	35%	32%	29%	27%	25%	24%	22%	21%	20%	19%	18%
200 or more	43%	38%	34%	31%	28%	26%	24%	23%	21%	20%	19%	18%	17%

Table 16. Simultaneity factor taken from the Aicarr Excel spreadsheet.

The outlet temperature of the utilities is set at 48 °C and must never drop below 45 °C. Additionally, a maximum recharge time for the storage tank is set to one hour at most.

Once these basic parameters have been established, the sizing of the storage tank and the maximum power of the heat pump can be performed. To this end, two sizings have been carried out, considering two different configurations of the system. In the first case, the production system with storage tank placed on the domestic hot water circuit has been considered: this system has the advantage of optimizing the effect of the storage tank and minimizing the power of the heat exchanger. However, it requires greater attention to control Legionella, as domestic hot water accumulates in the tank.

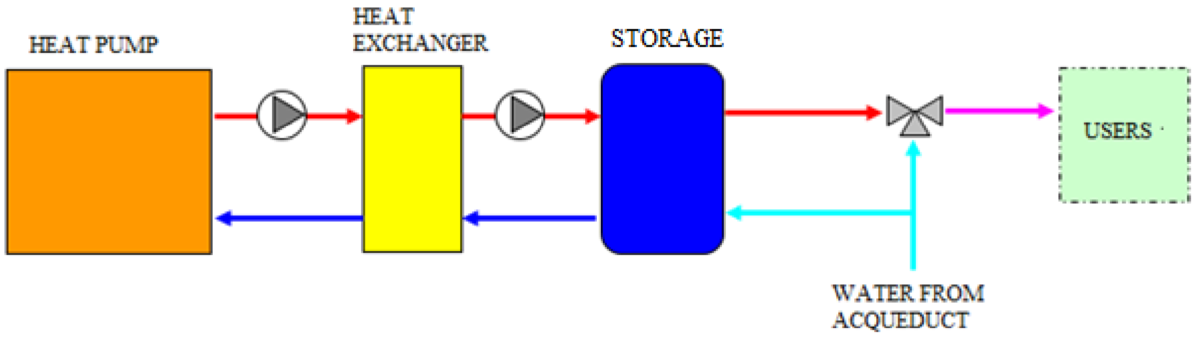


Figure 19. First configuration scheme: storage tank placed on the DHW circuit.

The prevention of legionella in domestic hot water tanks is essential to ensure a safe environment for users. One of the first preventive measures is to keep the water at high temperatures, generally above 50°C, as legionella thrives in warmer environments. For this reason, hot cycles are also important to regularly clean and disinfect the systems to remove any accumulations of sediments or bacteria, including legionella itself.

To avoid water stagnation, it is advisable to regularly flush the water systems. Furthermore, it is crucial to monitor and maintain the systems in good condition, identifying and promptly resolving any issues such as leaks or sediment accumulations that could promote legionella growth [22].

Some situations may require the use of water treatment devices, such as filters or disinfection systems, to further reduce the risk of contamination.

Therefore, despite the reduced power and storage capacity required to meet the demand for domestic hot water, there is a need to implement many precautions to avoid problems for users. This solution may involve lower initial investment costs, but if not properly treated, it could pose a potential health risk to users.

The second configuration involves producing DHW with storage located on the primary circuit. This system has the advantage of not requiring special legionellosis controls because there is no accumulation of domestic hot water. On the other side, under similar conditions to the previous configuration, it requires a higher-powered heat exchanger and a larger storage volume.

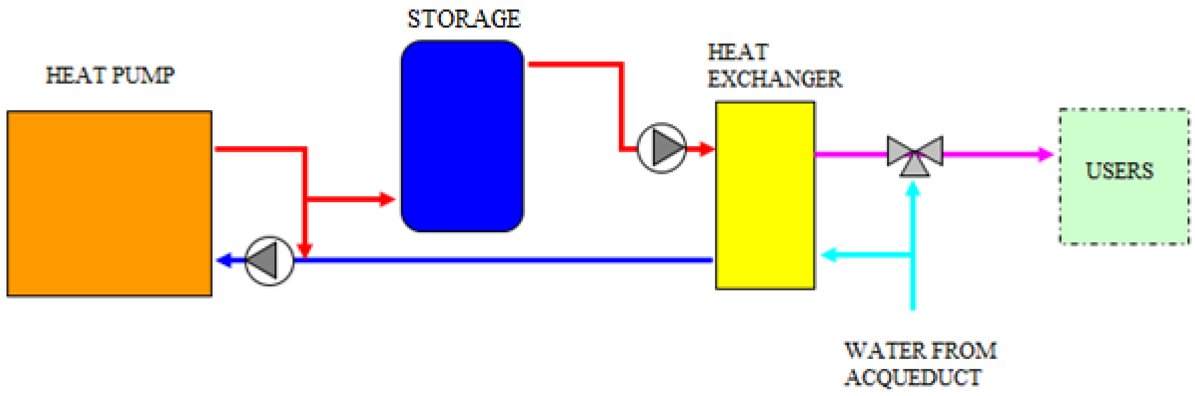


Figure 20. Second configuration scheme: storage tank placed on primary circuit.

As can also be seen from the scheme in Figure 19, the water contained in the tank is the technical water produced by the heat pump. The domestic hot water intended for users, on the other hand, is generated as needed through heat exchange with the technical water. Therefore, the domestic hot water does not stagnate in any tank, thus avoiding the need to treat it to prevent or eliminate the risk of legionella.

3.5. SCENARIOS

Once the operating conditions have been established and the proper operation of the heat pumps has been verified in various configurations, it is essential to also evaluate the economic aspects to determine which configuration is best suited for the case study. In addition to the economic analysis based solely on energy cost, other factors have been considered, such as carbon dioxide emissions and primary energy, over the course of the 10-year simulation.

In addition to this evaluation, two other analyses were conducted using energy prices from two specific years as reference points: 2018 and 2022. These two years were selected for their notable features in the sphere of economic analysis.

2018 represents a typical year with stable energy prices, which was considered as a reference point for a normal situation not influenced by significant global events. In contrast, 2022 shows very high energy prices due to the energy crisis.

In summary, 2018 was selected as an optimistic scenario, while 2022 was chosen as a pessimistic scenario regarding energy prices from the end user’s point of view.

The data used for this analysis were obtained from the ARERA website [23], stored in the dedicated data collection section.

	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Electricity price [euro/kWh]	0.19	0.19	0.19	0.19	0.19	0.21	0.21	0.19	0.25	0.56

Table 17. Electricity price year by year.

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Gas price [euro/Sm^3]	0.90	0.84	0.81	0.74	0.74	0.80	0.79	0.71	0.84	1.30

Table 18. Gas price year by year.

3.6. KEY PERFORMANCE INDICATORS

As anticipated in the previous paragraph, the analysis conducted on these configurations to select the best one includes the study of additional indicators beyond the economic energy savings. These indicators encompass carbon dioxide emissions, primary energy usage, and the percentage of renewable energy utilized. Identifying the proportion of renewable energy is significant given the global trend towards complete electrification and, consequently, towards a more sustainable world driven by "green" technologies. These indicators are calculated from the final energy, which equals the electricity consumption for heat pumps and the energy input into the boiler for configurations based solely on the boiler. . For the latter, the final energy is expressed as the net energy obtained from the simulation divided by the overall plant efficiency (Formula 3.1). Concerning the hybrid configuration, the final energy is calculated summing the two components of final energy, associated to the heat pump and to the boiler described so far. From here, it is possible to calculate the primary energy using coefficients provided by UNI/TS 11300 [24] based on the energy vector utilized.

	$f_{n,ren}$	f_{ren}	f_{tot}
Electrical energy	1.95	0.47	2.42
Natural gas	1.05	0	1.05

Table 19. UNI/TS 11300 coefficient for the calculation of the primary energy.

Where:

- $f_{n,ren}$: coefficient representing the non-renewable component of the energy vector in terms of primary energy
- f_{ren}: coefficient representing the renewable component of the energy vector in terms of primary energy
- f_{tot}: sum of the two previous components

Making explicit:

$$E_{primary} = E_{final} * f_{tot} = E_{final} * (f_{n,ren} + f_{ren}) \quad (3.13)$$

As can be seen in the Table below, the regulations directly provide the factor necessary for calculating the renewable component. It is worth noting that natural gas has a value of f_ren= 0 since it is not a renewable energy vector.

The carbon dioxide emissions are also calculated from the final energy, again using specific coefficients. Regarding electric energy, the coefficient utilized is based on the ISPRA report [25] for the year 2021. For the carbon dioxide emissions, the coefficient used is the standard emission factor from IPCC 2006 [26].

Type	**Standard emission factor, c_{em} [t CO_2/MWh]**
Electrical energy	0.260
Natural gas	0.202

Table 20. Standard emission factor for electrical energy and natural gas.

As an example:

$$CO_2\ emissions = final\ energy \cdot c_{em} \tag{3.14}$$

CHAPTER 4

RESULTS

In this section, the results related to the analyses considered in the previous chapter will be presented. In particular, in the heat pump section, the modification made to the model to apply it to smaller-sized heat pumps will be discussed.

4.1.1. Results pre-retrofit

The results used for the comparison are based on the 10-year EPW. The outcomes of the simulation are illustrated in the subsequent graphs.

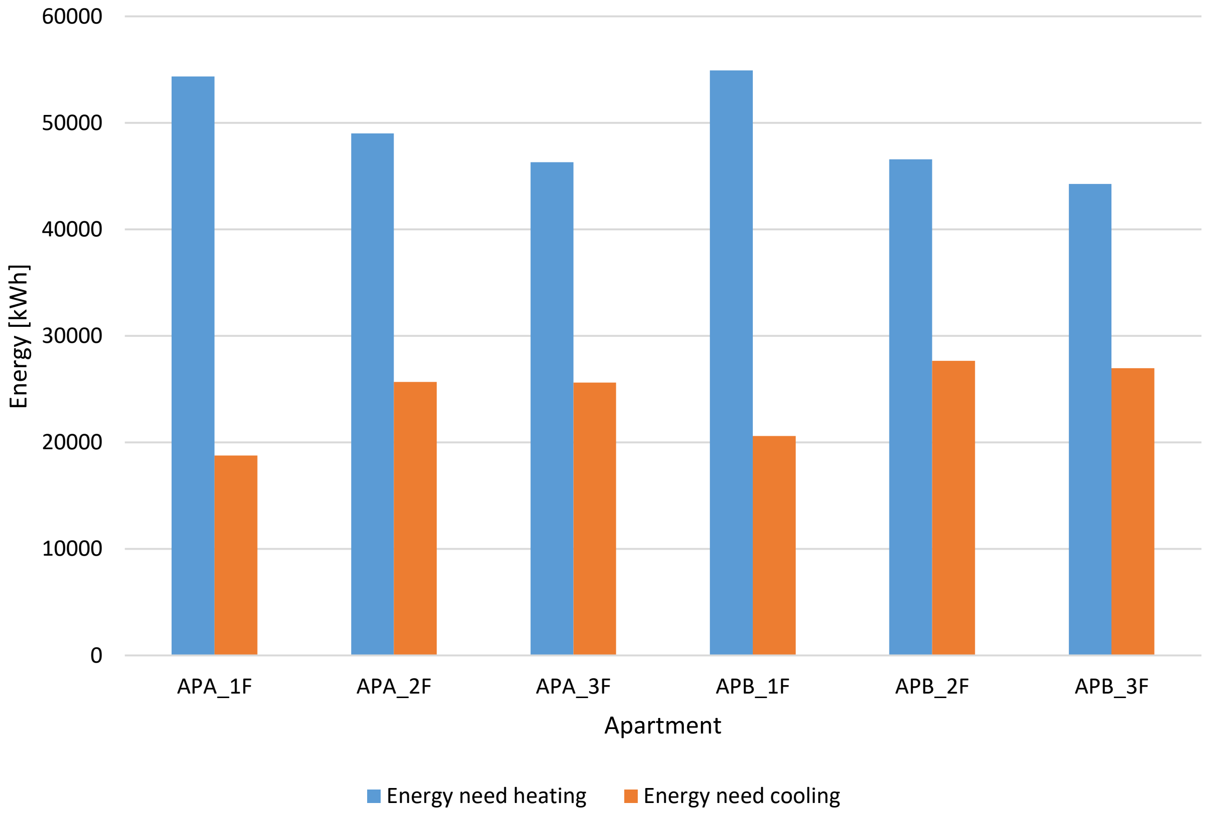


Figure 21. Energy needs of the apartments pre-retrofit from simulation based on the 10-year simulation.

In addition to the energy requirements of each apartment, the peak thermal power for each apartment was also analysed. The results are presented in the following graph.

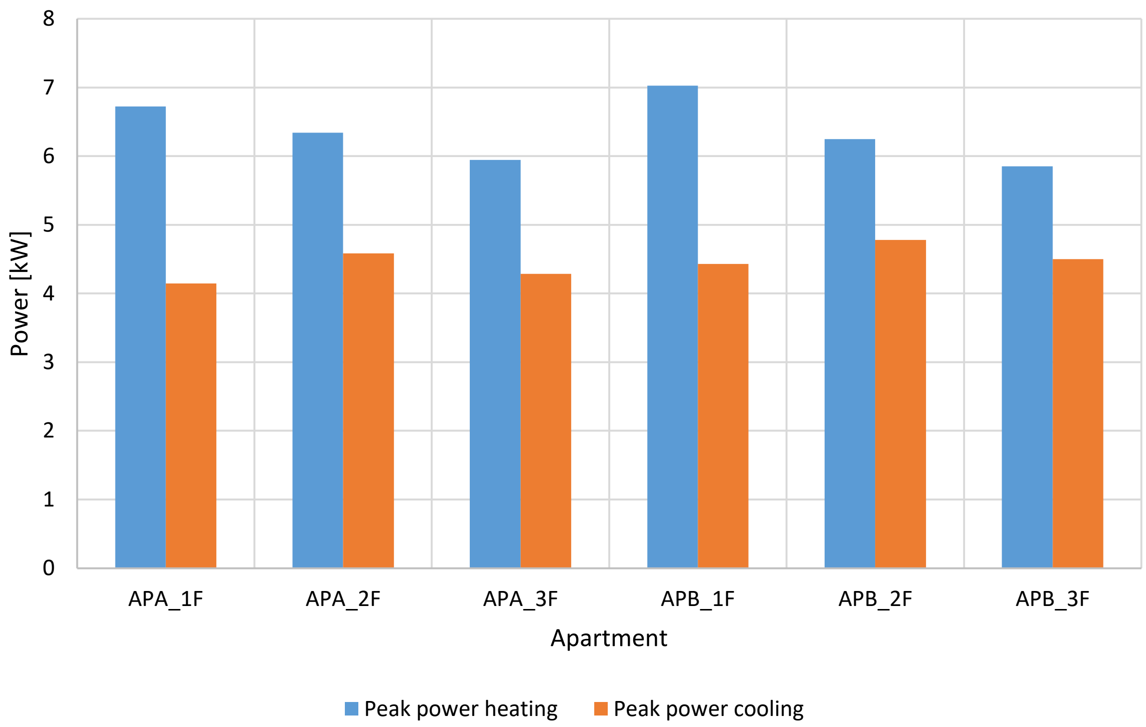


Figure 22. Peak power of the apartments pre-retrofit from simulation based on the 10-year simulation.

These results were processed by summing the power or energy components for each thermal zone of the individual apartment. What is most crucial for the design of the condominium's heating system is the determination of the peak thermal power required by the condominium itself. Determining this value is possible by analysing the thermal power needed by the condominium on an hourly basis: the final peak power results in 53.36 kW.

The final peak power is the peak power that must be produced by the heat generator, which is the peak power obtained by the simulation divided by the overall efficiency (Formula 3.1).

Later, the same results are presented in tabular form for a better understanding of the numerical values.

	Energy heating [kWh]	Energy Cooling [kWh]	Peak power heating [kW]	Peak power cooling [kW]
APA_1F	54355	18765	6.73	4.15
APA_2F	49005	25679	6.34	4.59
APA_3F	46321	25610	5.95	4.29
APB_1F	54946	20598	7.03	4.43
APB_2F	46596	27651	6.25	4.78
APB_3F	44259	26981	5.85	4.50
Total	295481	145285		

Table 21. Peak power and energy need per apartment diversified in heating and cooling along the 10-year simulation.

Table 22 shows the specific heating demand for each apartment. Since this analysis focuses exclusively on heating system replacement, the specific cooling value is omitted. With a 10-year climatic file available, it is possible to evaluate this value year by year, obtaining an average value for the 10 years. The value reported in the following Table is the average value over the 10 years.

	Net surface [m^2]	Specific primary heating energy [$kWh/(m^2*year)$]
APA_1F	83.04	100.49
APA_2F	83.04	89.76
APA_3F	75.43	85.72
APB_1F	83.33	99.56
APB_2F	83.33	85.37
APB_3F	74.58	82.04

Table 22. Specific primary heating energy per apartment.

The specific primary energy has been calculated considering the coefficient in Table 19.

Subsequently, a more in-depth analysis was conducted on the temperatures within the various rooms. This detailed analysis proves to be very useful because, determining the temperatures within the different rooms, translates into an assessment of thermal comfort. Specifically, for insulated buildings, the operative temperature tends to be generally higher, fluctuating around the set point condition. On the other hand, for non-insulated buildings, the operative temperature varies more widely, deviating significantly from the set point conditions.

The analysis was carried out on each floor, with the selection of a reference room for each level. Additionally, attention was given to monitoring temperatures in the garages, a choice that indirectly reflects the effectiveness of insulation.

For simplicity, only the graphs referring to the "Zona Giorno" will be reported.

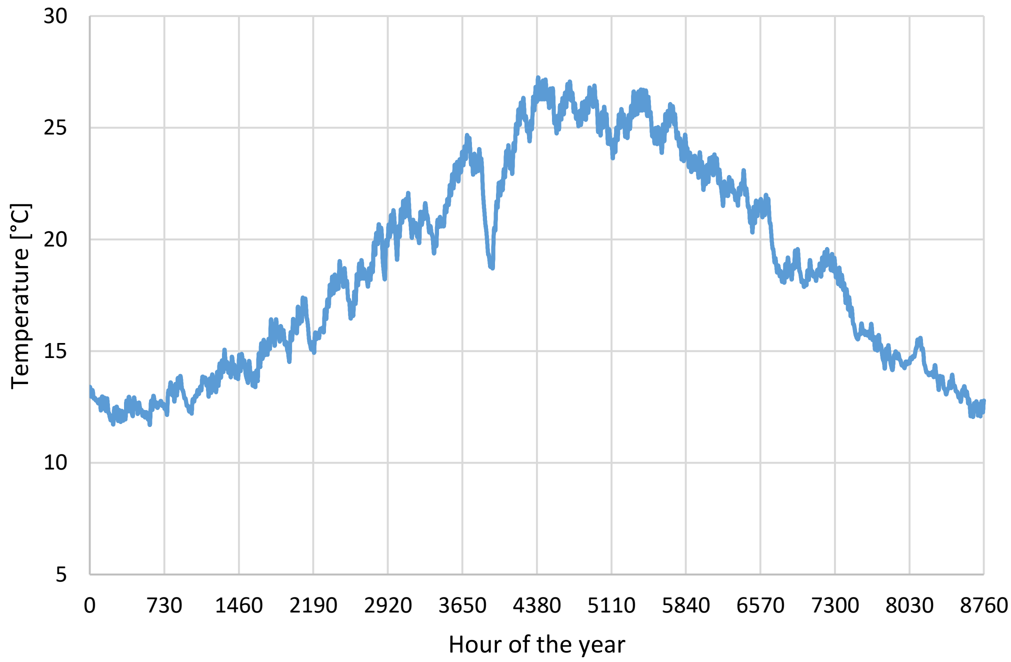


Figure 23. Operative temperature trend of the thermal zone Garage along the TRY.

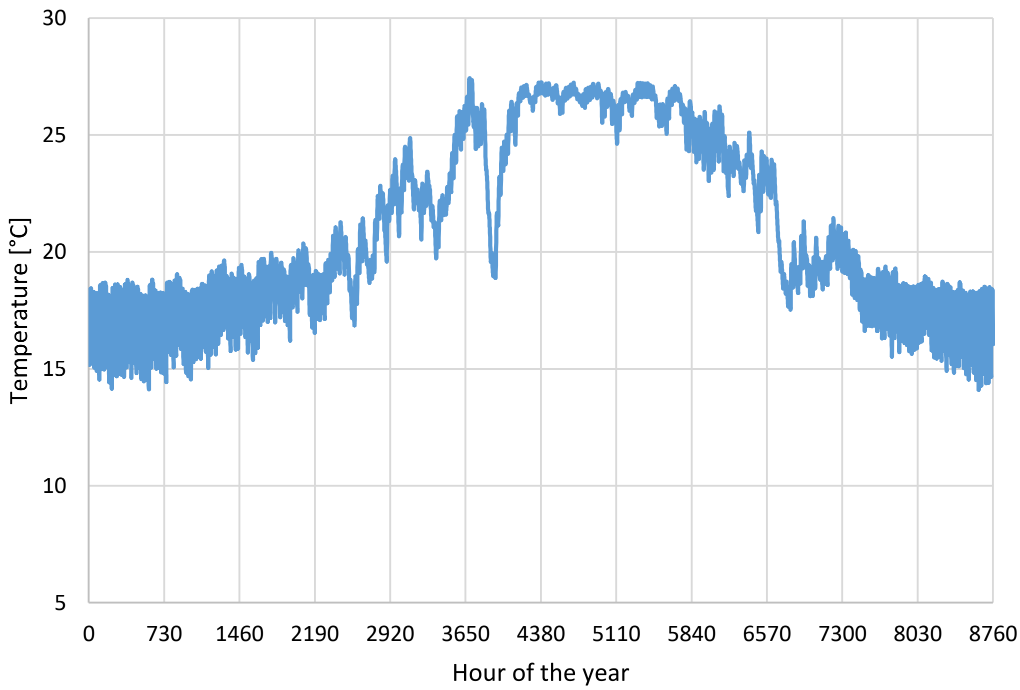


Figure 24. Operative temperature trend of the thermal zone ZG_APA_1F along the TRY.

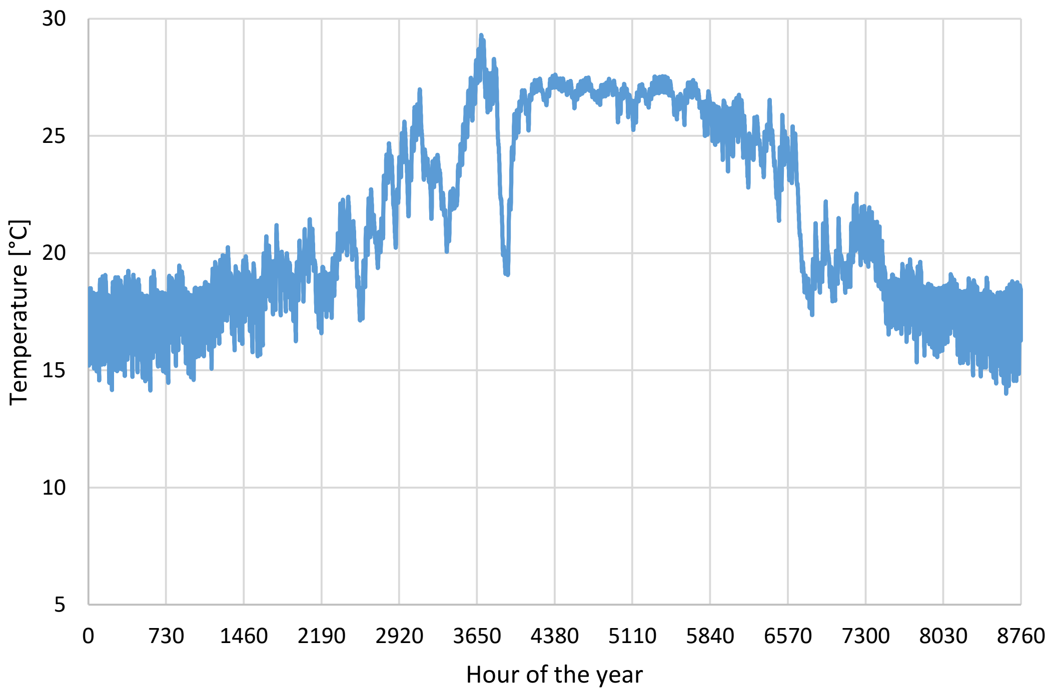


Figure 25. Operative temperature trend of the thermal zone ZG_APB_2F along the TRY.

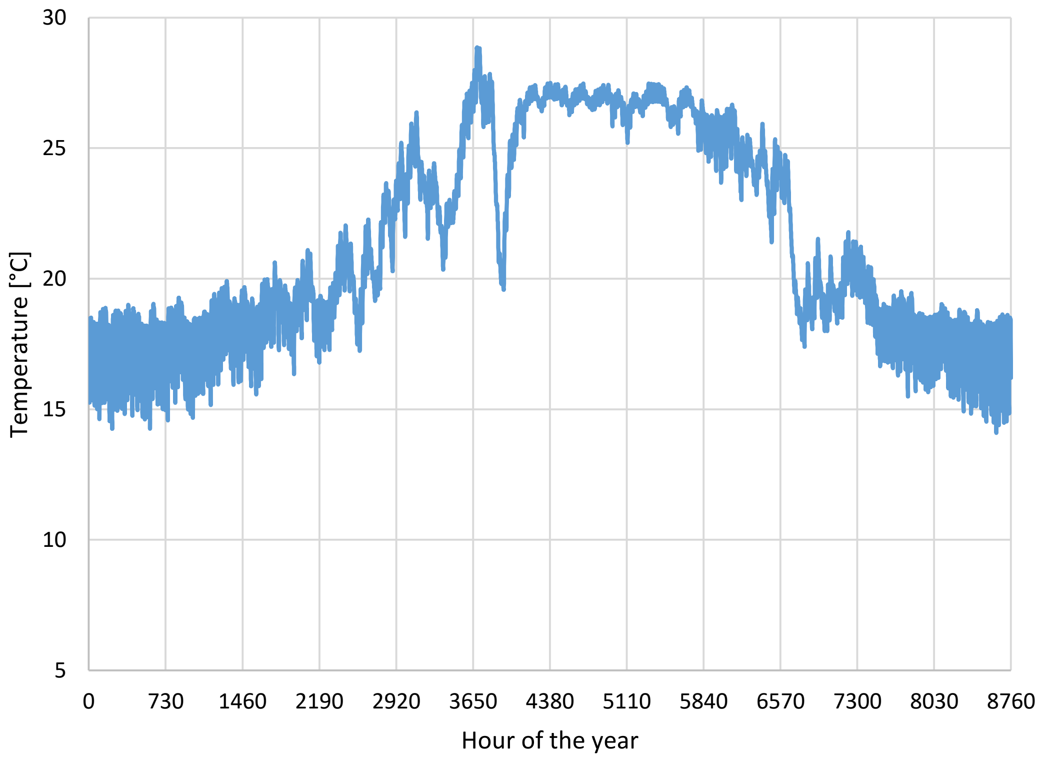


Figure 26. Operative temperature trend of the thermal zone ZG_APA_3F along the TRY.

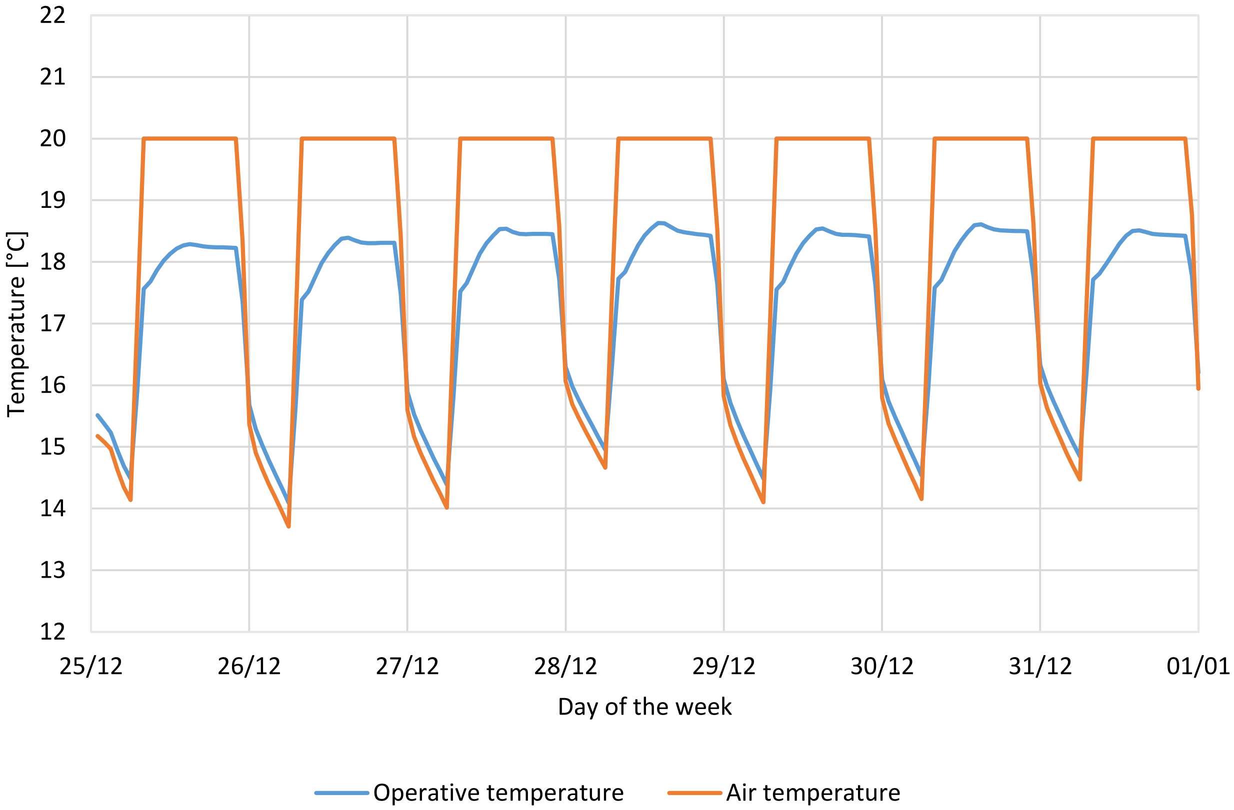


Figure 27. Operative and air temperature for the last week of the TRY for ZG_APA_3F.

As can be observed from the graphs, the operative temperatures, especially during the heating period, exhibit a significant variation. This is due to the limited insulation provided by the building envelope. On the other hand, during the summer season, the fluctuation is much more subdued since cooling has been set active throughout the entire season.

It is also noteworthy that the minimum temperature during the winter period falls below 15 degrees. This condition may lead to thermal discomfort; therefore, the thermal insulation could help to reduce this problem. Looking at the chart regarding the last week of the year TRY, it can be noticed that the operating temperature differs by at least 1.5 degrees compared to the ideal air temperature due to the poor thermal insulation of the building.

4.1.2. OpenStudio model validation

By analysing the simulation results with the 10-year EPW file, it was possible to calculate the energy demand for the 2019/2020 heating season. The demand amounted to 31318 kWh and applying the previously calculated overall efficiency (Formula 3.1), results in a final energy consumption of 43863 kWh.

Comparing the real value of 43615 kWh obtained from the bills with the simulation results, a difference of 0.57% indicates a slight overestimation in the simulation data compared to the real values.

However, the accuracy of the model falls within the range specified by UNI/TR 11775 [27], as it satisfies the following condition:

$$-0.05 \leq \frac{C_0 - C_e}{C_e} \leq 0.05 \tag{4.1}$$

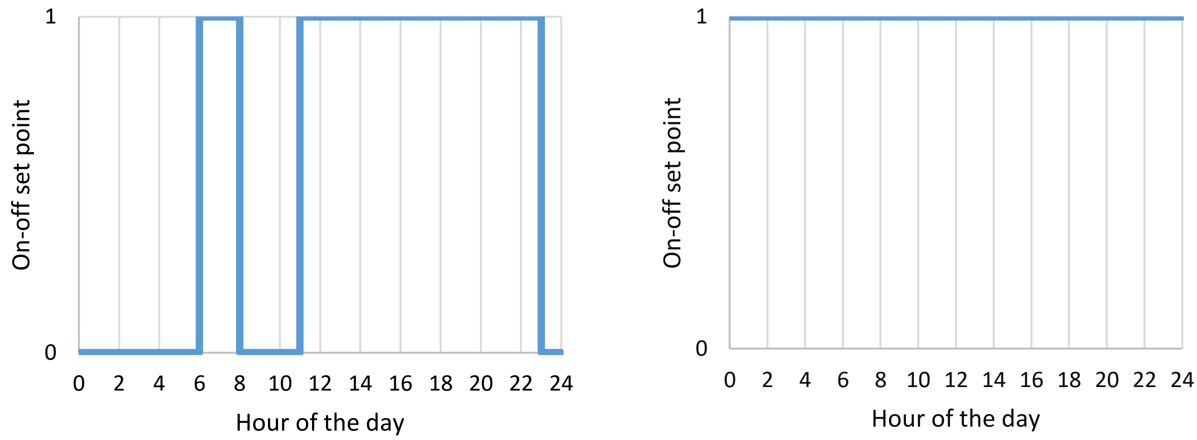
Where C_0 represents the value obtained by the simulation and C_e represents the real value.

In conclusion, it can be stated that the model developed through the software has been successfully validated. Consequently, it is possible to proceed with future energy efficiency simulations, asserting the validity of the obtained results.

4.1.3. Results post-retrofit

After model validation, it is now possible to proceed with the simulation, considering the appropriate modifications to the building envelope aimed at improving energy efficiency. The changes made to the building envelope are detailed in Table 5 and Table A5.

A substantial modification applied to this simulation concerns the heating hours and associated schedules. According to the regulation (D.P.R. 412/1993) [28] applicable to climatic zone E, where Padua is located, a maximum number of heating hours is set at 14 from October 15th to April 15th. The new schedules and set points are detailed below:



Figures 28. Switch-on profile for the heating and cooling season post-retrofit.

The switch-on profile graphs represent also the graph of the set point temperatures. In particular, the set point temperatures for the winter season is always 20 °C while for the summer season it has been set to a constant temperature equal to 26 °C from 15/06 to 15/09.

To ensure a consistent data comparison, this simulation was also conducted using the EPW file employed in the pre-retrofit phase.

The outcomes of the simulation are illustrated in the subsequent graphs.

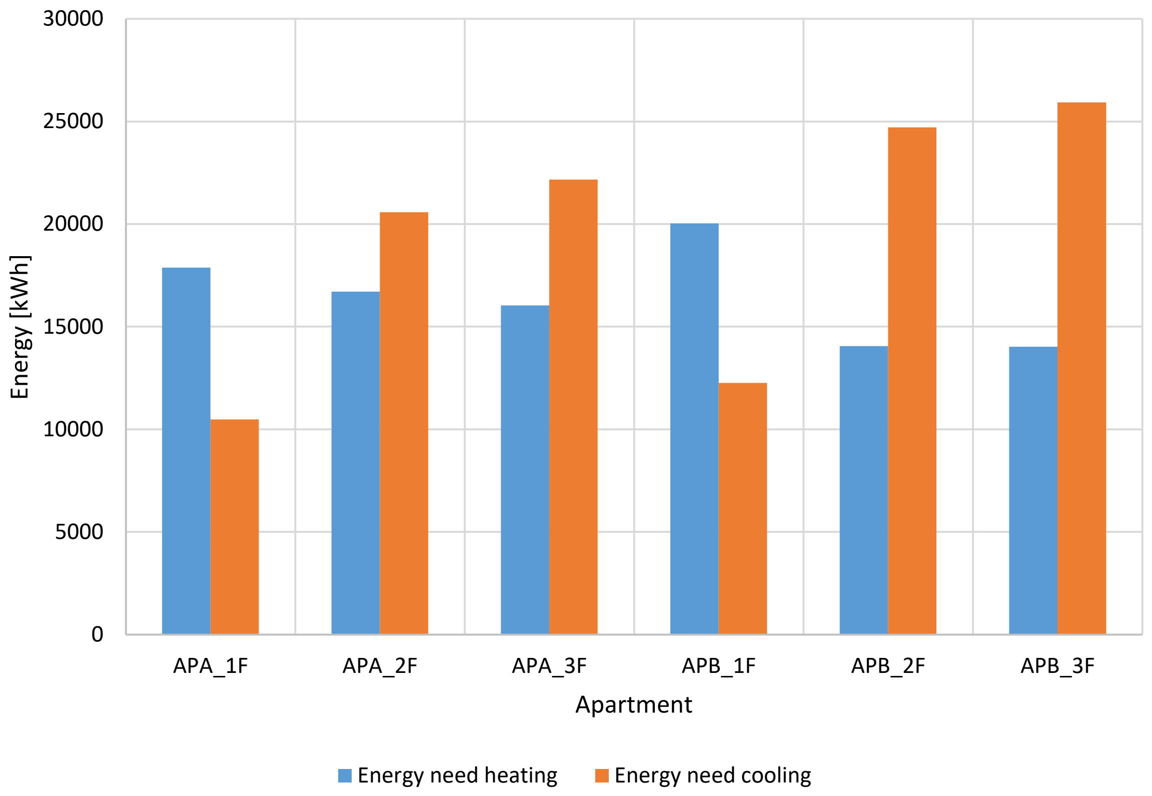


Figure 29. Energy need of the apartments post-retrofit.

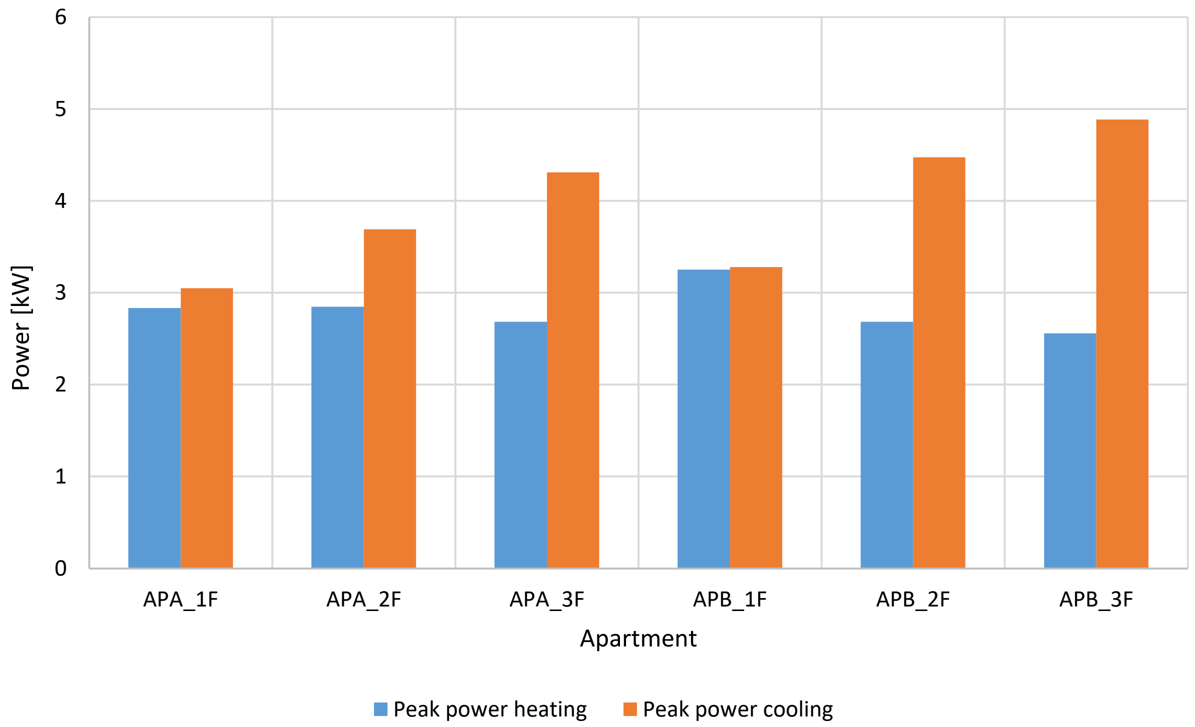


Figure 30. Peak power of the apartments post-retrofit.

Analysing the graphs, it is possible to observe a drastic reduction in the energy demand for each thermal zone, coupled with a decrease in the peak thermal power required for heating or cooling. The overall energy

need for heating has been reduced by 66.6%, while the energy need for cooling has been reduced by 20%Additionally, special attention should be given to the building's peak final thermal power, which amounts to 21.3 kW, 60% lower than the pre-retrofit case.
Later, the same results are presented in tabular form.

	Energy heating [kWh]	**Energy Cooling [kWh]**	**Peak power heating [kW]**	**Peak power cooling [kW]**
APA_1F	17877	10489	2.8	3.1
APA_2F	16712	20583	2.8	3.7
APA_3F	16031	22164	2.7	4.3
APB_1F	20032	12265	3.3	3.3
APB_2F	14051	24716	2.7	4.5
APB_3F	14018	25921	2.6	4.9
Total	98721	116138		

Table 23. Numerical results of the simulation.

The specific final energy weighted on a 10-year period results are:

	Net surface [m²]	**Specific primary heating energy [kWh/(m²*year)]**
APA_1F	83.04	70.16
APA_2F	83.04	63.90
APA_3F	75.43	61.30
APB_1F	83.33	69.41
APB_2F	83.33	53.86
APB_3F	74.58	53.68

Table 24. Specific primary heating energy per apartment.

Unlike the pre-retrofit scenario, in calculating the post-retrofit specific final energy, the heat pump has been considered as the only heating technology. This results in an overall system efficiency of 0.79, derived from the overall efficiency of Formula 3.1, minus the generation efficiency since there is no boiler.
Just like in the pre-retrofit scenario, an analysis of temperatures within various thermal zones has been carried out. The selected thermal zones are the same as those in the pre-retrofit case, allowing for a direct comparison of these zones before and after the modifications to the building envelope.

In particular, the temperatures considered for these graphs refer to the year 2019. It was decided to use only one year to better focus on the trends.

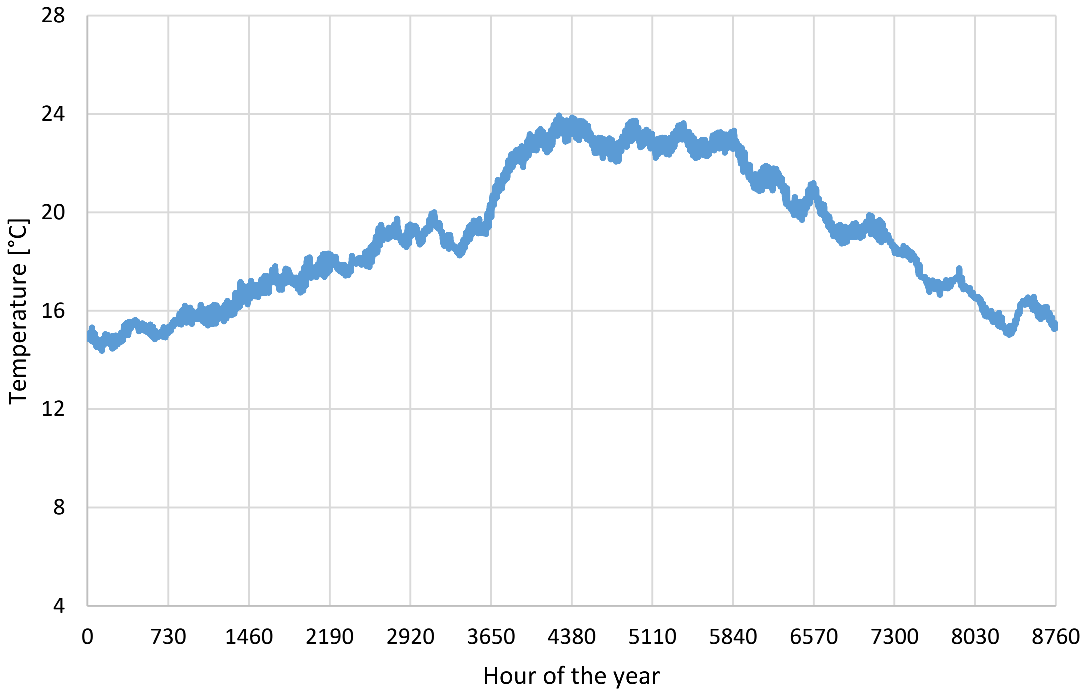


Figure 31. Operative temperature trend of the thermal zone Garage along the year 2019.

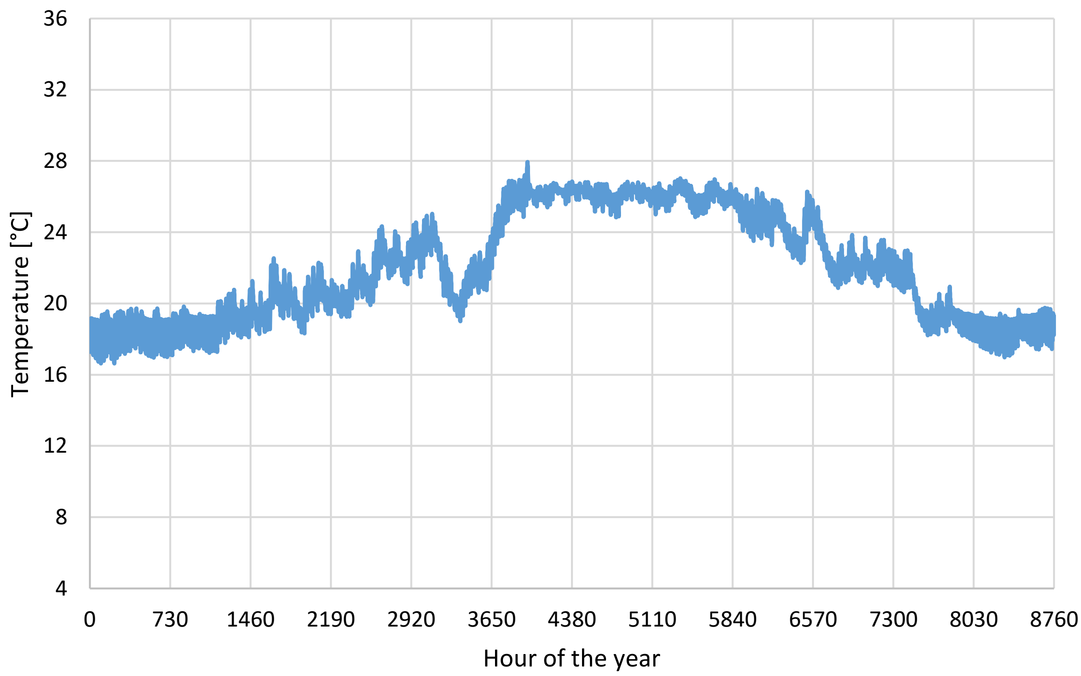


Figure 32. Operative temperature trend of the thermal zone APA_1F along the year 2019.

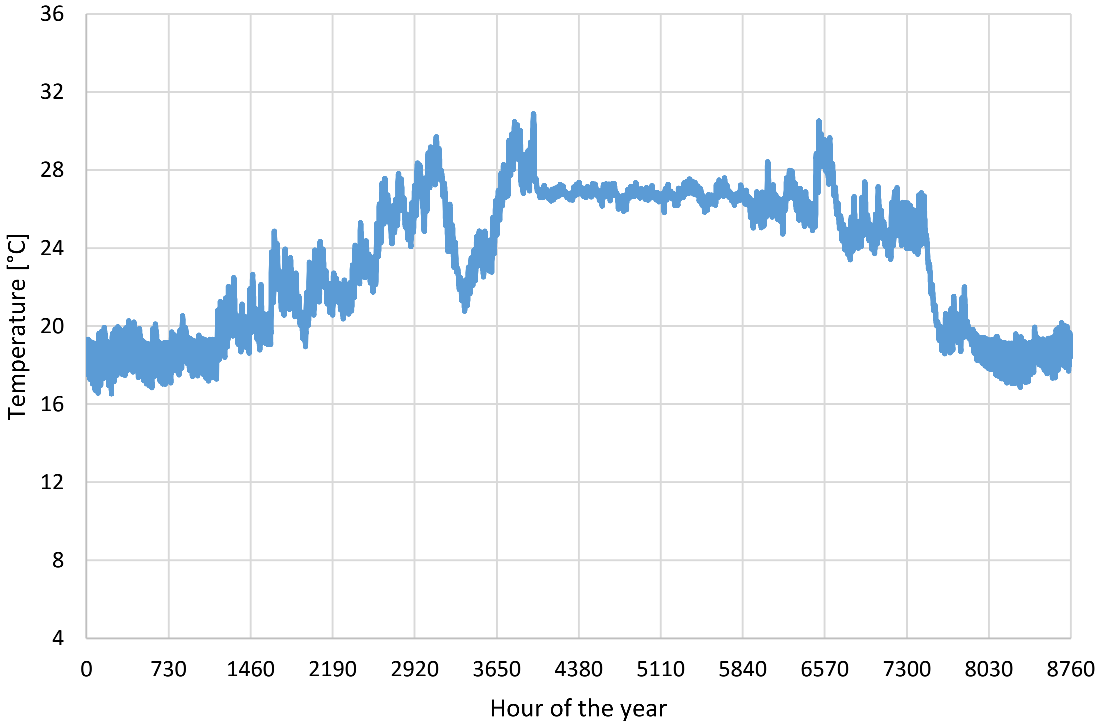


Figure 33. Operative temperature trend of the thermal zone APB_2F along the year 2019.

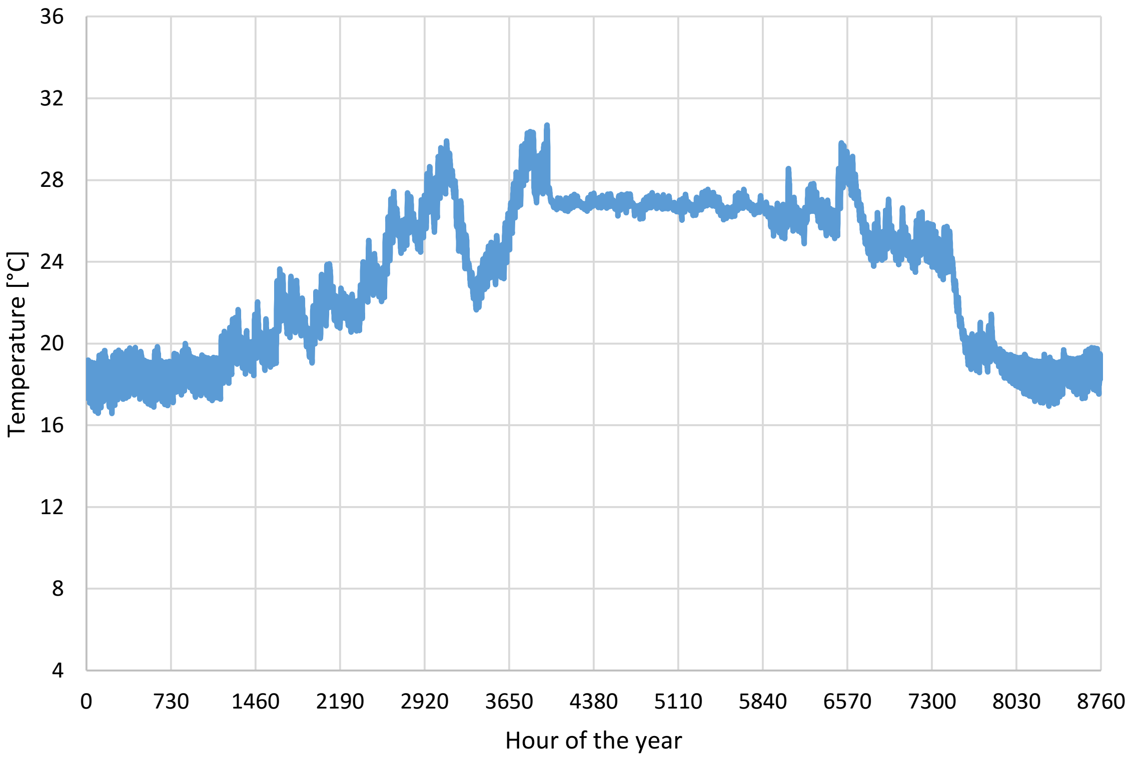


Figure 34. Operative temperature trend of the thermal zone APA_3F along the year 2019.

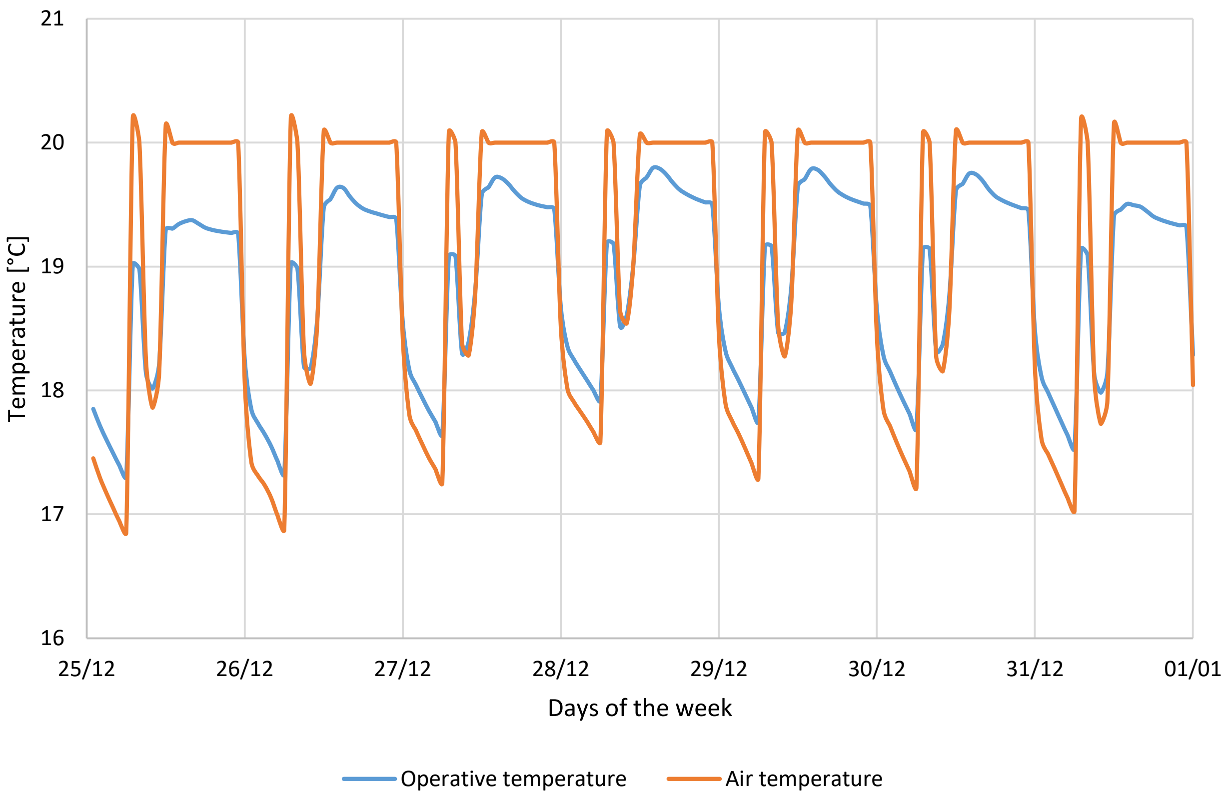


Figure 35. Operative and air temperature for the last week of the 2019 for ZG_APA_3F.

As can be seen from the graphs, in the various inhabited thermal zones, the temperature does not drop below 16 °C, also showing less fluctuation compared to the non-insulated case. This results in greater thermal comfort and a lower energy requirement for heating the environment, as evident in the simulation results. Looking at Figure 35, it can be noted that the operating temperature is one degree higher than the non-insulated case during heating hours. It is worth noting that, thanks to the insulation, the operating temperature never drops below the air temperature during the period when the heating system is turned off, leading to improved thermal comfort.

4.1.4. Pre and post-retrofit comparison: differences in terms of energy need

As evident, the interventions carried out on the building envelope have dramatically reduced both the thermal demand of individual condominiums and their peak powers. Consequently, there is also a halving of the condominium's peak power throughout the year.

It is noticeable that the energy required in the post-retrofit case is one-third of that needed in the pre-retrofit scenario, precisely at 33.4%. This means that the changes made to the envelope allow for a 66.6% energy saving.

This analysis was conducted considering the final energy needed to meet the building's energy demand. Since net energy (building demand, simulation result) and final energy are correlated by the total efficiency (Formula 3.1), this savings can also be applied to the building's energy demand.
However, for the economic analysis, it is necessary to refer to the final energy, which corresponds to the quantity of gas consumed. Assuming the high heating value of natural gas at 11.07 kWh/Sm^3 and a price of 1.1 €/Sm^3, the savings resulting from energy efficiency measures can be calculated.
The quantity of gas used in the pre-retrofit case is equivalent to 26692 Sm^3, while the amount consumed in a hypothetic post-retrofit case, i.e. with the same generator, is 8918 Sm^3. Considering the unit price of natural gas, there is an expenditure of 29361 euros for the pre-retrofit scenario and 9810 euros for the post-retrofit scenario, implying a 10-year savings of 19551 euros.

4.1.5. Comparison between the TRY's energy need and modified EPW's energy need

What is interesting to verify is the difference between TRYand the modified EPW file created using real data. In particular comparing the results related to the heating and cooling thermal requirements.
Regarding the results of the TRY file:

	Energy need [kWh]
Heating	10819
Cooling	10444

Table 25. Energy need obtained using the TRY file.

The results obtained with the modified EPW file are:

	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Heating [kWh]	10509	7635	10374	10035	11128	10456	9381	9659	10263	9498
Cooling [kWh]	11087	7815	12602	10672	13352	11917	13006	10853	11411	13134

Table 26. Energy need obtained using the modified EPW file, year by year.

By comparing the results, it's possible to notice that they also differ significantly from the TRY. To provide a more straightforward view of the difference, in the Table below, the percentage differences relative to the TRY are reported.

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Heating [kWh]	-2.9%	-29.4%	-4.1%	-7.3%	2.9%	-3.4%	-13.3%	-10.7%	-5.1%	-12.2%
Cooling [kWh]	6.2%	-25.2%	20.7%	2.2%	27.8%	14.1%	24.5%	3.9%	9.3%	25.8%

Table 27. Relative differences for the 10-year's energy need compared with the TRY file.

These values are simply calculated dividing the energy difference (heating or cooling) between the single year and the TRY for the energy need value of the TRY (heating or cooling)

It is possible to notice that the year 2014 presents the maximum difference compared with the TRY, resulting in around 30% less energy-consuming in the heating season than the TRY case. In the other hand, the year the requires more energy for cooling is the 2017, needing around 28% more energy than the TRY.

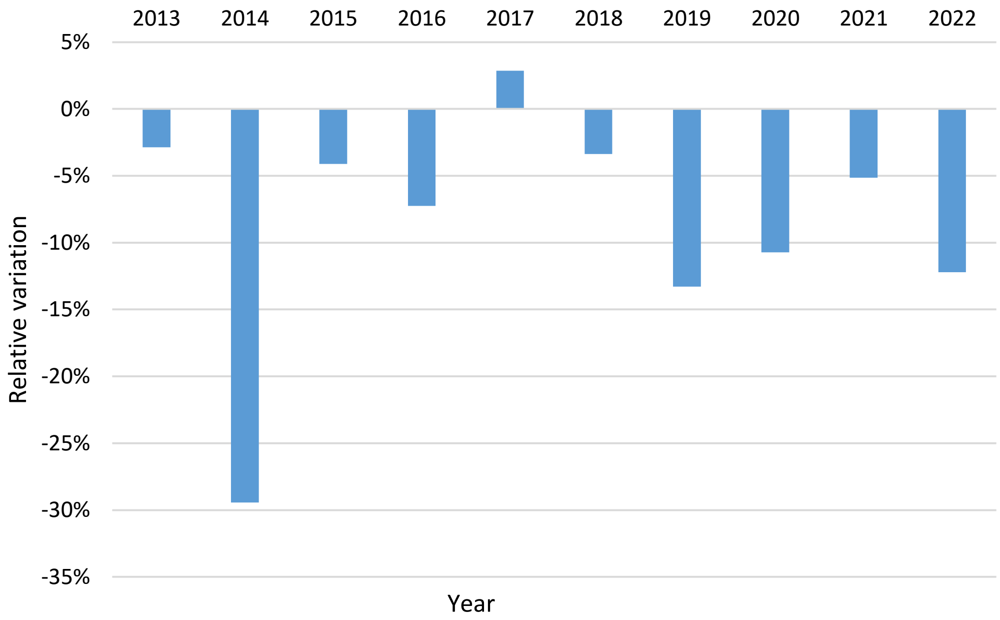


Figure 36. Relative variations for the heating demand.

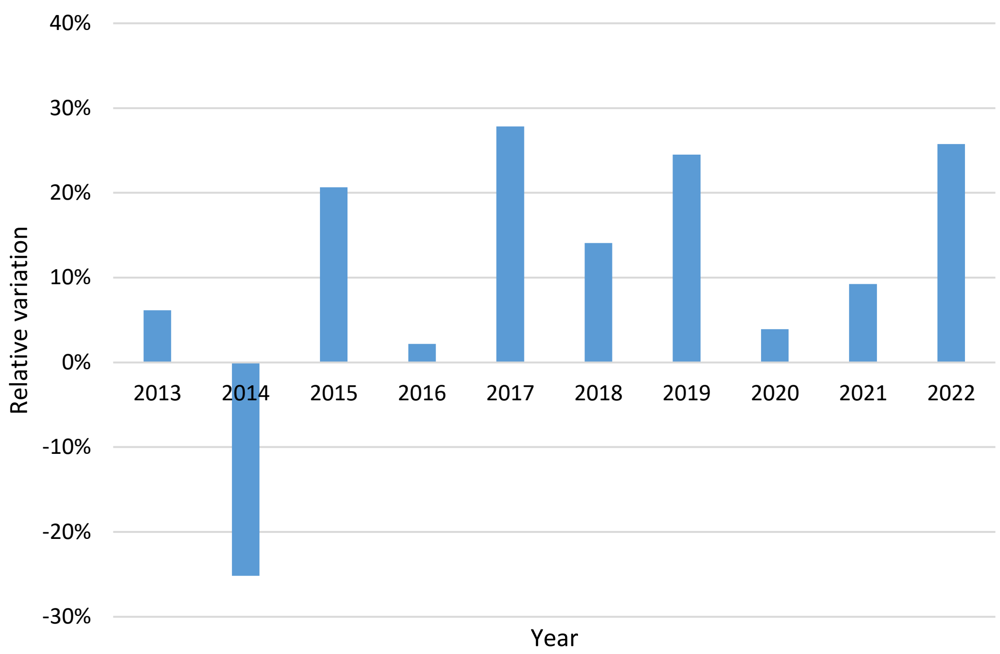


Figure 37. Relative variations for the cooling demand.

The RMSE associated to these cases are:

	RMSE
Heating	11.96%
Cooling	18.55%

Table 28. RMSE values associated to the variation of energy need between TRY file and the modified EPW file.

As highlighted, the RMSE value is higher in the case of cooling, indicating that the results derived from the modified file are significantly different from the TRY result. A similar situation is observed in the case of heating; however, the variation in the results of the latter is lower.

4.2. ANALYSIS OF THE RADIATORS' THERMAL OUTPUT

Having the number of elements, the type of radiators per apartment, and their thermal output, it's easy to calculate the overall thermal output provided for each apartment. This analysis was carried out both for the pre-retrofit and post-retrofit cases, allowing for a comparison of the difference in peak power required to heat the apartment. The calculation is straightforward, as it involves multiplying the thermal output of each radiator by the number of elements comprising the radiator.

Referring to tables 2B and 3B in Annex B, the total thermal output per apartment is reported in the tables below, for both the pre-retrofit and post-retrofit cases.

	Total thermal output [W]	Power needed [W]	Difference
Apartment 1A	7383	5428	-
Apartment 1B	7686	5725	-
Apartment 2A	4783	4766	-
Apartment 2B	5247	5236	-
Apartment 3A	6789	5051	-
Apartment 3B	6719	5044	-

Table 29. Total thermal output compared with the thermal power needed by each apartment, pre-retrofit.

	Total thermal output [W]	Power needed [W]	Difference
Apartment 1A	2909	2530	-
Apartment 1B	3050	2888	-
Apartment 2A	1784	2606	822
Apartment 2B	2133	2456	323
Apartment 3A	2757	2466	-
Apartment 3B	2745	2344	-

Table 30. Total thermal output compared with the thermal power needed by each apartment, post-retrofit.

As can be seen from the Table 30, using the heat pump as the heat production system results in a peak thermal power deficit for two apartments. There are multiple solutions: the first involves raising the hot water production temperature of the heat pump, but this significantly affects the machine's performance since the highest power demand occurs at lower outside temperatures. The second solution is to replace the existing radiators with more efficient types. Since this is the most plausible and simple solution, it was decided to apply it on this case study.

Based on the data from Table 2B, it was decided to replace all the radiators in apartment 2A with aluminium plate radiators, particularly the flat ones. They were chosen for their high thermal output per element, potentially leading to a reduction in radiator width and thus reducing their overall footprint. Attention was paid to the height of the radiators as well: this latter was chosen based on the height of the previous radiators to avoid issues arising from inability to fit them into the designated niche. The same reasoning was applied to apartment 2B, where all radiators, except the towel radiator in the bathroom, were replaced with the same aluminium radiators used in apartment 2A. Special attention was given to power distribution in various rooms; in fact, radiator replacement was carried out while maintaining proportionality of demand in individual rooms. Below are the updated power ratings for each apartment.

	Total thermal output [W]	Power needed [W]	Difference
Apartment 2A	2845	2606	-
Apartment 2B	2664	2456	-

Table 31. Total thermal power considering the modifications made on the radiators.

Considering the modifications made to the various radiators in the building, it can be stated that the thermal power required for each apartment is also met with the help of the heat pump as a heat producer. Therefore, it is possible to proceed with the analysis of the heat pump application to the case study without encountering any issues.

4.3. ANALYSIS OF HEAT PUMP PERFORMANCES

It is now possible to apply the model to the real case. To do so, it is necessary to reprocess the results from the simulation to obtain the data, then elaborated to obtain the same combinations presented in the matrix **F**. Having to verify the actual operation of the heat pump under different weather conditions, it was decided to proceed with the simulation using the ten-year EPW file. Since the simulation was conducted on an hourly basis, the values for each column will be 87600, corresponding to the number of hours in ten years. During this reprocessing, it is important to consider that the thermal power or energy demand obtained from the simulation refers to the net energy of the building. Consequently, it is necessary to divide this result by the total efficiency (Formula 3.1), excluding the generation efficiency, to obtain the final thermal power required for the sizing of the heat pump.

At this point there the need to evaluate the thermal power that the heat pump must supply. Since it was decided to pair it to the energy need of the building, the model is not required.

Then, using the coefficients in Formula 13.3, it is possible to calculate the COP value for each hour.

Since, by law, the heating system can remain on for a maximum of 14 hours, some results related to the energy demand are equal to 0. Since the cooling aspect is included in the simulation, attention must be paid to avoid considering these the data in the analysis: as the heat pump should be modelled only for heating, these data points must be excluded. During the analysis, data related to the system-off period and the summer period have been filtered. With the hourly thermal power produced by the heat pump, together with the COP calculated with the model, it is possible to calculate the electrical power absorbed by the heat pump.

$$Electrical\,power = \frac{Thermal\,power}{COP} \tag{4.2}$$

To get a more comprehensive understanding of the heat pump's performance over the past 10 years, it is advisable to analyse the SCOP, which is dependent on the total energy produced by the heat pump. Specifically, the SCOP is defined as:

$$SCOP = \frac{Total\ thermal\ energy\ produced\ by\ the\ heat\ pump}{Total\ electrical\ energy\ absorbed\ by\ the\ heat\ pump} \tag{4.3}$$

Regarding this simulation,

	Unit 29
SCOP	1.93
Thermal energy produced [kWh]	124958
Electrical energy absorbed [kWh]	64867

Table 32. Simulation results of Unit 29.

After carefully analysing the operation of the heat pump over 10 years, it emerged that it operates for the most part well below its nominal conditions, resulting in a low COP value. Based on this analysis, the decision was made to use two smaller-sized heat pumps placed in parallel. This way, the first heat pump operates at its maximum, closer to its nominal conditions, resulting in a higher COP. The second heat pump is used to cover the thermal peaks required by the building.

Specifically, both heat pumps considered are produced by Galletti, and the models are MPI DC 10H (Unit 10 later on) and MPI DC 14H (Unit 14 later on), with nominal thermal powers of 11.4 kW and 15.7 kW, respectively.

The size was chosen based on the analysis on the operation of the Unit 29 model, as it was observed that it operates mostly around 40% of its nominal power. Considering the nominal power of 33.8 kW, this corresponds to a power of approximately 14 kW.

Later, in the comparison, the Unit 29 heat pump will not be considered.

At this stage, since we can no longer apply the assumption used for the Unit 29 regarding the thermal power, it is necessary to reapply the model. Having already discussed its formulation, only the vectors **x** and **y**, along with the matrix **F**, necessary for the model will be presented. The vector **x** is composed of the column:

- 1: column composed of ones
- T_{air}: external air temperature
- $T_{w,out}$: outlet water temperature

And the matrix **F** is then defined as

$$F_{PT} = \left[1_i;\ T_{air,i}; \left(T_{w,out} - t_{air}\right)_i;\ \left(T_{w,out} - t_{air}\right)_i^{\ 2}\right] \tag{4.4}$$

Obtaining:

$$y_{model} = c_1 \cdot 1 + c_2 \cdot T_{air} + c_3 \cdot \left(T_{w,out} - t_{air}\right) + c_4 \cdot \left(T_{w,out} - t_{air}\right)^2 \tag{4.5}$$

Knowing these vectors and this matrix is possible to proceed with the interpolation useful to obtain the coefficient needed for the analysis. In particular, they are

$$PT_{100\%,Unit10} = 11.993 \cdot 1 + 0.241 \cdot T_{air} - 0.0574 \cdot \left(T_{w,out} - t_{air}\right) + \\ -9.62 * 10^{-5} \cdot \left(T_{w,out} - t_{air}\right)^2 \tag{4.6}$$

$$PT_{100\%,Unit14} = 17.864 \cdot 1 + 0.319 \cdot T_{air} - 0.161 \cdot \left(T_{w,out} - t_{air}\right) + \\ +0.00131 \cdot \left(T_{w,out} - t_{air}\right)^2 \tag{4.7}$$

For the calculation of the thermal power developed by the heat pump, it was assumed to operate at the nominal frequency by applying the coefficients indicated above. If the thermal power exceeds the building's thermal demand, it has been limited to this latter value. Given these two scenarios, there is a need to apply two different COP models based on the developed thermal power. In the event that the developed thermal power is lower than the building's demand (operation of the heat pump at nominal frequency), the following coefficients are applied.

$$COP_{100\%,Unit10} = 2.692 \cdot 1 - 0.0543 \cdot T_{air} - 0.135 \cdot \left(T_{w,out} - T_{air}\right) + \\ +0.00117 \cdot \left(T_{w,out} - T_{air}\right)^2 - 1.074 \cdot \left(\frac{P_t}{P_{t,N}}\right)^2 + 5.009 \cdot \frac{P_t}{P_{t,N}} \tag{4.8}$$

$$COP_{100\%,Unit14} = 3.988 \cdot 1 - 0.0421 \cdot T_{air} - 0.115 \cdot \left(T_{w,out} - T_{air}\right) + \\ +0.000815 \cdot \left(T_{w,out} - T_{air}\right)^2 - 0.266 \cdot \left(\frac{P_t}{P_{t,N}}\right)^2 + 2.62 \cdot \frac{P_t}{P_{t,N}} \tag{4.9}$$

In case the thermal power developed by the heat pump needs to be limited:it happens because the second heat pump is used to cover the load not provided by the first heat pump. From the model, there is a maximum value of thermal power that can be developed by the heat pump. If this value turns out to be greater than the required thermal demand, the thermal power that the heat pump must develop is therefore "limited" compared to the maximum value it can produce. A similar situation arises when the required thermal demand of the building is less than the maximum thermal power that the heat pump can develop. The following coefficients are used for the COP since it works in partial load.

$$COP_{part,Unit10} = 3.997 \cdot 1 - 0.0105 \cdot T_{air} - 0.110 \cdot \left(T_{w,out} - T_{air}\right) + \\ +0.000874 \cdot \left(T_{w,out} - T_{air}\right)^2 - 1.116 \cdot \left(\frac{P_t}{P_{t,N}}\right)^2 + 3.181 \cdot \frac{P_t}{P_{t,N}} \tag{4.10}$$

$$COP_{part,Unit14} = 3.983 \cdot 1 - 0.00948 \cdot T_{air} - 0.097 \cdot \left(T_{w,out} - T_{air}\right) + \\ +0.00649 \cdot \left(T_{w,out} - T_{air}\right)^2 - 1.144 \cdot \left(\frac{P_t}{P_{t,N}}\right)^2 + 3.113 \cdot \frac{P_t}{P_{t,N}} \tag{4.11}$$

To model the heat pump's operation, it was decided to apply another model for partial operation below 25% of the nominal power. Specifically, being an inverter heat pump, it is possible to operate at different frequencies. Working at conditions much lower than nominal translates to operating at a lower frequency. This choice was made after verifying the building's requirements (thermal power and associated external temperature) using catalogue data to check if the building's needs could be met under that operating condition of the heat pump. For this model, only catalogue data referring to "Nominal Data at Minimum Frequency" were considered. In this case, these coefficients vectors are composed by four row each because there were not considered the column related to $P_t/P_{t,N}$ and its square.

The coefficients for the two heat pumps are reported below:

$$COP_{25\%,Unit10} = 3.436 \cdot 1 + 0.00339 \cdot T_{air} - 0.0529 \cdot \left(T_{w,out} - T_{air}\right) + \\ +0.000259 \cdot \left(T_{w,out} - T_{air}\right)^2 \tag{4.12}$$

$$COP_{25\%,Unit14} = 3.131 \cdot 1 - 0.00804 \cdot T_{air} - 0.0282 \cdot \left(T_{w,out} - T_{air}\right) + \\ -7.39 * 10^{-5} \cdot \left(T_{w,out} - T_{air}\right)^2 \tag{4.13}$$

In the following Table are collected all the RMSE related to the models so far presented for Unit 10 e Unit 14.

UNIT 10		**UNIT 14**	
	RMSE		**RMSE**
$\boldsymbol{P_{t,100\%'}}$	1.374%	$\boldsymbol{P_{t,100\%'}}$	0.954%
$\boldsymbol{COP_{100\%}}$	1.042%	$\boldsymbol{COP_{100\%}}$	1.115%
$\boldsymbol{COP_{part}}$	9.707%	$\boldsymbol{COP_{part}}$	9.779%
$\boldsymbol{COP_{25\%}}$	6.875%	$\boldsymbol{COP_{25\%}}$	6.005%

Table 33. RMSE for the models of both heat pump.

For the graphical representation of these error, please refer to the Annex C

Low value of RMSE translates into high reliability of the model in predicting the behaviour of heat pumps based on system conditions. Its ability to accurately adapt to catalogue data suggests that the model is a valuable tool for predictions in the context of heat pump performance.

In general, the RMSE doesn’t exceed the threshold of 10%, thus the models are affordable.

The thermal energy that needs to be supplied by heat pump 2 is calculated as the difference between the total building demand and the energy supplied by heat pump 1. However, the power of heat pump 2 is limited, assuming it operates at a maximum equal to that of heat pump 1. Upon examining its operation over ten years, it was observed that it primarily operates at much lower powers than the nominal power. Therefore, the partial load COP model was applied to find the COP of such operation.

Once both models were applied to the case study, the COP values for the heat pump were obtained, which are useful for calculating electrical energy consumption. Subsequently, the 10-year SCOP was also calculated. Considering the final energy equal to 124963 kWh, the "Remaining Energy" that must be supplied by an external heat source, such as an electric resistance, is simply calculated by subtracting the sum of the two values of thermal energies provided by the heat pumps, as shown in the following table, from the total value of the initial final energy reported above.

UNIT 10				**UNIT 14**			
	THERMAL ENERGY [kWh]	**ELECTRICAL ENERGY [kWh]**	**SCOP**		**THERMAL ENERGY [kWh]**	**ELECTRICAL ENERGY [kWh]**	**SCOP**
Heat pump 1	116235	44185	2.64	**Heat pump 1**	123285	44321	2.79
Heat pump 2	8499	5393	1.58	**Heat pump 2**	1678	1141	1.47
Remaining energy [kWh]	229	/	/	**Remaining energy [kWh]**	0	0	/

Table 34. Energies related to the parallel operation of the selected heat pumps.

As previously mentioned, if the heat pumps are unable to provide the required energy, an electric heater is activated to meet the demand. Therefore, it is crucial to assess the maximum power that this electric heater must provide. From the analysis conducted, it has been found that for the Unit 10 heat pump, the required power is 7.8 kW. Regarding the Unit 14 heat pump, the power is zero, as the parallel operation of the two heat pumps allows for the complete satisfaction of the building's heating needs.

Applying the weather compensated curve and the cut-off to the case study, it was decided to shut down the heat pump for outdoor temperatures below 1°C. This decision was made after analysing the heat pump's performance over the 10-year simulation period. In the following table, the results concerning the hybrid systems are reported

Hybrid	**UNIT 10**	**UNIT 14**
Thermal energy heat pump [kWh]	116235	123285
Electrical energy heat pump [kWh]	44185	44321
SCOP	2.64	2.79
Energy boiler (no gen efficiency) [kWh]	8728	1646
Final energy boiler [kWh]	9698	1829
Peak power boiler [kW]	14.6	10.6

Table 35. Hybrid systems simulation results, without any regulation.

To determine the final energy of the boiler, it is necessary to also consider the generation efficiency. The value of 124963 kWh was simply obtained by dividing the net energy resulting from the simulation by the efficiency defined by Formula 3.1, without taking into account generation (as it is not relevant for heat pumps). In other words, the value represented by "Energy boiler (no gen efficiency)" expresses the energy coming out the boiler, not the "raw" one entering. Therefore, the two items have been distinguished, with and without generation efficiency for the boiler, in order to provide an accurate assessment of the energy performance of the system.

As can be noticed, the results of the heat pumps of both sizes are equal to the previous case: this is because the operating principle remains the same.

Hybrid	**UNIT 10**	**UNIT 14**
Regulation	WCC	WCC
Thermal energy heat pump [kWh]	116611	123297
Electrical energy heat pump [kWh]	40752	41006
SCOP	2.87	3.02
Energy boiler (no gen efficiency) [kWh]	8320	1634
Final energy boiler [kWh]	9245	1816
Peak power boiler [kW]	14.57	10.58

Table 36. Hybrid systems simulation results: weather compensated curve application.

Types of regulation:

WCC = weather compensated curve

co = cut-off

Hybrid	**UNIT 10**	**UNIT 14**
Regulation	WCC + co	WCC + co
Thermal energy heat pump [kWh]	102296	104810
Electrical energy heat pump [kWh]	33985	33299
SCOP	3.02	3.15
Energy boiler (no gen efficiency) [kWh]	22635	20120
Final energy boiler [kWh]	25150	22356
Peak power boiler [kW]	21.35	21.35

Table 37. Hybrid systems simulation results: weather compensated curve and cut-off application.

The results of the simulation show a clear improvement in the performance of the heat pumps, as anticipated. Despite the thermal power being unaffected by the SCOP, a significant reduction in electrical energy consumption is observed. This improvement directly leads to a reduction in associated energy costs.

A comparison between the cases with and without the application of the weather compensated curve reveals the importance of this control strategy. Specifically, the use of the weather compensated curve leads to a further reduction in electrical energy consumption over the 10-year simulation period, despite the supplied thermal energy remaining relatively constant.

This highlights the hybrid system's ability to reliably meet the building's thermal needs over the long term.

Analysing the case with the cut-off, one notices a further increase in the performance of the heat pumps, due to the fact that they operate in more favourable conditions. On the other hand, there is the need to install a boiler with higher power to meet the building's thermal demand, since the heat pump, in the most critical condition, remains off.

4.4. SIZING OF HEAT PUMP FOR CENTRALIZED DHW PRODUCTION

Given all the parameters to be respected, it was possible to calculate both the heat pump power and the storage tank dimensions for both configurations.

In the Table below are listed all the results.

Storage tank on DHW circuit (first configuration)		**Storage tank placed on primary circuit (second configuration)**	
Power of the heat pump [kW]	60	Power of the heat pump [kW]	95
Storage tank capacity [litres]	1600	Storage tank capacity [litres]	2000

Table 38. Power of the heat pumps and storage tank capacities for both configurations.

As can be observed, in the first configuration, a lower power and storage capacity are obtained compared to the second configuration, as expected. It is important to remember that this system also serves as a heating system. Taking into account the peak power value obtained from the post-retrofit simulation of 21.3 kW, it can be seen that both configurations adequately meet the demand. However, the results reported in the Table 38 only consider the hypotheses described so far, particularly the guaranteed maximum simultaneous usage time of at least 20 minutes. To size the system optimally, it is also necessary to consider the time taken by the heat pump to charge the hot water tank under design conditions after the usage period. It is important to note that the longer the required time, the less time these configurations can be used for heating the building, leaving it uncovered for that period. Therefore, it is essential to size these configurations considering a sufficient time to perform both operations without causing inconvenience. The time limit set for this case study is 30 minutes. Considering this assumption as well, the thermal powers of the two systems increase significantly, reaching a required power of 115 kW.

This power value is very high: as the power increases, so does the cost, which is not convenient considering the existing solution in the individual apartments of the building. Therefore, it was decided to install the heat pump for space heating only, thus leaving the production of domestic hot water unchanged.

4.5. COMPARISON OF THE SCENARIOS

In this section, the different configurations studied for the condominium will be analyzed. They will be examined by type, comparing only configurations with a sole heat pump and then hybrid configurations. The best configurations for each type will then be compared to determine the optimal configuration, directly contrasting them with the already installed boiler system. The analysis will be based on Key Performance Indicators, so not all results will be explicitly stated. Therefore, reliance must be placed on Annex D for this. In the final analysis it has been considered a maintenance cost for the boilers of 500 €/year.
Once the best configuration is defined, the investment payback period will also be presented. This will be provided at the end because it depends on the energy cost difference of the best configuration.

4.5.1. Comparison of only-heat pump configurations

The following table compares various characteristic values of heat pumps and boilers, providing a comparative analysis of absorbed electrical energy, thermal power produced, primary energy and carbon dioxide emissions. In particular, it highlights the difference between the values of heat pumps and those of boilers, emphasizing the advantages in terms of energy efficiency and environmental sustainability offered by the former compared to the latter.

10-year comparison	**2xUnit 10**	**2xUnit 10**	**2xUnit 14**	**2xUnit 14**	**Boiler**
Type, regulation	HP, -	HP, WCC	HP, -	HP, WCC	/
Thermal energy HP [kWh]	124734	124719	124939	124939	/
Electricity consumed [kWh]	49861	46006	45611	42284	/
SCOP heat pump 1	2.64	2.87	2.79	3.02	/
SCOP heat pump 2	1.56	1.62	1.46	1.47	/

Electricity cost [euro]	11737	10820	10757	9961	/
Primary energy [kWh]	120664	111336	110379	102326	146107
Renewable ratio [kWh]	24133	22267	22076	20465	/
CO_2 emissions [t CO_2]	12.964	11.962	11.859	10.994	28.108
Delta primary energy	17.41%	23.80%	24.45%	29.96%	/
Delta CO_2 emissions	53.88%	57.44%	57.81%	60.89%	/

Table 39. Key performance indicators for only-heat pump configurations.

Where:

- HP = heat pump

The Table above allows for a direct comparison of the configurations with only heat pumps, providing a clearer view of each key performance indicator value. As can be seen, the configurations with Unit 10 fail to fully meet the building's energy demand, thus requiring the installation of electric resistances to compensate for this energy deficit. On the other hand, configurations with Unit 14 do not encounter this issue; in fact, they manage to supply all the energy required by the building. What is most significant is the use of electric energy to meet the thermal demand. Indeed, the Unit 14 configuration with a weather compensated curve proves to be the configuration requiring the least expenditure of electric energy. This stems from the operation of the heat pump; in fact, this configuration exhibits the highest SCOP for heat pumps 1 and 2, resulting in lower costs as depicted in the Table. Requiring less energy, the primary energy consumption and associated CO_2 emissions are lower. Consequently, the difference compared to the primary energy and emissions from the boiler is greater.
Therefore, the best configuration is the Unit 14 with weather compensated curve.

4.5.2. Comparison of hybrid configurations

10-year comparison	**Unit 10**	**Unit 10**	**Unit 10**	**Unit 14**	**Unit 14**	**Unit 14**
Type, regulation	Hy, -	Hy, WCC	Hy, WCC + co	Hy, -	Hy, WCC	Hy, WCC + co
Gas consumed [Sm^3]	876	835	2272	165	164	2020

Electricity consumed [kWh]	44185	40752	33985	44321	41006	33299
SCOP heat pump 1	2.64	2.87	3.02	2.79	3.02	3.15
Total cost energy [euro]	11173	10319	10098	10601	9806	9708
Primary energy [kWh]	117109	108326	108653	109176	101141	104058
Renewable part [kWh]	21385	19724	16449	21451	19847	16117
CO_2 emissions [t CO_2]	13.447	12.463	13.917	11.893	11.028	13.174
Delta primary energy [kWh]	19.85%	25.86%	25.63%	25.28%	30.78%	28.78%
Delta CO_2 emissions [t CO_2]	52.16%	55.66%	50.49%	57.69%	60.76%	53.13%
Cost including maintenance [euro]	16173	15319	15098	15601	14806	14708

Table 40. Key performance indicators for hybrid configurations.

Where:

- Hy = hybrid system

The Table above highlights the key performance indicators of hybrid configurations. Unlike the case with only heat pumps, in this study, a cut-off for the heat pumps was also applied. Since heat pumps perform better at higher outdoor temperatures, they exhibit a higher SCOP compared to other configurations. Consequently, the electricity consumption is lower, both due to the cut-off and the higher SCOP value. However, the cut-off significantly affects the boiler's operation. In fact, the gas usage values in these configurations are much higher, 2.7 and 12.3 times respectively for Unit 10 and Unit 14, compared to the minimum value of the configurations with the same heat pump.

Looking at the energy price, it is noted that the Unit 14 configuration with weather compensated curve and cut-off has the lowest value. However, despite this, it is not the configuration that requires the least primary energy; that would be Unit 14 with only the weather compensated curve.

The configuration emitting the least CO_2 over the course of the 10-year simulation is Unit 10 with a weather compensated curve. However, despite these strengths, the configuration that is best in terms of costs is Unit 14 with cut-off and weather compensated curve, even considering maintenance costs. Therefore, future analyses will be carried out considering this configuration.

4.5.3. Optimal configuration for the case study and effect of energy prices on key performance indicators

10-year simulation	2xUnit 14	Unit 14	Boiler
Type, regulation	HP, WCC	Hy, WCC + co	
Energy cost [euro]	9961	9708	10604
Primary energy [kWh]	102326	104058	146107
Renewable part [kWh]	20465	16117	/
CO_2 emissions [t CO_2]	10.994	13.174	28.11
Delta primary energy	29.96%	28.78%	/
Delta CO_2 emissions	60.89%	53.13%	/
Cost including the maintenance	9961	14708	15604

Table 41. Key performance indicators of the best configurations, compared with the boiler.

As evidenced by the Table above, the hybrid configuration with Unit 14 weather compensated curve and cut-off presents the best economic results in terms of energy. In fact, over the 10 years of simulation, it's the technology with the lowest energy cost, which are €896 less than the boiler. What stands out the most are the data related to CO_2 emissions and primary energy. With this technology, there's a huge reduction in the latter, seeing primary energy lower by 28.78% (42049 kWh) compared to the boiler. Even more significant is the reduction in carbon dioxide emissions, less than half compared to the only-boiler configuration, precisely 53.13% (14.939 tons). Despite these low emission values, the heat pump-only configuration with Unit 14 and weather compensated curve allows for even fewer emissions, specifically 2.18 tons less respect to the hybrid configuration. Regarding the energy cost for this configuration, it is 2.6% higher than the hybrid configuration of the same heat pump: the primary energy used, instead, is 1.66% lower.

Regarding the analysis with 2022 prices, it can be noted that the total energy costs are extremely high due to the high unit cost of electricity. Therefore, as long as the unit cost of electricity remains so high, configurations involving the heat pump are not economically viable, despite the reduction in emissions and primary energy consumption.

10-year, 2022 prices	2xUnit 14	Unit 14	Boiler
Type, regulation	HP, WCC	Hy, WCC + co	
Total energy cost [euro]	23687	21238	16288
Cost including the maintenance	23687	26238	21288

Table 42. Total energy cost considering the prices of year 2022.

The opposite happens when the same simulation is done considering the energy prices of the year 2018. In this case, the costs related to heat pumps become convenient again, therefore they remain the most cost-effective solution.

10-year, 2018 prices	2xUnit 14	Unit 14	Boiler
Type, regulation	HP, WCC	Hy, WCC + co	
Total energy cost [euro]	8961	8670	10041
Cost including the maintenance	9763	13670	15041

Table 43. Total energy cost considering the prices of year 2018.

However, since this configuration doesn't require boilers, it doesn't require mandatory maintenance, thus saving on these costs over the years. In fact, this configuration turns out to be the least expensive considering all the costs associated with each case.

Considering all the conditions listed previously, the best configuration is the one with dual Unit 14 heat pumps and weather compensated curve, which allows narrowing the gap between boiler and heat pump even with very high electricity prices, as seen for 2022. In the event that the unit cost of electricity returns to normal values, this configuration becomes even more convenient.

Considering the investment cost of 10879 euro and the money saving of 5643 euro over a 10-year period based on the real energy cost trend, the payback time results 19.3 years, equivalent to 19 years and 4 months. For a better visualization, these results are collected in the Table below.

The unit price used to determine the investment cost is based on the 2023 Veneto price list, resulting in a value of €346.5 per kW [29].

10-year period	2xUnit 14
Type, regulation	HP, WCC
Price per unit of power, HP [euro/kW]	346.5
Investment cost [euro]	10879
Savings [euro]	5643
Payback time [year]	19.3

Table 44. Investment cost and payback time for the best configuration.

4.5.4. Key performance indicators of the underfloor heating and energy price effect

This analysis allows to highlight the results related to the underfloor heating system compared to the current boiler system installed. To view the complete results, please refer to Annex D.2. The logical framework followed remains similar to that used for evaluating the optimal configuration in radiator systems. Consequently, the key performance indicators related to the two heat pumps paired with underfloor heating will be presented, with a focus on the best solution. Subsequently, this configuration will be compared with the use of the boiler and with the best solution for the retrofit. Specifically, the results obtained in the 10-year simulation are:

10-year comparison	2xUnit 10	2xUnit 14
Type, regulation	HP, -	HP, -
Thermal energy HP [kWh]	124904	124939
Electricity consumed [kWh]	38543	36955
SCOP heat pump 1	3.37	3.43
SCOP heat pump 2	1.89	1.98
Electricity cost [euro]	9073	8720
Primary energy [kWh]	93273	89432
Renewable part [kWh]	18655	17886
CO_2 emissions [t CO_2]	10.021	9.608
Delta primary energy	36.16%	38.79%
Delta CO_2 emissions	64.35%	65.82%

Table 45. Key performance indicators for underfloor heating.

As evident from the Table, the parallel operation of Unit 14 heat pumps fully meets the building's thermal demand, whereas Unit 10 requires an auxiliary system to provide the remaining 35 kWh. Furthermore, it is observed that Unit 14 operates at higher efficiencies, as evidenced by the higher SCOPs associated with it compared to Unit 10. This also reflects in the electrical energy required to provide the required heat: in fact, the electrical energy follows the SCOP trend, resulting in lower consumption for Unit 14. The same trend is observed for the associated cost of electrical energy. With less demand for electrical energy, other indicators also show lower values. Consequently, the best configuration appears to be the one with parallel operation of Unit 14.

By comparing this solution with boiler and parallel functioning of Unit 14 with radiators, it is possible to observe:

10-year simulation	2xUnit 14	Unit 14	Boiler
Type, regulation	HP UFH	Hy, WCC + co	
Energy cost [euro]	8720	9708	10604
Primary energy [kWh]	89432	104058	146107

Renewable part [kWh]	17886	16117	/
CO_2emissions [t CO_2]	9.608	13.174	28.11
Delta primary energy	38.79%	28.78%	/
Delta CO_2emissions	65.82%	53.13%	/
Cost including the maintenance	8720	14708	15604

Table 46. Comparison between the underfloor heating, the previous best solution and the actual one.

Where

- UFH = underfloor heating.

The underfloor heating configuration stands out for its significant energy savings compared to options with radiators. Specifically, this configuration allows for a 14% saving in primary energy compared to the hybrid solution, while there is even a 38.8% saving compared to the boiler-only scenario. This also translates into a notable reduction in carbon dioxide emissions into the environment. Furthermore, since there is no need for a boiler in the system, there are no annual maintenance costs associated with it, resulting in additional savings. The subsequent tables confirm this trend, even considering energy prices from the years 2022 and 2018, unlike the hybrid configuration. In practice, underfloor heating remains advantageous even with particularly high energy prices.

10-year, 2022 prices	**2xUnit 14**	**Unit 14**	**Boiler**
Type, regulation	HP UFH	Hy, WCC + co	
Total energy cost [euro]	20702	21238	16288
Cost including the maintenance	20702	26238	21288

Table 47. Total energy cost considering the prices of year 2022.

10-year, 2018 prices	**2xUnit 14**	**Unit 14**	**Boiler**
Type, regulation	HP UFH	Hy, WCC + co	
Total energy cost [euro]	7832	8670	10041
Cost including the maintenance	7832	13670	15041

Table 48. Total energy cost considering the prices of year 2018.

The analysis conducted so far does not take into account the investment cost. Furthermore, this system requires a complete substitution of the heating system since the existing radiators are no longer needed. Additionally, there is a need to create the underfloor heating system from scratch. Therefore, the investment costs are much higher compared to the hybrid case with radiators.

Given an existing condominium, it is more convenient to use dry underfloor heating, as it allows for the installation of components above the existing floor. The price for this type of flooring is 70 euro/m^2 (average value based on the 2023 Veneto price list [29]), and considering the total area of the condominium of 482.6 m^2 (as indicated in Table 1), the investment cost amounts to approximately 33782 euros. To this value, the cost of the heat pumps used must be added. Overall, this results in a final cost of 48289 euros. Considering a saving of 6884 euros every 10 years, the investment payback period amounts to 70 years. Therefore, the investment for this system is not convenient despite the numerous advantages listed.

10-year period	**2xUnit 14**
Type, regulation	HP UFH
Specific UFH price [euro/m^2]	70
Price per unit of power, HP [euro/kW]	346.5
Investment cost [euro]	48289
Savings [euro]	6884
Payback time [year]	70

Table 49. Investment cost and payback time for the underfloor heating.

CHAPTER 5

CONCLUSIONS

The purpose of this thesis was to evaluate the technical and economic characteristics of different configurations including air-to-water heat pumps coupled with an old building with six apartments. The building envelope underwent several refurbishment works. Before the retrofit there was no thermal insulation of the walls and only one apartment had high performance windows. Both windows and thermal insulation of the wall were installed respecting the minimal requirements for climatic zone E, since the case study building is located in Padua. EnergyPlus software with OpenStudio was used to evaluate the differences in energy needs for space heating of the building pre- and post-retrofit.

The heating load of the whole building was reduced by 67%, thus having a significant influence on the operating costs. Besides the benefits from the economical point of view, the thermal insulation also improves the indoor thermal comfort. This improvement was reported by showing the operative temperature and the air temperature of reference rooms, indicating a higher operative temperature in the post-retrofit case (around 1.1°C higher during operation).

The thermal output of the already existing terminal units, i.e. radiators, was verified for each apartment of the building, thus setting the minimum supply temperature of the heating system.

This feasibility check was necessary because the performance of air-source heat pumps improves as long as the supply temperature to the terminal units is reduced. Since the corresponding mean water temperature in the radiators (and therefore their thermal output) is lower than the standard one, the radiators will work off-design conditions.

Using the heat pump as heat source, two apartments presented a deficit in peak power produced by the radiators when the supply temperature was set to 50°C. Therefore, increasing the heat exchange surface of existing radiators (i.e. replacing them with bigger low temperature radiators) in two apartments is recommended to avoid thermal discomfort during wintertime.

The behaviour of the heat pump was simulated using a regression of operating points declared in the technical datasheet of heat pump manufacturers.

Different types of configurations were analysed: single heat pump (33.8 kW), double heat pump (11.7 kW and 15.4 kW) and hybrid systems (same size as the double heat pump) properly controlled with weather compensated curve and with a cut-off temperature for the hybrid systems. The 11.7 kW heat pump is called Unit 10 while the 15.4 kW heat pump is called Unit 14.

The application of the model to the single heat pump showed that the latter pump was working mainly at partial load, around 40% of its rated power. Consequently, this configuration leads to high operating costs due to low seasonal COP, equal to 1.93.

Because of this problem, it was decided to study the behaviour of two heat pumps with rated power close to the 40% of the rated power of the single configuration's heat pump, i.e. 11.7 kW and 15.4 kW.

In these cases, it was possible to note a significant increase in the performance of the heat pumps, translating in a SCOP of the Unit 10 heat pump of 2.64 for the main heat pump. For the Unit 14 case, the SCOP is 2.79 for the main one. Considering the hybrid systems, the SCOP raised again because of the cut-off temperature. The latter is usually implemented in the control systems to operate the heat pump when the external air temperature is higher, and using the gas boiler in the remaining periods.

For these cases, the SCOP is respectively 3.02 and 3.15. The best configuration to be coupled to the building was chosen based on other key performance indicators, such as the CO_2 emissions, the primary energy consumption and the "return of the investment" measured in years. Considering the costs for the mandatory maintenance of centralized gas boilers, the most suitable configuration is the one with two Unit 14 heat pumps principally due to lower years needed to pay back the initial investment (17 years without incentives).

Further analysis where performed. In particular, it was decided to use the heat pump also to produce the DHW and replace radiators with radiant floors.

Two solutions were studied for centralized DHW production: a mixed hot water tank and a thermal energy storage with an external heat exchanger for DHW production. Both solutions lead to very high power for the heat pump and big volume tank. This occurs because refilling the tank after the period of use under 30 minutes, which results in a heating capacity of 115 kW.

Considering a deeper retrofit with the installation of radiant floors, the double heat pump solutions were able to fulfil the energy demand for space heating with a SCOP of 3.37 (Unit 10) and 3.43 (Unit 14) for the main heat pump. Moreover, also the energy costs and the CO_2 emissions are low, but the investment cost are very high, thus leasing to a very high payback time without incentives (around 70 years).

In conclusion, the best solution for this retrofit is the double Unit 14 controlled by the weather compensated curve.

Future studies will compare the results obtained in this work with measured data from retrofitted buildings with air-source heat pumps and/or hybrid systems.

ANNEX A: STATIGRAPHIES

A.1. BUILDING ENVELOPE PRE-RETROFIT

External wall					
	Thickness [m]	Conductivity [W/(m*K)]	Density [kg/m^3]	Specific heat [J/(kg*K)]	Thermal resistance [(m^2*K)/W]
Internal plaster	0.02	0.7	1400	1000	0.029
Brick	0.25	0.779	1800	840	0.321
External cement mortar	0.02	0.9	1800	1000	0.022
Total thermal conductivity [W/(m^2*K)]					1.85
Load-bearing inner wall					
	Thickness [m]	Conductivity [W/(m*K)]	Density [kg/m^3]	Specific heat [J/(kg*K)]	Thermal resistance [(m^2*K)/W]
Internal plaster	0.01	0.7	1400	1000	0.029
Brick	0.14	0.779	1800	840	0.180
External cement mortar	0.01	0.7	1400	1000	0.029
Total thermal conductivity [W/(m^2*K)]					2.18

Table A1. Stratigraphy of the opaque components.

Internal partition					
	Thickness [m]	Conductivity [W/(m*K)	Density [kg/m^3]	Specific heat [J/(kg*K)]	Thermal resistance [(m^2*K)/W]
Internal plaster	0.01	0.7	1400	1000	0.029
Hollow brick	0.08	0.779	775	840	0.2
External cement mortar	0.01	0.7	1400	1000	0.029
Total thermal conductivity [W/(m^2*K)]					2.06
Attic floor					
	Thickness [m]	Conductivity [W/(m*K)	Density [kg/m^3]	Specific heat [J/(kg*K)]	Thermal resistance [(m^2*K)/W]
Internal plaster	0.01	0.7	1400	1000	0.029
Floor slab	0.18	0.377	950	840	0.3
Mat	0.06	1.4	2000	1000	0.043
Fiberglass insulating mat	0.2	0.046	20	920	5000
Total thermal conductivity [W/(m^2*K)]					0.201

Table A1. Stratigraphy of the opaque components.

Inter-storey slab					
	Thickness [m]	Conductivity [W/(m*K)	Density [kg/m^3]	Specific heat [J/(kg*K)]	Thermal resistance [(m^2*K)/W]
Ceramic tiles	0.015	1.5	2000	1000	0.01
Mat	0.06	1.4	2000	1000	0.043
Floor slab	0.18	0.377	950	840	0.3
Internal plaster	0.01	0.7	1400	1000	0.029
Total thermal conductivity [W/(m^2*K)]					1.38
Floor against the ground					
	Thickness [m]	Conductivity [W/(m*K)	Density [kg/m^3]	Specific heat [J/(kg*K)]	Thermal resistance [(m^2*K)/W]
Cement mortar	0.03	1.4	2000	670	0.021
Floor slab	0.22	0.632	2000	1000	0.330
Concrete foundation	0.1	1.16	2000	1000	0.086
Gravel	0.2	1.2	1700	1000	0.167
Total thermal conductivity [W/(m^2*K)]					1.27

Table A1. Stratigraphy of the opaque components.

Component	Glazed area [m²]	Frame area [m²]	Glazed thermal transmittance [W/(m²*K)]	Frame thermal transmittance inside/outside [W/(m²*K)]	Total thermal transmittance [W/(m²*K)]
Double window in anodized aluminium 120x150 cm	1.4	0.4	5.7	2.3/5.9	2.7
Double window in anodized aluminium 240x240 cm	5.06	0.7	5.7	2.3/5.9	2.78
Double window in anodized aluminium 120x240 cm	2.3	0.58	5.7	2.3/5.9	2.69
Double window in anodized aluminium 90x150 cm	0.98	0.37	5.7	2.3/5.9	2.62
Double window in anodized aluminium 160x240 cm	3.22	0.62	5.7	2.3/5.9	2.73
Double window in anodized aluminium 160x150 cm	1.96	0.44	5.7	2.3/5.9	2.71
Double-glazed window in PVC 120x150 cm	1.4	0.4	1.1	2	1.51
Double-glazed window in PVC 120x240 cm	2.3	0.58	1.1	2	1.48
Double-glazed window in PVC 90x150 cm	0.98	0.37	1.1	2	1.61
Double-glazed window in PVC 160x240 cm	3.22	0.62	1.1	2	1.4
Double-glazed window in PVC 160x150 cm	1.96	0.44	1.1	2	1.44

Tables A2. Characteristics of the transparent components.

Below are collected all the components of the building envelope, subdivided by apartments.

Apartment 1A					
Confining environment	**Type of the component**	**Orientation**	**Description**	**Area [m²]**	**Transmittance [W/(m²*K)]**
E	OP	N	External wall	18.5	1.85
E	OP	E	External wall	29.1	1.85
E	OP	S	External wall	11.4	1.85
E	TR	E	Double window in anodized aluminium 120x150 cm	1.8	2.7
E	TR	E	Double window in anodized aluminium 160x240 cm	3.84	2.73
E	TR	E	Double window in anodized aluminium 90x150 cm	1.35	2.62
E	TR	E	Double window in anodized aluminium 160x150 cm	2.4	2.71
E	TR	S	Double window in anodized aluminium 120x150 cm	1.8	2.7
E	TR	S	Double window in anodized aluminium 120x240 cm	2.88	2.69
U (stairwell)	OP		Internal partition	18.8	2.15
U (garage)	OP		Inter-storey slab	80	1.38
A (apt. 2A)	OP		inter-storey slab	80	1.38

Tables A3. Areas and transmittances of building components subdivided by apartments (heated zones).

Apartment 1B					
Confining environment	**Type of the component**	**Orientation**	**Description**	**Area [m²]**	**Transmittance [W/(m²*K)]**
E	OP	N	External wall	18.5	1.85
E	OP	E	External wall	27.8	1.85
E	OP	S	External wall	9.3	1.85
E	TR	E	Double window in anodized aluminium 120x150 cm	1.8	2.7
E	TR	E	Double window in anodized aluminium 160x240 cm	3.84	2.73
E	TR	E	Double window in anodized aluminium 90x150 cm	2.7	2.62
E	TR	E	Double window in anodized aluminium 240x240 cm	5.76	2.78
E	TR	S	Double window in anodized aluminium 120x240 cm	2.88	2.69
U (stairwell)	OP		Internal partition	19.7	2.15
U (garage)	OP		Inter-storey slab	77.7	1.38
A (apt. 2B)	OP		inter-storey slab	77.7	1.38

Tables A3. Areas and transmittances of building components subdivided by apartments (heated zones).

Apartment 2A					
Confining environment	**Type of the component**	**Orientation**	**Description**	**Area [m²]**	**Transmittance [W/(m²*K)]**
E	OP	N	External wall	18.5	1.85
E	OP	E	External wall	29.1	1.85
E	OP	S	External wall	11.4	1.85
E	TR	E	Double-glazed window in PVC 120x150 cm	1.8	1.51
E	TR	E	Double-glazed window in PVC 160x240 cm	3.84	1.4
E	TR	E	Double-glazed window in PVC 90x150 cm	1.35	1.61
E	TR	E	Double-glazed window in PVC 160x150 cm	2.4	1.44
E	TR	S	Double-glazed window in PVC 120x150 cm	1.8	1.51
E	TR	S	Double-glazed window in PVC 120x240 cm	2.88	1.48
U (stairwell)	OP		Internal partition	18.8	2.15
A (apt. 1A)	OP		Inter-storey slab	80	1.38
A (apt. 3A)	OP		inter-storey slab	80	1.38

Tables A3. Areas and transmittances of building components subdivided by apartments (heated zones).

Apartment 2B					
Confining environment	**Type of the component**	**Orientation**	**Description**	**Area [m²]**	**Transmittance [W/(m²*K)]**
E	OP	N	External wall	18.5	1.85
E	OP	E	External wall	27.8	1.85
E	OP	S	External wall	9.3	1.85
E	TR	E	Double window in anodized aluminium 120x150 cm	1.8	2.7
E	TR	E	Double window in anodized aluminium 160x240 cm	3.84	2.73
E	TR	E	Double window in anodized aluminium 90x150 cm	2.7	2.62
E	TR	E	Double window in anodized aluminium 240x240 cm	5.76	2.78
E	TR	S	Double window in anodized aluminium 120x240 cm	2.88	2.69
U (stairwell)	OP		Internal partition	19.7	2.15
A (apt. 1B)	OP		Inter-storey slab	77.7	1.38
A (apt. 3B)	OP		inter-storey slab	77.7	1.38

Tables A3. Areas and transmittances of building components subdivided by apartments (heated zones).

Apartment 3A					
Confining environment	**Type of the component**	**Orientation**	**Description**	**Area [m²]**	**Transmittance [W/(m²*K)]**
E	OP	N	External wall	18.5	1.85
E	OP	E	External wall	29.1	1.85
E	OP	S	External wall	11.4	1.85
E	TR	E	Double window in anodized aluminium 120x150 cm	1.8	2.7
E	TR	E	Double window in anodized aluminium 160x240 cm	3.84	2.73
E	TR	E	Double window in anodized aluminium 90x150 cm	1.35	2.62
E	TR	E	Double window in anodized aluminium 160x150 cm	2.4	2.71
E	TR	S	Double window in anodized aluminium 120x150 cm	1.8	2.7
E	TR	S	Double window in anodized aluminium 120x240 cm	2.88	2.69
U (stairwell)	OP		Internal partition	18.8	2.15
A (attic)	OP		Attic floor	71.4	0.201
A (apt 2A)	OP		inter-storey slab	71.4	1.38

Tables A3. Areas and transmittances of building components subdivided by apartments (heated zones).

Apartment 3B					
Confining environment	**Type of the component**	**Orientation**	**Description**	**Area [m²]**	**Transmittance [W/(m²*K)]**
E	OP	N	External wall	18.5	1.85
E	OP	E	External wall	27.8	1.85
E	OP	S	External wall	9.3	1.85
E	TR	E	Double window in anodized aluminium 120x150 cm	1.8	2.7
E	TR	E	Double window in anodized aluminium 160x240 cm	3.84	2.73
E	TR	E	Double window in anodized aluminium 90x150 cm	2.7	2.62
E	TR	E	Double window in anodized aluminium 240x240 cm	5.76	2.78
E	TR	S	Double window in anodized aluminium 120x240 cm	2.88	2.69
U (stairwell)	OP		Internal partition	19.7	2.15
A (attic)	OP		Attic floor	68.4	0.2
A (apt. 2B)	OP		inter-storey slab	68.4	1.38

Tables A3. Areas and transmittances of building components subdivided by apartments (heated zones).

Garage and technical rooms					
Confining environment	**Type of the component**	**Orientation**	**Description**	**Area [m²]**	**Transmittance [W/(m²*K)]**
E	OP	N	External wall	18.5	1.85
E	OP	N	Steel overhead door	27.8	1.85
E	OP	E	External wall	9.3	1.85
E	OP	E	Steel overhead door	1.8	2.7
E	OP	S	External wall	3.84	2.73
E	OP	S	Steel overhead door	2.7	2.62
E	OP	O	External wall	5.76	2.78
E	OP		Floor against the ground	2.88	2.69
Attic					
Confining environment	**Type of the component**	**Orientation**	**Description**	**Area [m²]**	**Transmittance [W/(m²*K)]**
E	OP		Inclined roof	71.4	2.1
E	OP		Inclined rood	68.4	2.1

Tables A4. Areas and transmittances of building components of the unheated zones.

A.2. BUILDING ENVELOPE POST-RETROFIT

External wall: no terraces and garages.					
	Thickness [m]	Conductivity [W/(m*K)	Density [kg/m^3]	Specific heat [J/(kg*K)]	Thermal resistance [(m^2*K)/W]
Internal plaster	0.02	0.7	1400	1000	0.029
Brick	0.25	0.779	1800	840	0.321
External cement mortar	0.02	0.9	1800	1000	0.022
EPS	0.12	0.035	15	1340	3.429
Total thermal conductivity [W/(m^2*K)]					0.252
External wall: terraces					
	Thickness [m]	Conductivity [W/(m*K)	Density [kg/m^3]	Specific heat [J/(kg*K)]	Thermal resistance [(m^2*K)/W]
Internal plaster	0.02	0.7	1400	1000	0.029
Brick	0.25	0.779	1800	840	0.321
External cement mortar	0.02	0.9	1800	1000	0.022
Aerogel	0.01	0.016	200	1030	0.69
EPS	0.05	0.035	15	1340	3.429
Total thermal conductivity [W/(m^2*K)]					0.215

Tables A5. Stratigraphy of the opaque components after retrofit.

ANNEX B: CHARACTERISTICS OF THE RADIATORS

APARTMENT 1A						
Material	**Type**	**Length [mm]**	**Height [mm]**	**Depth [mm]**	**N° Elements**	**N° Column**
Cast iron	Plate	420	880	125	7	4
Cast iron	Plate	720	560	125	12	4
Cast iron	Plate	845	560	125	14	4
Cast iron	Plate	480	560	125	6	4
Cast iron	Plate	420	880	125	7	4
Cast iron	Plate	600	560	125	10	4
Cast iron	Plate	420	880	125	7	4
APARTMENT 1B						
Material	**Type**	**Length [mm]**	**Height [mm]**	**Depth [mm]**	**N° Elements**	**N° Column**
Cast iron	Plate	480	870	110	8	3
Aluminium flat	Plate	640	870	95	8	5
Aluminium flat	Plate	720	570	95	9	6
Aluminium flat	Plate	560	570	95	7	6
Aluminium flat	Plate	480	570	95	6	6
Aluminium flat	Plate	720	870	95	9	5
Aluminium flat	Plate	720	570	95	9	6
APARTMENT 2A						
Material	**Type**	**Length [mm]**	**Height [mm]**	**Depth [mm]**	**N° Elements**	**N° Column**
Steel	Tubular	270	890	110	6	3
Steel	Column	450	600	150	10	4
Steel	Column	645	600	150	14	3
Cast iron	Plate	360	560	125	6	4
Steel	Column	285	900	150	6	3
Steel	Column	450	600	150	10	3
Steel	Column	235	900	150	5	3

APARTMENT 2B						
Material	**Type**	**Length [mm]**	**Height [mm]**	**Depth [mm]**	**N° Elements**	**N° Column**
Steel	Column	305	900	150	7	4
Cast iron	Column	360	870	145	6	4
Steel	Column	450	600	150	10	3
Steel	Column	450	600	150	10	3
Steel	Towel radiator	540	1490		35	1
Steel	Column	525	900	150	11	3
Steel	Column	450	600	150	10	3
APARTMENT 3A						
Material	**Type**	**Length [mm]**	**Height [mm]**	**Depth [mm]**	**N° Elements**	**N° Column**
Aluminium round	Plate	395	880	80	5	5
Steel	Column	785	600	150	17	3
Steel	Column	1100	600	150	24	3
Steel	Column	645	600	150	14	3
Steel	Column	455	900	150	10	3
Steel	Column	725	600	150	16	3
Steel	Column	370	900	150	8	3
APARTMENT 3B						
Material	**Type**	**Length [mm]**	**Height [mm]**	**Depth [mm]**	**N° Elements**	**N° Column**
Steel	Column	425	900	150	9	3
Steel	Column	370	900	150	8	3
Steel	Column	875	600	150	19	3
Steel	Column	455	600	150	10	3
Steel	Column	605	600	150	13	3
Steel	Column	805	900	150	17	3
Steel	Column	830	600	150	18	3

Table 1B. Radiators' characteristics per each apartment.

Material	Type	N° column	Height [mm]	Thermal output per element: $\Delta T = 50\ K$
Cast iron	Plate	4	880	145
Cast iron	Plate	4	560	98.6
Aluminium flat	Plate	5	870	173.8
Aluminium flat	Plate	6	570	123.2
Steel	Column	4	600	80.2
Steel	Column	3	600	61.6
Steel	Column	3	900	88.9
Steel	Column	4	900	116.9
Towel radiator	/	1	1490	793
Steel	Tubular	3	900	88.9
Aluminium round	Plate	5	880	163

Table 2B. Thermal output in standard conditions for each type of radiator .

Material	Type	N° column	Height [mm]	Characteristic coefficient	Thermal output per element: $\Delta T = 25\ K$
Cast iron	Plate	4	880	1.338	57.4
Cast iron	Plate	4	560	1.348	38.7
Aluminium flat	Plate	5	870	1.348	68.3
Aluminium flat	Plate	6	570	1.324	49.2
Steel	Column	4	600	1.282	33
Steel	Column	3	600	1.29	25.2
Steel	Column	3	900	1.293	36.3
Steel	Column	4	900	1.315	47
Towel radiator	/	1	1490	1.249	333.6
Steel	Tubular	3	900	1.293	36.3
Aluminium round	Plate	5	880	1.369	63.1

Table 3B. Characteristic coefficients and thermal output for each type of radiator in non-standard condition.

ANNEX C: GRAPHICAL REPRESENTATION OF THE MODEL'S ERROR

UNIT 10

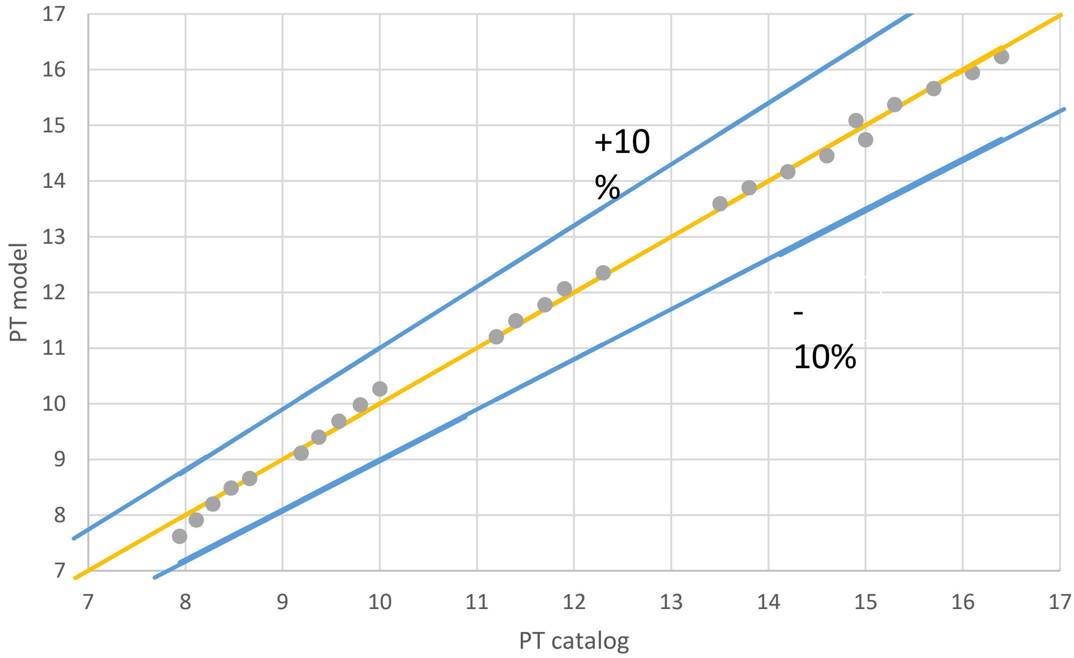


Figure 1.C. Relative error of the model for PT, Unit 10.

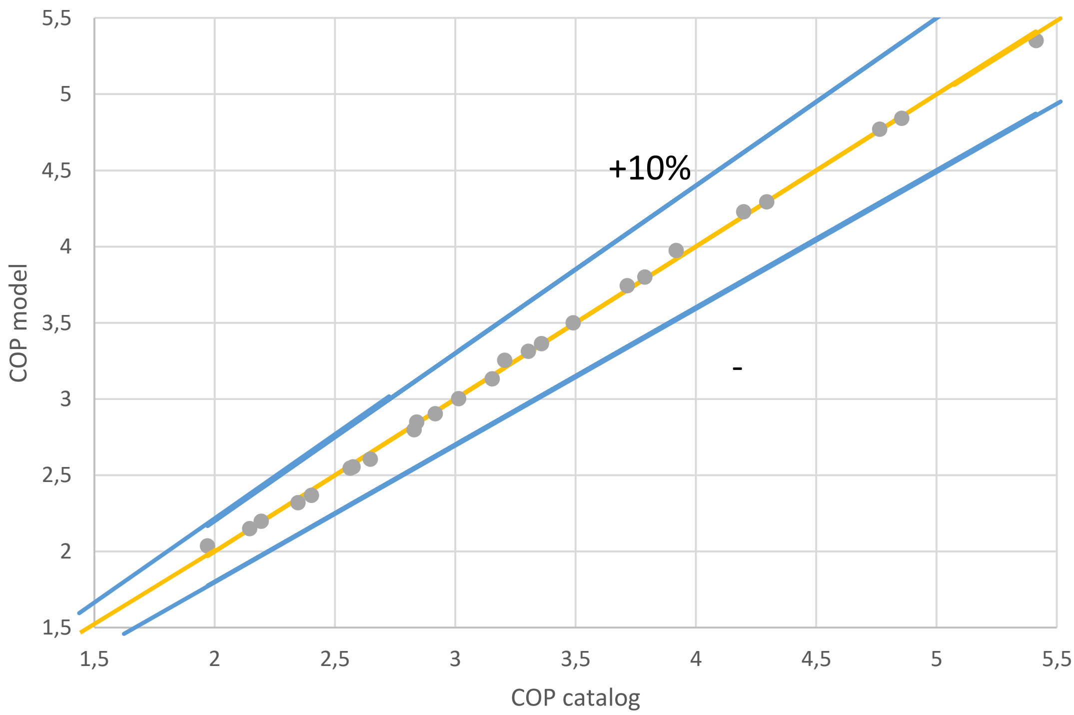


Figure 2.C. Relative error of the model for $COP_{100\%}$, Unit 10.

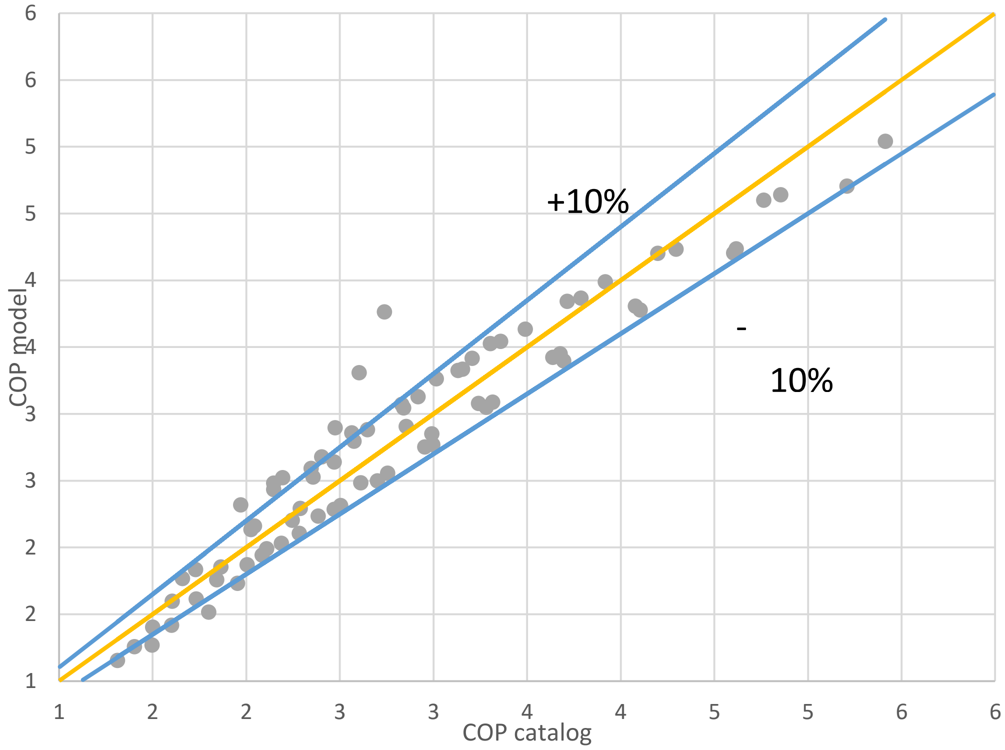


Figure 3.C. Relative error of the model for COP_{gen}, Unit 10.

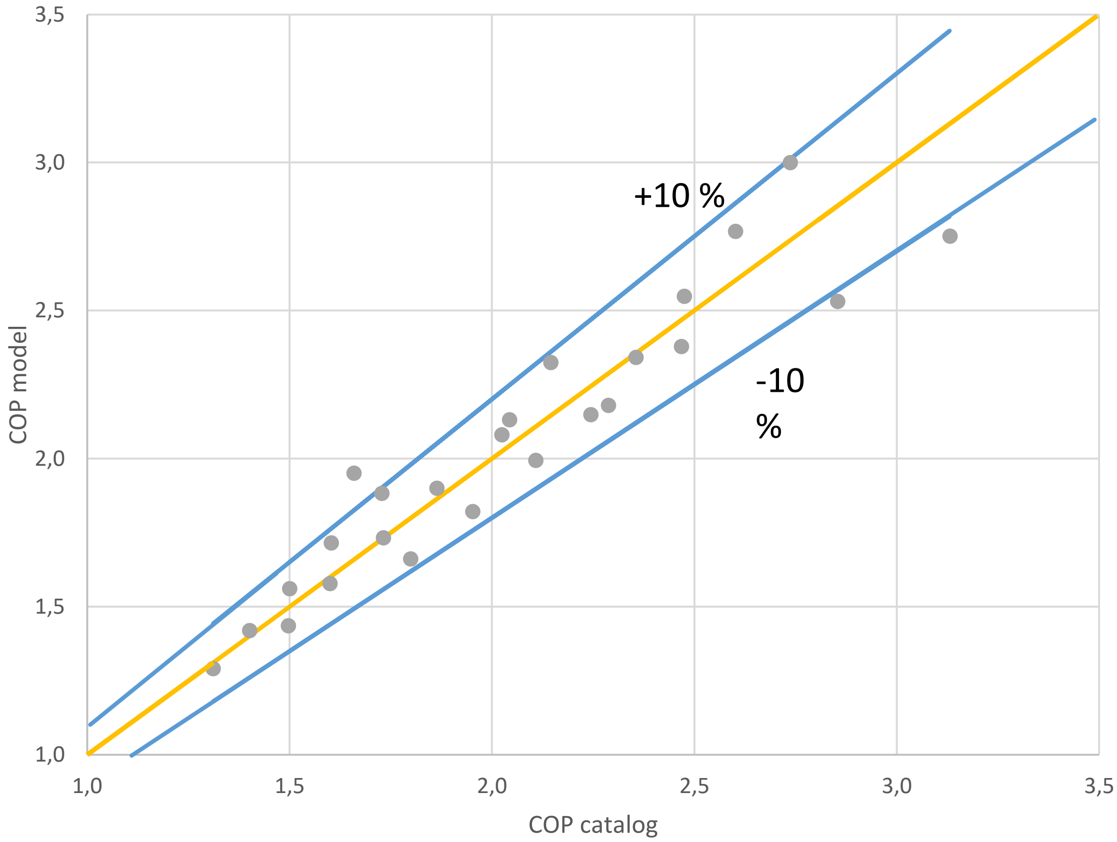


Figure 4.C. Relative error of the model for $COP_{25\%}$, Unit 10.

UNIT 14

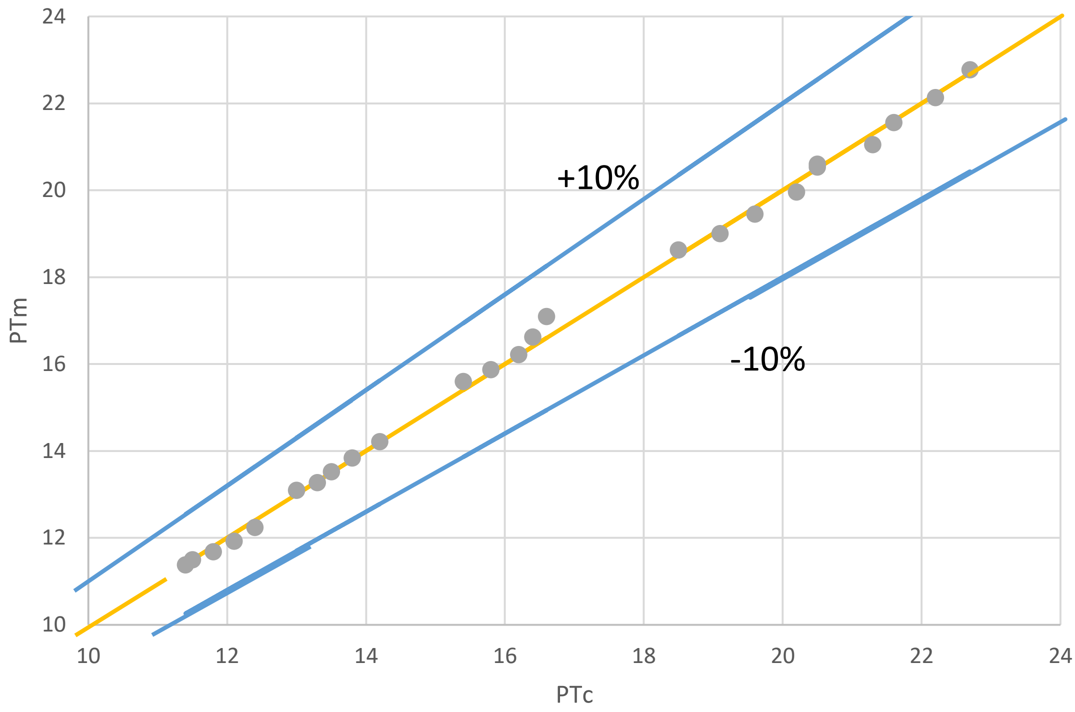


Figure 5.C. Relative error of the model for PT, Unit 14.

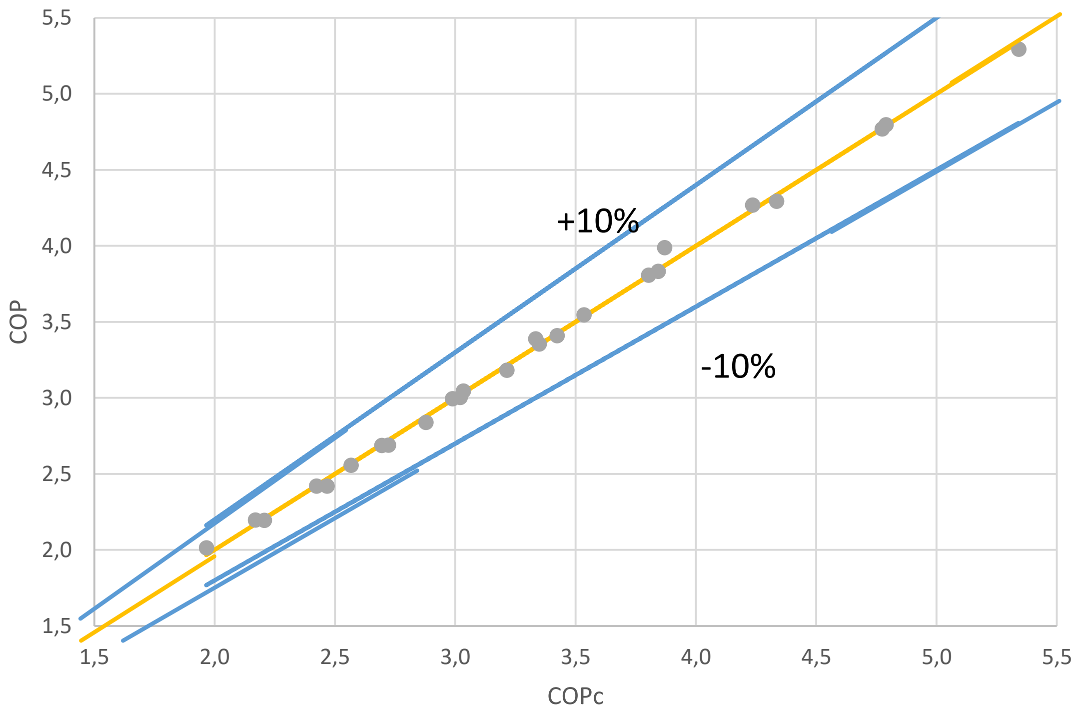


Figure 6.C. Relative error of the model for $COP_{100\%}$, Unit 14.

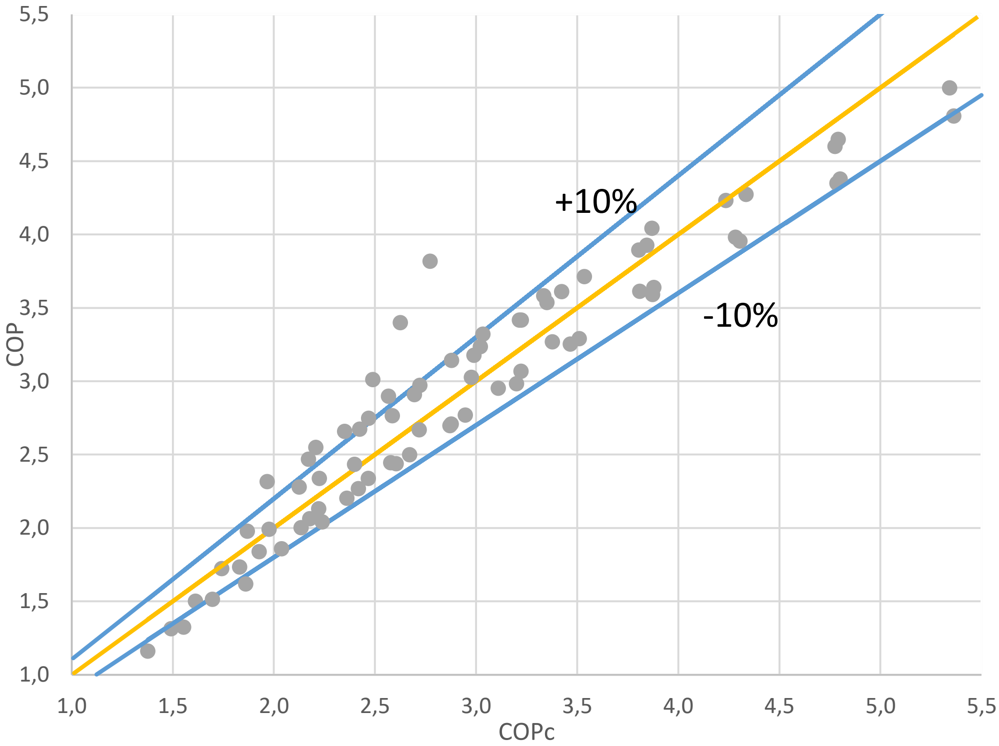


Figure 7.C. Relative error of the model for COP_{gen}, Unit 14.

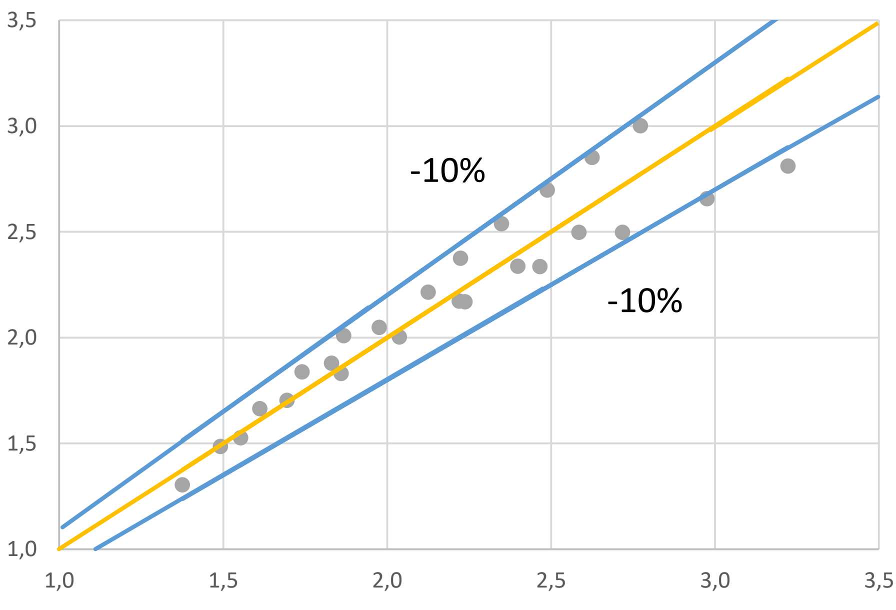


Figure 8.C. Relative error of the model for $COP_{25\%}$, Unit 14.

ANNEX D: DETAILED RESULTS

D.1. RADIATOR HEATING SYSTEM

WCC = weather compensated curve

c-o = cut-off

HP = heat pump

10-year comparison	2xUnit 10	2xUnit 10	2xUnit 14	2xUnit 14	Boiler
Type, regulation	HP, -	HP, WCC	HP, -	HP, WCC	
Power heat pump (A7°C, W40-45°C) [kW]	2x11.4	2x11.4	2x15.7	2x15.7	/
Thermal energy HP [kWh]	124734	124719	124939	124939	/
Electricity consumed [kWh]	49861	46006	45611	42284	/
SCOP heat pump 1	2.64	2.87	2.79	3.02	
SCOP heat pump 2	1.56	1.62	1.46	1.47	/
Net energy demand [kWh]	98935	98935	98935	98935	98935
Electricity cost [euro]	11737	10820	10758	9961	/
Total cost energy [euro]	11737	10820	10758	9961	10604
Final energy consumption [kWh]	124939	124939	124939	124939	139149
Primary energy [kWh]	120664	111336	110379	102326	146107
Renewable part [kWh]	24133	22267	22076	20465	/
CO_2emissions [t CO_2]	12.964	11.962	11.859	10.994	28.11
Delta primary energy [kWh]	25443	34771	35728	43780	/
Delta CO_2emissions [t CO_2]	15.144	16.146	16.249	17.114	/
Cost including maintenance [euro]	11737.08	10820.32	10757.83	9960.72	15604

Table 1C. Comparison between only-heat pump configurations over 10 years.

10-year comparison	Unit 10	Unit 10	Unit 10	Unit 14	Unit 14	Unit 14	Boiler
Type, regulation	Hy, -	Hy, WCC	Hy, WCC + co	Hy, -	Hy, WCC	Hy, WCC + co	
Power heat pump (A7°C, W40-45°C) [kW]	11.40	11.40	11.40	15.70	15.70	15.70	/
Max power boiler [kW]	14.57	14.57	21.35	10.58	10.58	21.35	/
Thermal energy HP [kWh]	116235	116611	102296	123285	123297	104810	/
Thermal energy boiler [kWh]	8728	8320	22635	1646	1634	20120	/
Total thermal energy [kWh]	124963	124931	124931	124931	124931	124931	/
Final energy boiler [kWh]	9697	9245	25150	1829	1816	22356	/
Gas consumed [Sm^3]	876	835	2272	165	164	2020	/
Electricity consumed [kWh]	44185	40752	33985	44321	41006	33299	/
SCOP heat pump 1	2.64	2.87	3.02	2.79	3.02	3.15	/
Net energy demand [kWh]	98935	98935	98935	98935	98935	98935	98935
Gas cost [euro]	720	686	1997	134	133	1774	/
Electricity cost [euro]	10453	9633	8101	10467	9673	7934	/
Total cost energy [euro]	11173	10319	10098	10601	9806	9708	10604
Final energy consumption [kWh]	124939	124939	124939	124939	124939	124939	139149
Primary energy [kWh]	117109	108326	108653	109176	101141	104058	146107
Renewable part [kWh]	21385	19724	16449	21451	19847	16117	/
CO_2emissions [t CO_2]	13.447	12.463	13.917	11.893	11.028	13.174	28.11
Delta primary energy [kWh]	28997	37781	37454	36930	44966	42048	/
Delta CO_2emissions [t CO_2]	14.661	15.645	14.192	16.215	17.080	14.934	/
Cost including maintenance euro]	16173	15319	15098	15601	14806	14708	15604

Table 2C. Comparison between hybrid configurations over 10 years.

10-year comparison, 2018 prices	**2xUnit 10**	**2xUnit 10**	**2xUnit 14**	**2xUnit 14**	**Boiler**
Type, regulation	HP, -	HP, WCC	HP, -	HP, WCC	
Power heat pump (A7°C, W40-45°C) [kW]	2x11.4	2x11.4	2x15.7	2x15.7	/
Thermal energy HP [kWh]	124734	124719	124939	124939	/
Electricity consumed [kWh]	49861	46006	45611	42284	/
SCOP heat pump 1	2.64	2.87	2.79	3.02	/
SCOP heat pump 2	1.56	1.62	1.46	1.47	/
Net energy demand [kWh]	98935	98935	98935	98935	98935
Electricity cost [euro]	10567	9750	9666	8961	/
Total cost energy [euro]	10567	9750	9666	8961	10041
Final energy consumption [kWh]	124939	124939	124939	124939	139149
Primary energy [kWh]	120664	111336	110379	102326	146107
Renewable part [kWh]	24133	22267	22076	20465	/
CO_2emissions [t CO_2]	12.964	11.962	11.859	10.994	28.108
Delta primary energy [kWh]	25443	34771	35728	43780	/
Delta CO_2emissions [t CO_2]	15.144	16.146	16.249	17.114	/
Cost including maintenance [euro]	10567	9750	9666	8961	15041

Table 3C. Comparison between only-heat pump configurations over 10 years considering the prices of the year 2018.

10-year comparison, 2018 prices	**Unit 10**	**Unit 10**	**Unit 10**	**Unit 14**	**Unit 14**	**Unit 14**	**Boiler**
Type, regulation	Hy, -	Hy, WCC	Hy, WCC + co	Hy, -	Hy, WCC	Hy, WCC + co	
Power heat pump (A7°C, W40-45°C) [kW]	11.40	11.40	11.40	15.70	15.70	15.70	/
Max power boiler [kW]	14.57	14.57	21.35	10.58	10.58	21.35	/
Thermal energy HP [kWh]	116235	116611	102296	123285	123297	104810	/
Thermal energy boiler [kWh]	8728	8320	22635	1646	1634	20120	/
Total thermal energy [kWh]	124963	124931	124931	124931	124931	124931	/
Final energy boiler [kWh]	9697	9245	25150	1829	1816	22356	/
Gas consumed [Sm^3]	876	835	2272	165	164	2020	/
Electricity consumed [kWh]	44185	40752	33985	44321	41006	33299	/
SCOP heat pump 1	2.64	2.87	3.02	2.79	3.02	3.15	/
Net energy demand [kWh]	98935	98935	98935	98935	98935	98935	98935
Gas cost [euro]	699.74	667.06	1814.76	131.94	131.01	1613.13	/
Electricity cost [euro]	9364.11	8636.54	7202.58	9392.95	8690.43	7057.19	/
Total cost energy [euro]	10064	9304	9017	9525	8821	8670	10041
Final energy consumption [kWh]	124939	124939	124939	124939	124939	124939	139149
Primary energy [kWh]	117109	108326	108653	109176	101141	104058	146107
Renewable part [kWh]	21385	19724	16449	21451	19847	16117	/
CO_2emissions [t CO_2]	13.447	12.463	13.917	11.893	11.028	13.174	28.108
Delta primary energy [kWh]	28997	37781	37454	36930	44966	42048	/
Delta CO_2emissions [t CO_2]	14.661	15.645	14.192	16.215	17.080	14.934	/
Cost including maintenance [euro]	15064	14304	14017	14525	13821	13670	15041

Table 4C. Comparison between hybrid configurations over 10 years considering the prices of the year 2018.

10-year comparison, 2022 prices	**2xUnit 10**	**2xUnit 10**	**2xUnit 14**	**2xUnit 14**	**Boiler**
Type, regulation	HP, -	HP, WCC	HP, -	HP, WCC	
Power heat pump (A7°C, W40-45°C) [kW]	2x11.4	2x11.4	2x15.7	2x15.7	/
Thermal energy HP [kWh]	124734	124719	124939	124939	/
Electricity consumed [kWh]	49861	46006	45611	42284	/
SCOP heat pump 1	2.64	2.87	2.79	3.02	/
SCOP heat pump 2	1.56	1.62	1.46	1.47	/
Net energy demand [kWh]	98935	98935	98935	98935	98935
Electricity cost [euro]	27932	25773	25551	23687	/
Total cost energy [euro]	27932	25773	25551	23687	16288
Final energy consumption [kWh]	124939	124939	124939	124939	14706
Primary energy [kWh]	120664	111336	110379	102326	146107
Renewable part [kWh]	24133	22267	22076	20465	/
CO_2emissions [t CO_2]	12.964	11.962	11.859	10.994	28.11
Delta primary energy [kWh]	25443	34771	35728	43780	/
Delta CO_2emissions [t CO_2]	15.144	16.146	16.249	17.114	/
Cost including maintenance [euro]	27932.17	25772.82	25551.34	23687.31	21288

Table 5C. Comparison between only-heat pump configurations over 10 years considering the prices of the year 2022.

10-year comparison, 2022 prices	Unit 10	Unit 10	Unit 10	Unit 14	Unit 14	Unit 14	Boiler
Type, regulation	Hy, -	Hy, WCC	Hy, WCC + co	Hy, -	Hy, WCC	Hy, WCC + co	
Power heat pump (A7°C, W40-45°C) [kW]	11.40	11.40	11.40	15.70	15.70	15.70	/
Max power boiler [kW]	14.57	14.57	21.35	10.58	10.58	21.35	/
Thermal energy HP [kWh]	116235	116611	102296	123285	123297	104810	/
Thermal energy boiler [kWh]	8728	8320	22635	1646	1634	20120	/
Total thermal energy [kWh]	124963	124931	124931	124931	124931	124931	/
Final energy boiler [kWh]	9697	9245	25150	1829	1816	22356	/
Gas consumed [Sm^3]	876	835	2272	165	164	2020	/
Electricity consumed [kWh]	44185	40752	33985	44321	41006	33299	/
SCOP heat pump 1	2.64	2.87	3.02	2.79	3.02	3.15	/
Net energy demand [kWh]	98935	98935	98935	98935	98935	98935	98935
Gas cost [euro]	1121	1068	2906	211	210	2583	/
Electricity cost [euro]	24752	22829	19039	24828	22972	18654	/
Total cost energy [euro]	25873	23897	21945	25040	23181	21238	16288
Final energy consumption [kWh]	124939	124939	124939	124939	124939	124939	14706
Primary energy [kWh]	117109	108326	108653	109176	101141	104058	146107
Renewable part [kWh]	21385	19724	16449	21451	19847	16117	/
CO_2emissions [t CO_2]	13.447	12.463	13.917	11.893	11.028	13.174	28.108
Delta primary energy [kWh]	28997	37781	37454	36930	44966	42048	/
Delta CO_2emissions [t CO_2]	14.661	15.645	14.192	16.215	17.080	14.934	/
Cost including maintenance [euro]	30873	28897	26945	30040	28181	26238	21288

Table 6C. Comparison between hybrid configurations over 10 years considering the prices of the year 2022.

D.2. UNDERFLOOR HEATING SYSTEM

10-year comparison	2xUnit 10	2xUnit 14	Boiler
Type, regulation	HP, -	HP, -	
Power heat pump (A7°C, W40-45°C) [kW]	2x11.4	2x15.7	/
Thermal energy HP [kWh]	124904	124938	/
Electricity consumed [kWh]	38543	36955	/
SCOP heat pump 1	3.37	3.43	
SCOP heat pump 2	1.89	1.98	/
Net energy demand [kWh]	98935	98935	98935
Electricity cost [euro]	9074	8721	/
Total cost energy [euro]	9074	8721	10604
Final energy consumption [kWh]	124939	124939	139149
Primary energy [kWh]	93273	89432	146107
Renewable part [kWh]	18655	17886	/
CO_2emissions [t CO_2]	10.021	9.608	28.11
Delta primary energy [kWh]	52833	56675	/
Delta CO_2emissions [t CO_2]	18.087	18.500	/
Cost including maintenance [euro]	9073	8720	15604

Table 7C. Comparison between heat pump configurations for underfloor heating over 10 years.

10-year comparison, 2018 prices	**2xUnit 10**	**2xUnit 14**	**Boiler**
Type, regulation	HP, -	HP, -	
Power heat pump (A7°C, W40-45°C) [kW]	2x11.4	2x15.7	/
Thermal energy HP [kWh]	124904	124938	/
Electricity consumed [kWh]	38543	36955	/
SCOP heat pump 1	3.37	3.43	/
SCOP heat pump 2	1.89	1.98	/
Net energy demand [kWh]	98935	98935	98935
Electricity cost [euro]	8168	7832	/
Total cost energy [euro]	8168	7832	10041
Final energy consumption [kWh]	124939	124939	139149
Primary energy [kWh]	93273	89432	146107
Renewable part [kWh]	18655	17886	/
CO_2emissions [t CO_2]	10.021	9.608	28.11
Delta primary energy [kWh]	52833	56675	/
Delta CO_2emissions [t CO_2]	18.087	18.500	/
Cost including maintenance [euro]	8168	7832	15041

Table 7C. Comparison between heat pump configurations for underfloor heating over 10 years considering the prices of the year 2018.

10-year comparison, 2022 prices	2xUnit 10	2xUnit 14	Boiler
Type, regulation	HP, -	HP, -	/
Power heat pump (A7°C, W40-45°C) [kW]	2x11.4	2x15.7	/
Thermal energy HP [kWh]	124904	124938	/
Electricity consumed [kWh]	38543	36955	/
SCOP heat pump 1	3.37	3.43	/
SCOP heat pump 2	1.89	1.98	/
Net energy demand [kWh]	98935	98935	98935
Electricity cost [euro]	21592	20702	/
Total cost energy [euro]	21592	20702	16288
Final energy consumption [kWh]	124939	124939	14706
Primary energy [kWh]	93273	89432	146107
Renewable part [kWh]	18655	17886	/
CO_2emissions [t CO_2]	10.021	9.608	28.11
Delta primary energy [kWh]	52833	56675	/
Delta CO_2emissions [t CO_2]	18.087	18.500	/
Cost including maintenance [euro]	21591.57	20702.38	21288

Table 7C. comparison between heat pump configurations for underfloor heating over 10 years considering the prices of the year 2022.

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