Assessing the decarbonization potential of new generation R290 high-temperature heat pumps for apartment buildings

Energy Reports 13 (2025) 2095–2105

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Assessing the decarbonization potential of new generation R290 high-temperature heat pumps for apartment buildings

Maria Ferrara [a,*], Michele Babuin [b], Enrico Fabrizio [a], Stefano P. Corgnati [a]

[a] *Department of Energy, Politecnico Di Torino, Turin, Italy*
[b] *Rhoss SpA, Codroipo (UD), Italy*

ARTICLE INFO

Keywords:
Heat pumps
Residential buildings
Space heating
Natural refrigerants
High-temperature
Propane

ABSTRACT

Electricity driven heat pumps, especially the air-to-water ones, represent a key technology for the decarbonization of existing residential buildings. In particular, new R290 (propane) heat pumps represent a valuable solution for substituting existing combustion boilers in hot water heating systems at medium/high temperature without the refurbishment of the building envelope. In this work, the feasibility and potential energy savings that can be obtained by the application of high-temperature R290 heat pumps with respect to the condensing boiler technology when retrofitting existing residential buildings equipped with high-temperature heating systems is assessed. The results show that the energy savings are of the order of the 20 % in terms of non-renewable primary energy when R290 heat pumps are compared to the most efficient and up-to-date condensing boilers. Larger emission savings can be obtained when heat pumps are fed by green electricity.

1. Introduction

It is well known that in order to achieve a global net-zero emissions scenario, supplying heat in residential buildings should achieve the elimination of coal- and oil-fired boilers and a dramatic decrease in gas-fired boilers (Tilche et al., 2022).

According to data from the European Environment Agency (EEA), the residential sector in the European Union (EU) accounts for more than 10 % of total greenhouse gas emissions, with heating being the largest contributor (European Environment Agency (EEA), 2023). Furthermore, the EU's Heating and Cooling Strategy (European Commission, Heating) aims to reduce the carbon intensity of heating by at least 1.5 % per year between 2021 and 2030, as also reinforced in the European Green Deal and the 'Fit for 55' package emphasizing that without increasing decarbonization efforts in this sector the EU energy and climate targets cannot be achieved, considering the cost-effectiveness of the heat pump technologies with respect to other energy efficiency measures (European Commission, Fit).

Also considering the accelerating trends towards electrification and efficiency improvement of final uses in new and existing buildings, electricity driven heat pumps represent a key technology for the decarbonization of the sector. Systems for Zero Energy Buildings have been characterized by a larger use of heat pumps (Ferrara et al., 2018) for both the possibility of exploiting renewable energy and being driven by green electricity (Ferrara et al., 2015). In Europe, the residential building stock is composed of approximately 120 million units, representing a significant potential market for heat pump adoption and expansion. The latest years have registered unprecedented sales record, with peak annual growth of 39 % in 2022. Currently, there are approximately 20 million heat pump units installed across the continent, with a market share of about 16 % indicating a substantial opportunity for growth within the heat pump market. In fact, it is expected that in the next few years the REpowerEU targets (Communication From The Commission To The European Parliament, The) will drive the market towards the phase-out of gas boilers and the consequent elimination of fossil fuels (European Heat Pump Association, 2023a).

Such rapid growth of the heat pump market in Europe is driven by various factors, including supportive policies and financial subsidies aimed at accelerating the energy transition and the subsequent economies of scale, which result in lower production costs and increased accessibility and affordability for consumers, further driving market growth (Nowak, 2021).

From a technological point of view, heat pumps are continuously evolving to meet the diverse heating needs of different contexts, as emerging from the ongoing activities of the IEA Technology Collaboration Program Annex 62 focused on heat pumps for multi-family residential buildings in cities (IEA TCP Annex 62, Heat). Advancements in

* Corresponding author.
E-mail address: maria.ferrara@polito.it (M. Ferrara).

https://doi.org/10.1016/j.egyr.2025.01.008
Received 5 March 2024; Received in revised form 28 December 2024; Accepted 4 January 2025
Available online 31 January 2025

Nomenclature

COP	Coefficient of Performance
DHW	Domestic Hot Water
E_{del}	Electrical energy use
EP_{nren}	Non-renewable primary energy
EP_{ren}	Renewable primary energy
PLF	part load factor
PLR	part load ratio
Q	thermal energy use
SPF	seasonal performance factor
$T_{w,load}$	temperature of the supply hot water
$T_{air,ext}$	outdoor air temperature
η	efficiency
Subscripts	
aux	auxiliary
d	design
H	space heating
i	i-time step
W	hot water

heat pump technology have enabled these systems to cover wide temperature ranges effectively, enhancing their versatility and applicability across various climatic conditions and building types. Among others, the air-to-water heat pump segment is experiencing the more rapid growth (Fig. 1), highlighting the increasing market penetration of the heat pump type that can be used in existing hydronic heating systems.

At the same time, there have been several challenges and shortcomings in the use of heat pumps in both new and existing buildings (Guidetti and Ferrara, 2023). The fact that heat pump applications in large residential buildings are less common than in single-family houses is because blocks of flats present a range of heat demand characteristics, which may lead to frequent mismatch between the designers' expectations and real performance, leading to higher running energy costs, if not properly addressed (Biglia et al., 2021). Also, the high thermal levels required by existing heating systems prevent heat pumps from replacing old boilers in existing buildings if a deep renovation of the entire building is not possible. In fact, large residential buildings generally have centralized heat production, low-performing building envelopes,

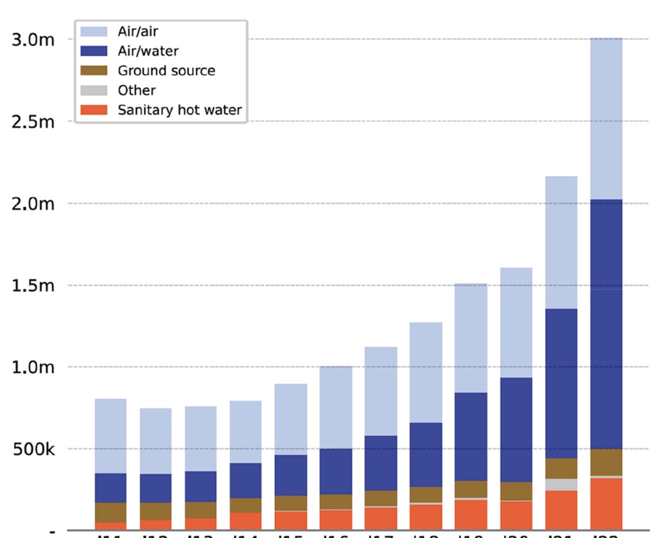

Fig. 1. Heat Pump market in Europe (number of units sold per year). Source: EHPA (European Heat Pump Association, 2023a).

medium to high supply hot water temperatures (65°C – 75°C), and a significant demand for domestic hot water production that may or may not be centralized.

In these cases, it is almost impossible to envision replacing system terminals with low-temperature terminals without deep renovation interventions on the building envelope. If retrofitting only involves the heat generator and existing terminals must be used, the aforementioned high working temperatures should be maintained. Ensuring heat pump systems that can address a variety of heat demand characteristics and guarantee adequate thermal levels is therefore key to promoting their adoption in multi-family residential buildings (European Heat Pump Association, 2023b).

Given this framework, the technology of R-290 (propane) heat pumps (Nawaz et al., 2017) can play a central role in driving the transition towards the adoption of clean energy solutions, as also foreseen by the latest IEA Energy Technology Perspectives, thanks to their high level of technological maturity and the consequent possibility of large-scale implementation in existing residential buildings – even though not (yet) retrofitted – where the temperature levels are 50 °C and over for the use with traditional radiators as heat emitters. This has also the potential to make the production of DHW easier and energy efficient (Du et al., 2020).

Regarding the problem of replacing the central heating plant in existing hot water systems equipped with radiators, various studies in the literature have shown that although the equipment was designed for supply water temperatures up to 75°C or 80°C on colder days, radiators were often over-dimensioned for safety and, in most cases, the supply hot water temperature can be reduced (Roca Reina et al., 2024). This is evidenced by studies conducted in Denmark (approximately 80 % of heating systems are over-dimensioned by 20–30 % compared to the current design heat load (Østergaard and Svendsen, 2018)), Sweden (total radiator surfaces are usually oversized (Ljunggren P, 2006)), and the Netherlands (the supply water temperature can be lowered to 55°C for 60 % of dwellings out of a set of 220 existing dwellings (Pothof et al., 2022)). In Italy, a recent study also showed the energy, environmental and economic potential of substituting existing heat generators with heat pumps, highlighting the fact that radiators are typically oversized in older apartment buildings (Schito et al., 2023).

These studies suggest that it is possible and reasonable to consider replacing the central heating plant and slightly reducing the supply water temperature to maximize the performance and profitability of the R-290 heat pump, where applicable. If heat pumps extract energy from air, the R-290 technology efficiency is less dependent on the outside temperature lower values and fluctuations. At the same time, the use of propane heat pumps brings some risks related to the flammability that should be carefully addressed (Tang et al., 2018), but that can be easily faced when the system is used to replace an existing fuel boiler.

1.1. Objectives and approach

Given this picture, the scope of this work is to investigate the applicability of medium-size R-290 air-to-water heat pumps to cover the energy needs for space heating and domestic hot water of existing residential buildings with optimized efficiency. In particular, this study is devoted to analyse the feasibility and potential energy savings related to the application of this innovative technology with respect to the other technologies that are currently more present in the market for application in retrofit of existing residential buildings equipped with high-temperature heating systems (typically, gas-boiler with radiators). To do so, the annual dynamics of the different energy needs of a typical existing multi-family building were studied in relation to a climate scenario that is representative of middle-European climate zones (Milan, Italy). The performance of the innovative heat pump system was then assessed based on a simulation model tailored on detailed performance curves provided by one Italian manufacturer for the specific real case study, therefore providing realistic results based on real data.

The obtained results were then studied in comparison to an existing condensing boiler in terms of primary energy and costs.

2. Materials and methods

The present work was conducted following a methodological process made of 4 main steps:

1. Identification of a reference building for the existing multi-family building typology in Italy to which a reference equipment scenario and the HP-based equipment retrofit scenario can be applied. Following reference data for the Italian building stock deriving from the EU TABULA project (Corrado et al., 2012), the reference building includes fixed data related to the building envelope and heating terminals, ready to be completed with different options of heat generator;
2. TRNSYS modelling of the so-determined case study building considering the option of the most-efficient fuel-based heating currently available on the market (gas condensing boiler) as heating generator;
3. TRNSYS modelling of the so-determined case study building considering the option of an innovative propane heat pump as heating generator;
4. Annual simulation of the heating loads and energy uses of the different modelled options and comparison of results.

2.1. The case study building

In order to study a multi-family building that is representative of the existing Italian building stock, a real building was selected as real reference building, according to the definition reported in (Corgnati et al., 2013) Also, in order to represent the typical heating-driven climate scenario of middle-Europe, the case study was selected in the Italian climate zone E, considering the weather conditions of the city of Milan (IWEC weather file).

The resulting reference case study is a 6-floors building, oriented along a east-west axis, where each floor is divided into 7 different units, for a gross heated floor surface of 2460 m^2 and gross heated volume of 6600 m^3 for the entire building. The building envelope is made of un-insulated masonry (thickness 30 cm – U value 0.9–1 W/m^2K), while windows are made of wooden-framed double-glazing (U=2.8 W/m^2K) with mean total solar energy transmittance (T-SET, also known as g-value) of 0.65. Some windows are shaded by external loggias, a typical feature of the Italian architecture, as shown in Fig. 1 where the typical floor plan is reported (Fig. 2).

According to the Italian regulation for climate zone E, the heating system is expected to operate between October 15th and April 15th. The heating setpoint is 20°C during the day (between 8 am and 22 pm), while the heating setback during the night is 18°C. The heating element of each space is a thermal radiator of a size that is demonstrated able to satisfy the heating needs operating at 65°C at design conditions (outdoor design temperature −5°C). The control of heat emitted by the radiator is done through the control of the supply water temperature following a climate curve that is proportional to the outdoor temperature. The equation of the climate curve is

$$T_{w,load} = -T_{air,ext} + 60[^\circ C] \tag{1}$$

where $T_{w,load}$ is the temperature of the supply hot water and $T_{air,ext}$ is the outdoor air temperature. Following this curve, and considering that the outdoor air temperature typically ranges between – 5 °C and 16 °C in Milan in the heating system operating season, the supply hot water temperature linearly ranges between 65 °C and 44 °C.

A domestic hot water (DHW) demand was also considered for the case study building. According to the European standard EN 15316:2018 (EN - European Standards, 2018), recently implemented in Italy by the technical standard UNI/TS 11300–2:2019 (25), the average daily consumption of domestic hot water is 3.9 m^3 for the entire building (111.7 l for each dwelling unit). In order to provide the hourly profile for instantaneous hot water demand to the dynamic model, the standard normalized hourly demand profile reported in Fig. 3 was used, provided the total absolute daily demand is equal to the above-mentioned value.

For the computation of thermal energy demand related to DHW production according to the method reported in (UNI - Italian Unification Body, 2019), the water delivery temperature was set to 45°C, the inlet cold water temperature was set to 12°C. The partial system efficiency related to the DHW distribution system was set to 0.7, according to the reference values for water system efficiencies reported in the Italian regulation for minimum performance requirements of buildings (Decreto interministeriale 26 giugno, 2015).

2.2. The gas condensing boiler modelling

As a reference case, a last-generation gas condensing boiler was modelled, as it is considered the most efficient alternative to heat pump when planning heating system renovation interventions. It has also been dynamically simulated through a model implementing, at each timestep, the following equations for determining the Part Load Ratio PLR (Eq. 2) and the related Part Load Factor PLF (Eq. 3), based on performance curves provided by Fabrizio et al, (2009) in a work focused on the dynamic modelling of efficiencies of gas condensing boilers with part load variability (UNI - Italian Unification Body, 2019):

$$PLR = \frac{P_i}{P_d} \tag{2}$$

Fig. 2. Typical floor plan of the 6-floor reference case study building, each apartment is denoted by a different capital letter.

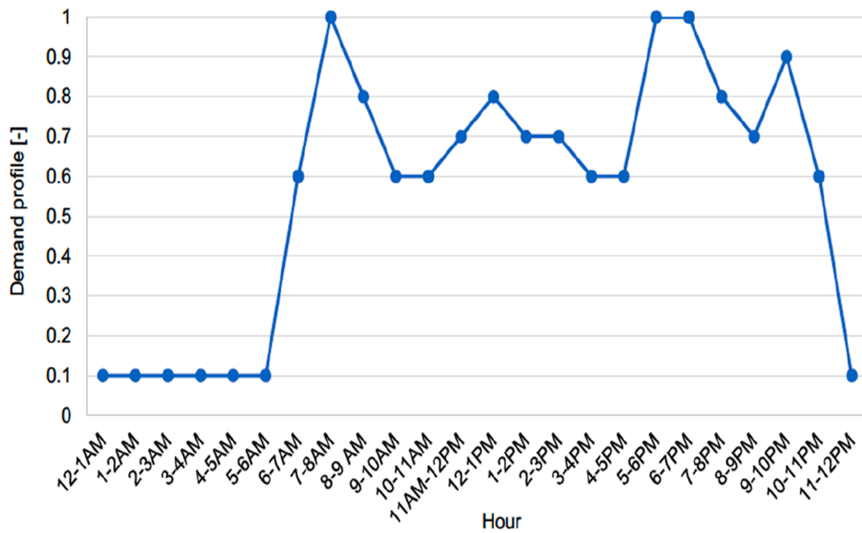

Fig. 3. Normalized standard Domestic Hot Water demand hourly profile used in the model (Source: ASHRAE 90.1 User Manual).

$$PLF = 1.102878 + 0.40960402 \bullet PLR - 1.8956168 \bullet PLR^2 + 2.1626771 * PLR^3 - -0.77911853 * PLR^4 \tag{3}$$

where P_i is the required heating capacity at the time step i and P_d is the design heating capacity resulting from the created building dynamic model at the design conditions.

Therefore, at each timestep i, the boiler efficiency η_i is determined by multiplying the rated efficiency η_d by the calculated PLF, as follows (Eq. 4):

$$\eta_i = \eta_d \bullet PLF \tag{4}$$

where η_d is set to 0.95 and PLF derives from Eq. 3. The efficiency curve of the condensing boiler slightly increases for part load conditions lower than the full load.

2.3. The R290 heat pump modelling

The R290 heat pump that is adopted in this work is a modular heat pumps for hot water production, air cooled with axial fans driven by EC brushless electric motors for electronic speed control, to be installed outdoors. Multiple modules can be combined to provide the required thermal capacity. The actual heating capacity at each working conditions can be arranged by controlling the activation in parallel of each heat pump module in cascade at full load or part load (around 50 % of the heating load) to better supply the required heating capacity.

Data regarding the heating capacity, the power consumption and the related COP of each heat pump module operating at full load have been provided by manufacturer, based on detailed certified laboratory testing for the purpose of characterising the real operating conditions of the studied equipment (Fig. 4). Left side graph of Fig. 4 shows the variation of the heating capacity (at full load) as a function of the outdoor air at the evaporator $T_{air,ext}$ and of three different supply hot water temperatures $T_{w,load}$. At lower operating outdoor temperature there is no variation in the heating output changing the supply water temperature. However, as can be seen in the right graph of Fig. 4, there is a large variation in the power consumed by the heat pump varying the $T_{w,load}$. Considering that the power consumption does not vary significantly (right graph of Fig. 4) while the heating output reduces (left graph of Fig. 4) while reducing the outdoor air temperature, the COP reported in Fig. 5, as a function of the outdoor air temperature follows a trend of reduction from 5 to 2.5 for the lowest supply hot water temperature. The electric fans of the evaporators at the different conditions are considered in the given values of power consumption and COP.

Each module can also operate at partial load (1 step - 50 % of full load), which leads to gradually increase COP values from + 2 % (at the highest $T_{w,load}$=65°C) up to + 8 % (at the lowest $T_{w,load}$=35°C). The R-290 heat pump model uses a modular structure with control algorithms set for maximum efficiency at each timestep. Before any module

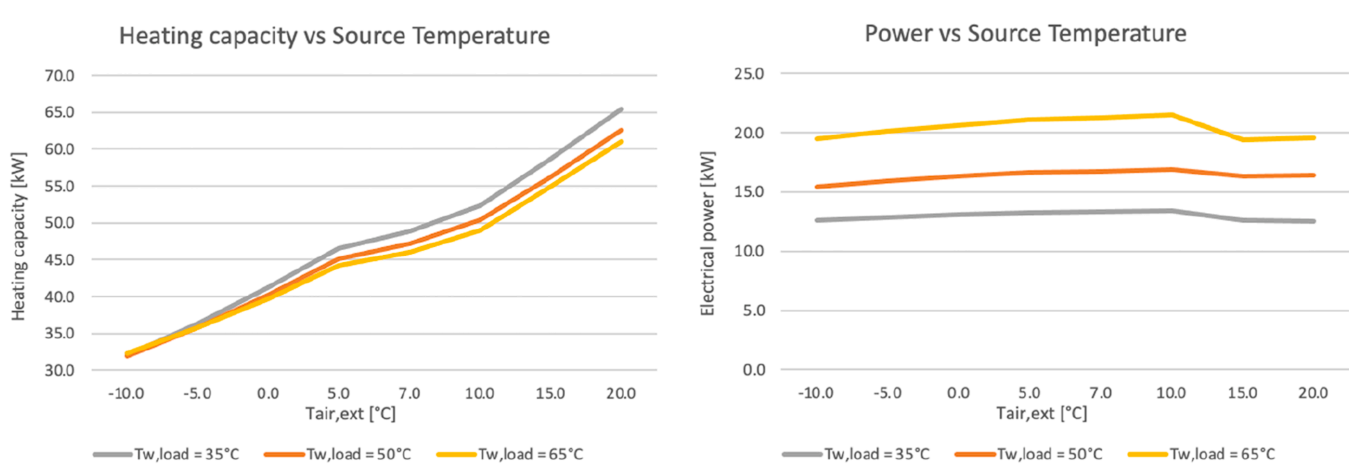

Fig. 4. Performance curves (heating output on the left and power consumption on the right) of the R290 heat pump module at full load.

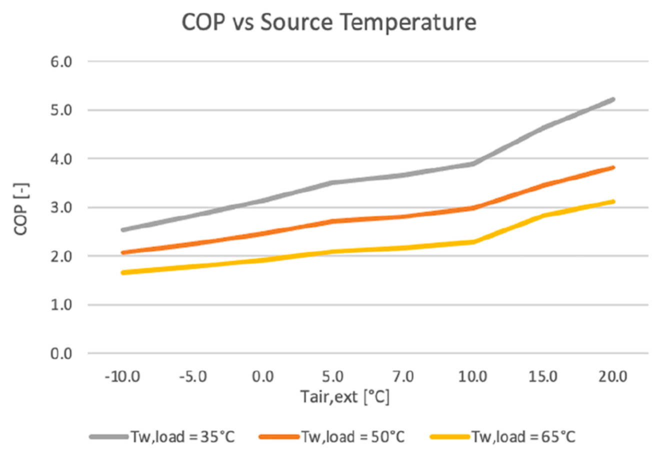

Fig. 5. COP curves of the R290 heat pump module at full load for three representative hot water load temperatures.

operates at full load, all modules run at partial load in parallel. If the combined heating capacity at partial load is insufficient, the first module then switches to full load.

If the energy use of the fans at the evaporator are considered in the COP, at the condenser side of each heat pump module a circulation pump on the hot water loop was modelled with an absorbed electrical power of 0.7 kW per heat pump. This follows the above-mentioned operation of the different equipment modules. following the operation of the different equipment modules.

2.4. The key performance indicators

In order to allow comparing the performance of the new R290 heat pump system to other conventional systems, a set of key performance indicators are used.

For the sake of clarity, we define the different energy-related quantities, according to the current Italian legislation and Standards on building energy calculation and performance assessment [UNI TS 11300] as follows:

- Energy needs. It indicates the net useful energy demand for a certain service. In this study, we refer to thermal energy needs for space heating and domestic hot water, which are dynamically calculated for the entire winter season as explained in Section 2.1;
- Energy use. It refers to heat or electricity used by technical systems to fulfil the different energy needs, calculated as the ratio between energy needs and the system efficiency considered for the calculation period. Such heat or electricity consumptions can also be used for computing energy costs, as they correspond to the amount of heat or electricity that is taken from the grid. In this study, we refer to heat consumption of the gas condensing boiler Q_{gas} (gross consumptions, including system losses) and to electricity consumption of the heat pump. Regarding system efficiencies, the average seasonal efficiency values are computed based on dynamic calculation of efficiencies for each timestep. For the HP system, the average COP is computed only considering the time in which the system is operating. Two values are calculated: one refers to the HP plant only (named "Average COP", without auxiliary pumps), while the other is named Seasonal Performance Factor (SPF) and includes all the components of the entire system (heat pump modules and auxiliaries). For the gas boiler, the efficiency is dynamically calculated as in 2.2 and averaged over the system operation hours, while the SPF also consider electrical auxiliaries and is used for comparison to other systems.
- Primary energy use. The specific non-renewable and renewable primary energy quantities are calculated considering the Italian reference primary energy factors for grid electricity ($f_{pe,nren,ele}$=1.95, $f_{pe,ren,ele}$=0.47) and gas ($f_{pe,nren,gas}$=1.05, $f_{pe,ren,gas}$=0). For the purpose of calculating the renewable contribution of the heat pump technology, the primary energy conversion factor $f_{pe,ren,hp}$= 1 is used to consider the free heat extracted from outdoor air at the heat pump source side.

For the purpose of comparing the two system configurations, the non-renewable primary energy use for heating and DHW $EP_{nrenH+W}$ is used as key performance indicator, where the lowest values indicate the best performance. Therefore, the non-renewable primary energy use related to the HP system $EP_{nrenH+W,HP}$ and to the gas boiler system $EP_{nrenH+W,gas}$ are computed as in Eqs. (5) and (6), respectively:

$$EP_{nrenH+W,HP} = \left(E_{del,H} + E_{del,H,aux} + E_{del,W} + E_{del,W,aux}\right) \bullet 1.95 \tag{5}$$

$$EP_{nrenH+W,gas} = \left(Q_{H+W}\right) \bullet 1.05 + E_{del,gas,aux} \bullet 1.95 \tag{6}$$

Where $E_{del,HP}$ and $E_{del,W}$ are the electricity consumptions of the HP modules dedicated to space heating and DHW, respectively, and $E_{del,H,aux}$ and $E_{del,W,aux}$ are the electrical consumptions related to the operation of auxiliary pumps for space heating and DHW, respectively; Q_{H+W} is the total heat consumption of the gas condensing boiler for space heating and DHW, $E_{del,gas,aux}$ is the electricity consumption of the auxiliary pumps of the gas-based system.

Instead, the renewable primary energy use related to the HP system $EP_{renH+W,HP}$ and the gas boiler system $EP_{renH+W,gas}$ are computed as in Eqs. (7) and (8), respectively:

$$EP_{renH+W,HP} = \left(E_{del,H} + E_{del,H,aux} + E_{del,W} + E_{del,W,aux}\right) \bullet 0.47 + Q_{air} \bullet 1 \tag{7}$$

$$EP_{renH+W,gas} = E_{del,gas,aux} \bullet 0 \tag{8}$$

The Renewable Energy Ratio (RER) is then considered to assess the impact of energy produced from renewable energy sources on the entire system and is usually considered in regulations when indicating a required amount of coverage of energy needs from renewable sources. Since the designed system uses different energy sources to produce a useful effect, the RER including heating and domestic hot water was evaluated using primary energy values, according to the Eq. (9)

$$RER_{H+W} = \frac{EP_{nren,H} + EP_{nren,W}}{EP_{nren,H} + EP_{nren,W} + EP_{ren,H} + EP_{ren,W}} \tag{9}$$

where $EP_{nren,H}$ and $EP_{nren,W}$ are the non-renewable primary energy uses for heating and DHW, respectively, while $EP_{ren,H}$ and $EP_{ren,W}$ are the renewable primary energy uses for heating and DHW. Such quantities are computed for each system according to Eqs. (5–8).

All the above-mentioned energy quantities are also expressed in specific terms [kWh/m^2] considering the gross heated floor surface of the case-study building (2460 m^2).

3. Results and Discussion

3.1. Building thermal loads

As a result of the dynamic thermal simulation of the building model (Type 56 in the TRNSYS model), the thermal load profile of the case study is reported in Fig. 4. As it can be seen, the heating system is working from October 15th to April 15th, according to the current Italian regulations for the use of centralized heating systems in residential multifamily buildings.

The resulting annual energy needs for space heating is 261 MWh, corresponding to a specific annual heating energy needs of 108 kWh/m^{2}y. Regarding domestic hot water, the resulting annual energy needs is 66 MWh, corresponding to a specific annual energy needs of 26.9 kWh/m^{2}y. Therefore, the total annual thermal energy needs for the entire building is 327 MWh, while the total thermal energy needs over the heating season is 294 kWh.

The resulting annual profiles of thermal loads for heating (red) and DHW (blue) are reported in Fig. 6, from hour 1 of the year (1st hour of Jan 1st) to hour 8760 (last hour of Dec 31st). The resulting dynamic profile of total (heating + DHW) hourly thermal loads over the heating season (Oct 15th – Apr 15th) is reported in Fig. 7.

3.2. Sizing and control of HP

Based on sizing simulation of peak design conditions in the defined climate boundaries, the required heating and DHW equipment design capacity resulted to be 281.3 kW and 15 kW, respectively.

At the design conditions of $T_{air,ext}$= -5°C (external air temperature) and $T_{w,load}$= 65°C (supply water temperature in the existing radiator system), the resulting number of heat pump modules dedicated to space heating is 8, being the rated heating capacity of one module operating at full load at the design conditions equal to 35.8 kW.

Therefore, the so-sized 8-module heat pump is modelled so that up to 8 modules operate at part load conditions before calling one module to operate at full load conditions, up to covering the heating load resulting from the building model type at each timestep.

One additional heat pump module is dedicated to DHW, whose full heating capacity at the design conditions is 35.5kW. It is expected to operate at partial load to ensure the domestic hot water is provided to the user at the required thermal level throughout the entire year.

3.3. Hourly and seasonal energy performance

The energy simulation of the R290 heat pumps system gives the results reported in Fig. 8. In particular, the curve of hourly values reordered in descending order of the heat load provided by the system is represented (black line) together with the related electrical power required by the heat pumps system (blue line). The power curve is not smooth as the heat load curve because the multiple heat pumps system cannot finely control the part load to follow the heat load, instead the control is given by the operation of the various 8 heat pump modules at full and part loads (16 steps). As regards the COP of the machine (without the energy use for water circulators), the increase trend is because lower heat loads usually correspond to more favourable outdoor air conditions and higher supply water temperatures. When the heat load is larger, the hourly COP of HP modules dedicated to space heating (red line) is around 1.7 (lowest load values) while it can reach values up to 5 when heat loads are smaller, outdoor temperatures are mild and supply water temperatures are the lowest.

As shown in the same Figure, the COP of the HP module dedicated to DHW (yellow line) ranges between 2 and 3.9.

Fig. 9 reports the weekly average COP values (blue points) of the entire system (all HP modules, dedicated to both space heating and DHW, including auxiliary pumps) in relation to the weekly average values of the outdoor air temperature (orange values). As expected, the lower the external temperature, the lower the average system efficiency, which ranges between 2 and 3 (average weekly COP values). The Seasonal Performance Factor is also reported with the grey dotted line, valued 2.27.

In detail, the average weekly net COP values related to HP modules operating for space heating and DHW, respectively, and the gross average weekly COP of the entire system (including auxiliary pumps) are reported in Fig. 10. This shows that at the centre of the heating season (between December and February), when external temperatures are lower and higher water temperature is called by radiators, the HP modules dedicated to DHW operates with higher efficiency than those operating for space heating, while the opposite occurs in the other periods. This demonstrates the ability of the modular structure of the propane-HP presented in this study to deal with different combinations of operating conditions with the highest possible efficiency.

Fig. 11 reports the hourly dynamics of the different involved input and output variables over a representative week in the winter season (week #51 of the year). The top graph reports the evolution of the external air temperature (orange line) and the resulting COP values of the different HP modules in operation: the yellow line refers to the HP module dedicated to DHW, while the red line refers to the average COP values of the HP modules operating to supply space heating. The bottom graph in Fig. 11 reports the dynamics of heating and DHW loads (red and yellow lines, respectively), the total resulting thermal load (grey line) and the total electrical power required by the entire system at each timestep (green line). This clearly shows how the real operating COP of the analysed HP system can significantly vary during the day depending

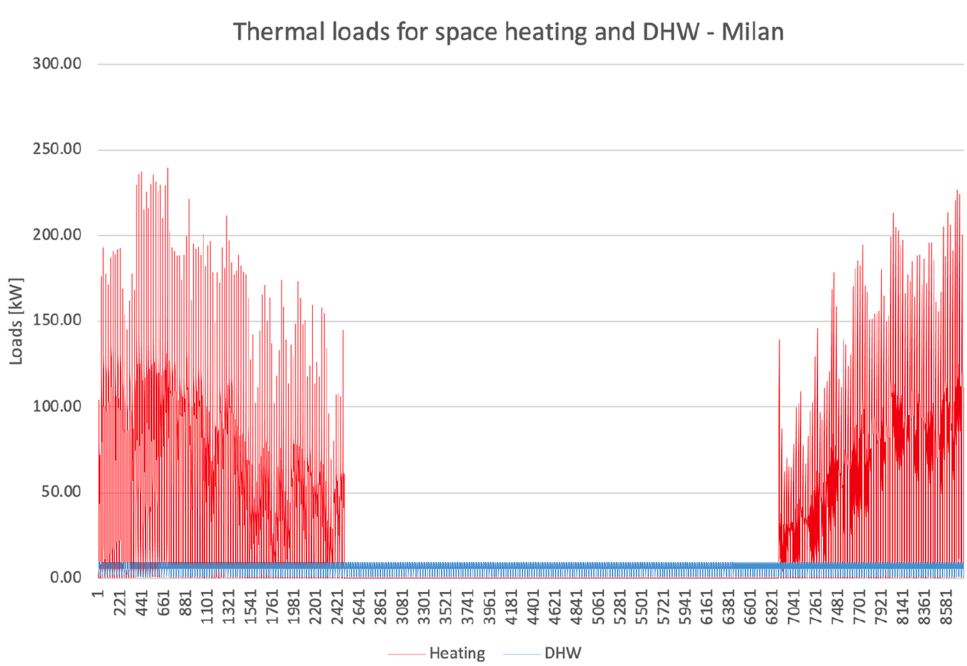

Fig. 6. Heating and DHW hourly load profiles for the whole multi-family building over the year.

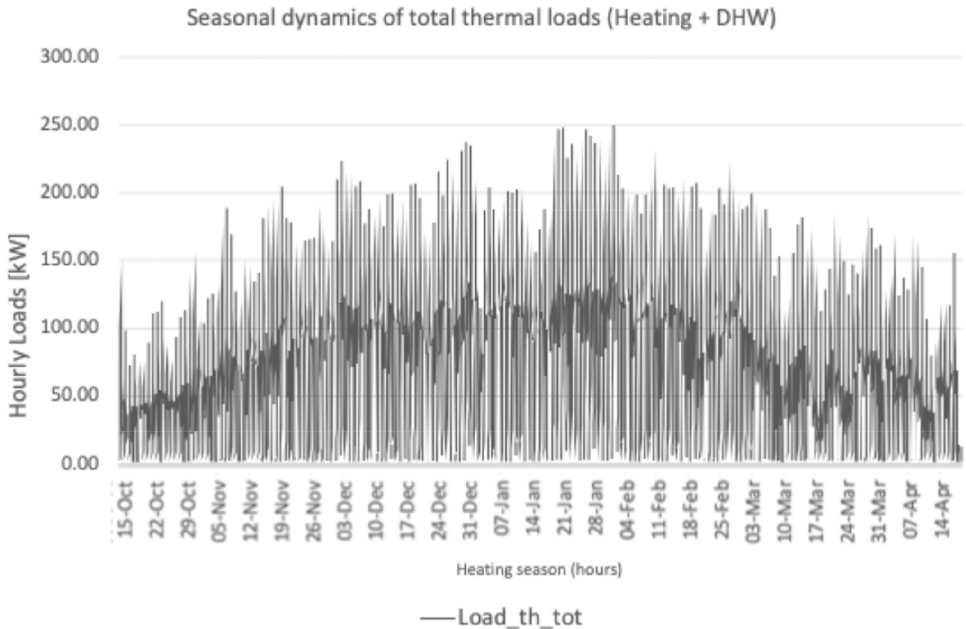

Fig. 7. Hourly dynamic of total thermal loads over the heating season (15th Oct – 15th Apr).

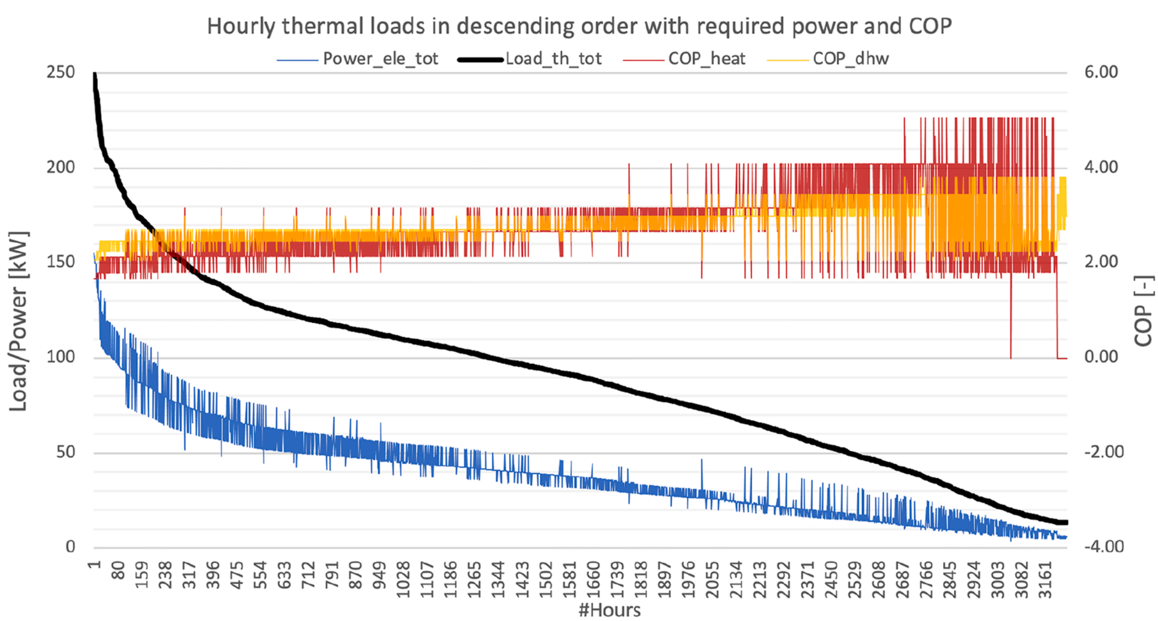

Fig. 8. Hourly operation of the analysed R-290 heat pump, ordered from highest to lowest total thermal loads (black), with indication of related electrical power (blue) and COP values for heating and DHW (red and yellow, respectively).

on the combination of thermal loads and source temperature (external air temperature) at each different timestep. Therefore, predictions of the real operating efficiency and of the consequent electricity consumptions are only possible if the system is properly modelled to allow its dynamic simulation.

Once analysed the system in its dynamic behaviour, it is possible to go back to the seasonal level to evaluate the feasibility and overall energy performance of the system. The seasonal values of the KPIs quantities used to assess the new propane HP system performance are reported in Table 1. The lower average (season) COP is the one that considers also the electricity use for the circulation auxiliaries of the supply water sides of heat pumps. Considering that the machines are fed by grid electricity only, the non-renewable primary energy indicator $EP_{nrenH+W,HP}$ is equal to 111 kWh_{pe}/m^2, of which 15 % is for DHW and 85 % is for space heating. The heat pump exploitation of the renewable source plus the renewable energy contribution from the grid electricity gives a renewable energy ratio equal to 54 %. If some electricity feeding the heat pumps may be fed by PV or other green source, this value may be easily increased up to the current requirement for deeply retrofitted buildings in Italy (60 %) or even further.

With respect to other heat pump technologies, the R-290 has similar seasonal performance levels (previous studies on R-410 air to water heat pumps have shown that the predicted annual COP is often below 2.5 in similar contexts (Le et al., 2019; Ferrara and Fabrizio, 2023). Moreover, the operation of other heat pump technologies is limited to 50°C as the maximum supply water temperature, leading to the need for a backup or integration system (gas boiler or thermal resistance) to cover the additional thermal loads for providing water at higher temperature levels to

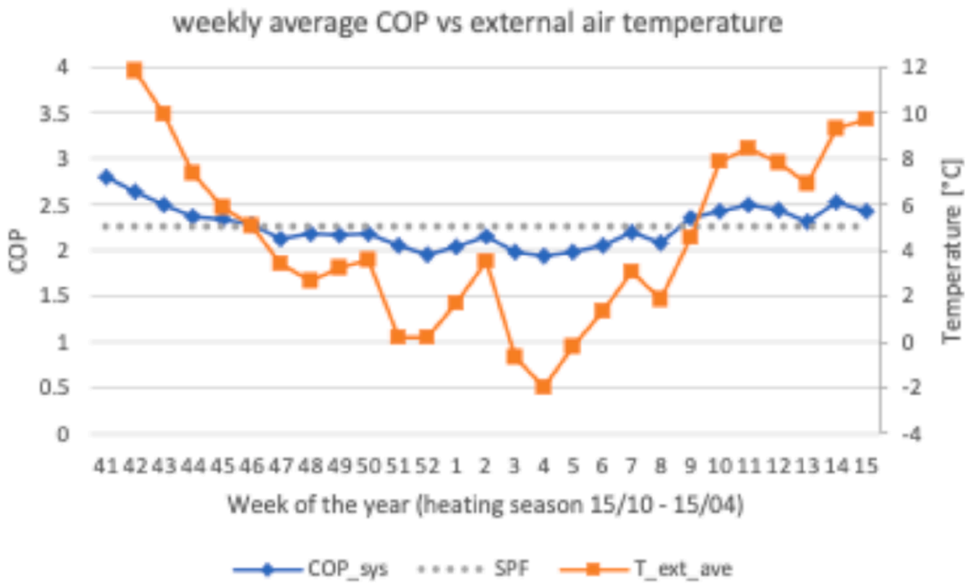

Fig. 9. Weekly average gross COP values (blue dots) of the entire system (including auxiliary pumps) in relation to the weekly average values of the external temperatures (orange dots) – the grey dotted line indicates the overall seasonal performance factor.

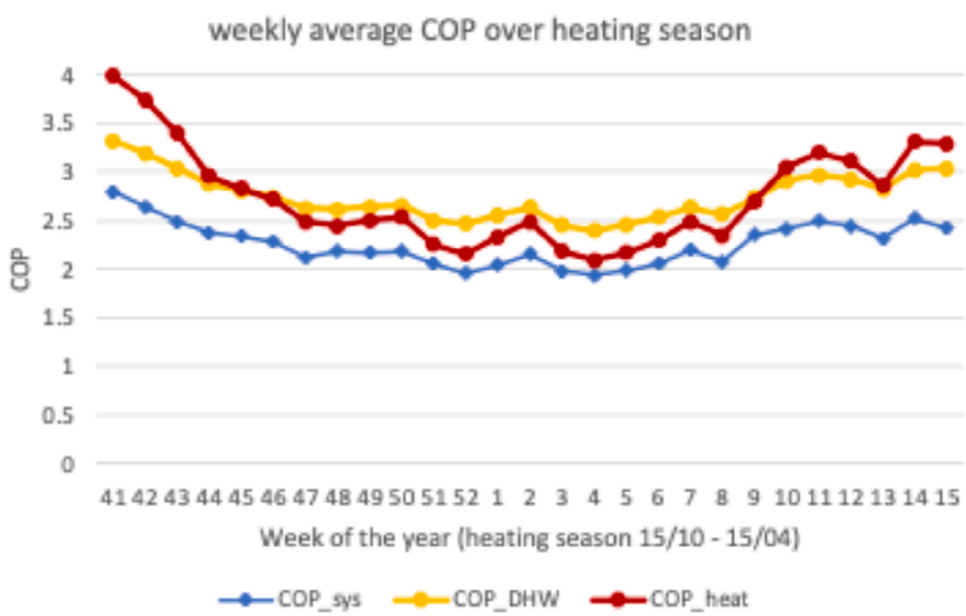

Fig. 10. Weekly average gross COP values (blue dots) of the entire system (including auxiliary pumps) over the heating season in relation to the COP of HP modules dedicated to space heating (red dots) and DHW (yellow dots).

operate with the existing radiator systems (Saffari et al., 2023), or the need for lowering the temperature level of the heating system with the consequent re-design of heating radiators (Zhuang et al., 2023).

Then, if we compare the energy performance results of the R290 heat pump solution to the base case of the condensing boiler (Table 2), it can be seen that the specific non-renewable primary energy use is 32 % higher than the one of the previous case. Considering that usually this solution may be installed as a refurbishment/revamping of existing fuel-based combustion systems (such as diesel oil boilers, old gas boilers without condensation, existing condensing boilers that does not fully exploit the benefits of the return water temperature to condensate the water vapour in the flues), potential energy savings are even much larger.

4. Conclusions

The main purpose of this study was to investigate if a renovation of existing heating system could be done by only replacing the existing heating generator (gas boiler) with the R290 heat pump technology. This is done through real performance data in operating conditions, that are essential to understand the ability of such technology to operate in dynamic conditions. Obtained results demonstrated that modular R290 heat pumps are a ready-to-use and convenient technology for the challenge of decarbonisation of high temperature water-based heating systems in existing buildings when they can replace an old gas boiler. Considering the limited operation range of other heat pump technologies, the possibility to reach high temperature levels (above 55°C, up to 70°C) represents the greatest potential for the use of R-290 heat pumps in the context of existing heating systems without requiring major

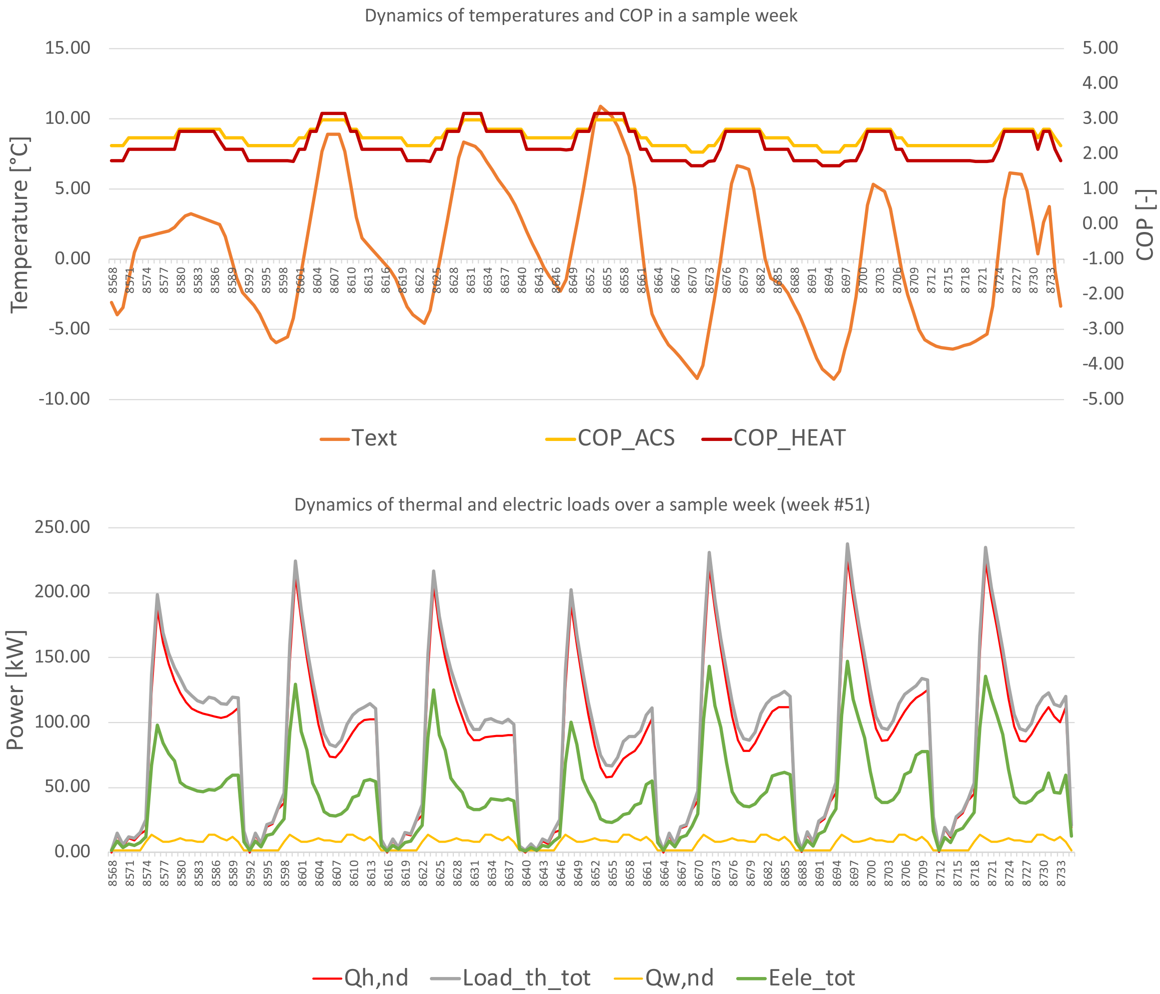

Fig. 11. Dynamic hourly operation of the analysed R-290 heat pump over a sample week (week 51): top - COP values (HP-modules for space heating in in relation to external temperatures; bottom - electrical power (yellow) and COP values for heating and DHW (grey and blue, respectively).

Table 1
Resulting performance and KPI of the case study building equipped with the R-290 HP.

KPI Description	Results	
	Value	u.m.
Overall seasonal electricity consumption of the heat pump	11,8822	kWh_e
Specific seasonal electricity consumption of the heat pump - $E_{del,H+W}$	48.3	kWh_e/m^2
Average COP (heat pump only)	2.71	-
Seasonal Performance Factor (with auxiliaries) - SPF_{HP}	2.26	-
Specific non-renewable primary energy use - $EP_{nrenH+W,HP}$	111.0	kWh_{pe}/m^2
Specific renewable primary energy use - $EP_{renH+W,HP}$	129.6	kWh_{pe}/m^2
RER (Renewable Energy Ratio)	54 %	-

Table 2
Resulting performance of the case study building equipped with gas condensing boiler.

KPI Description	Results	
	Value	u.m.
Overall seasonal heat consumption of the gas boiler	264,794	kWh_{th}
Specific seasonal heat consumption of the gas boiler	107.6	kWh_{th}/m^2
Seasonal Performance Factor (with auxiliaries) - SPF_{gas}	0.98	-
Specific non-renewable primary energy use -$EP_{nrenH+W,gas}$	146.2	kWh_{pe}/m^2
RER (Renewable Energy Ratio)	0.8 %	-

changes to the heating terminals. This is true under some circumstances that were considered for this study and are summarized here.

First, in this study, the fact that the radiators were sized (or oversized) for a 65° C supply water temperature makes it possible to simply substitute the hot water boiler with a heat pump, however this may not be applicable to all situations. There is evidence in the literature that oversized radiators are quite common in many EU countries, however, as a general rule, a thorough survey of existing radiators should be conducted (similar to what is done for monitoring and energy consumption metering) to determine if each radiator can achieve full load operation at the selected supply water temperature.

At the same time, while many modern R-290 heat pumps can reach even higher supply water temperatures (e.g., 75°C), this often leads to significant reductions in heating capacity and COP. In such cases, supplementary systems like small electric resistance heaters can be used to cover the heating load during the very limited periods of time when very high supply water temperatures are required.

Thus, it is important to remark that the outcome of this paper does not just suggest to change the gas boiler with the R-290 heat pump, but rather highlights the importance of determining the lowest possible design supply water temperature for the radiators in order to optimize the performance of the central heat pump.The simulated heat pump technology – under the current Italian energy costs and primary energy factors – has better energy and economic results than the current most performing solution (natural gas condensing boiler), which is demonstrated to be at least 20 % worse than the heat pump in terms of primary energy performance.

However, it is well recognized that the best integration of such heat pumps in existing residential buildings would be in combination to envelope retrofit (Fedrizzi, 2024), so that the size of the heat pump is reduced (or, as in this work, the number of heat pump modules is decreased) and, crucially, the design supply hot water temperature is reduced as well (because the existing radiators become oversized after the envelope renovation). However, this option, while potentially profitable due to reduced investment cost for the heat pump itself and reduced operational energy costs, should be carefully evaluated from a financial perspective because installation costs of the envelope renovation can be larger than its benefits, and largely dependent on existing subsidies, as in case of the recent Italian experience of the greatly discussed "Superbonus" incentive program (Codogno, 2024).

In a few years, moreover, this will be the only possible solution due to the planned phase-out of fuel-based boilers, therefore leading to the need of further work to demonstrate the applicability of the heat pump technology in other EU contexts. This allows moving towards phasing out of fossil fuels and decarbonization of buildings also in cases when building owners do not have the investment capacity for renovation measures other that replacing the old heating generator. Simultaneously, a widespread implementation of this heat pump retrofit strategy cannot be achieved in short timeframes due to the increased electricity demand it would entail. However, this study demonstrates that reductions in costs and primary energy consumption, while dependent on national conditions, can be substantial. Therefore, at the national level, policies accelerating a green transition through this approach may be beneficial and feasible. These policies should concurrently target the rate of growth of green electricity generation on the grid and the rate of decarbonization of existing water-based heating systems in buildings.

Also, in case of further retrofit interventions are implemented on a case study after the heat pump renovation, the modular structure of the system allows adaptation to variations and reduction of heating demand while preserving the optimal performance of the heat pump equipment.

Authors may wish to further investigate the effect of the variation of the climate control curve of the centralized system (that typically depends on the operation of the heating system itself) and of the water storages at the demand side. Moreover, new frequency driven compressors are ready to be installed into such heat pumps and may lead to greater COPs and a more refined control of the heat load at the use side.

Finally, scaling up from the single building to the city level is essential to understand the implications of such retrofit intervention on the electricity grid, while envisioning the potential integration with in-situ renewable production systems that have the potential to decrease the dependency from the grid.

CRediT authorship contribution statement

Stefano P. Corgnati: Supervision, Funding acquisition, Conceptualization. **Enrico Fabrizio:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Michele Babuin:** Validation, Resources, Data curation. **Maria Ferrara:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Maria Ferrara reports financial support was provided by FSE REACT-EU - PON Ricerca e Innovazione 2014–2020. Enrico Fabrizio reports financial support was provided by PNRR NEST Spoke 8 Project. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The present work has been developed within the activities of the Italian PNRR NEST Project, code PE0000021, Concession Decree No. 1561 of 11.10.2022 adopted by Ministero dell'Università e della Ricerca (MUR), CUP E13C22001890001, Project title "Network 4 Energy Sustainable Transition – NEST".

Maria Ferrara's activity has been carried out within the Ministerial Decree no. 1062/2021 and received funding from the FSE REACT-EU - PON Ricerca e Innovazione 2014–2020 (Asse IV "Istruzione e ricerca per il recupero" – Azione IV.4 – "Dottorati e contratti di ricerca su tematiche dell'innovazione" e Azione IV.6 – "Contratti di ricerca su tematiche Green": CUPE15F21003760001). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

This work is part of the contribution of the Authors to the activities of the IEA Annex 62 "Heat pumps for multi-family residential buildings in cities".

Data Availability

The data that has been used is confidential.

References

European Commission, Heating and Cooling Strategy, Avaliable at.

Communication From The Commission To The European Parliament, The European Council, The Council, The European Economic And Social Committee And The Committee Of The Regions REPowerEU Plan - COM/2022/230 final.

Biglia, A., Ferrara, M., Fabrizio, E., 2021. On the real performance of groundwater heat pumps: experimental evidence from a residential district. Appl. Therm. Eng. 192, 116887.

Codogno, L. Italy's Superbonus 110%: Messing up with demand stimulus and the need to reinvent fiscal policy. WP 12/2024, LUISS Institute for European Analysis and Policies.

Corgnati, S.P., Fabrizio, E., Filippi, M., Monetti, V., 2013. Reference buildings for cost optimal analysis. Appl. Energy 102, 983–993.

Corrado, v., Ballarini, I., Corgnati, S.P., Building Typology Brochure – Italy, Politecnico di Torino, Dipartimento Energia, 2012.

Decreto interministeriale 26 giugno 2015 - Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici. Appendice A.

Du, Y., Wu, J., Wang, C., 2020. Experimental study on dynamic characteristics of an R290 heat pump during defrost. Energy Build. 223, 110174.

EN - European Standards, EN 15316-3:2018 Energy Performance of Buildings - Method for Calculation of System Energy Requirements and System Efficiencies - Part 3: Space Distribution Systems (DHW, Heating and Cooling), 2018.

European Commission, "Fit for 55: how the EU will turn climate goals into law", Available at ⟨https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/⟩, Accessed in Ocotber 2023.

European Environment Agency (EEA), EU energy-related emissions by sector and gas Available at: ⟨https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer⟩ - Accessed in December 2023.

European Heat Pump Association, European Heat Pump Market and Statistics Report, 2023a.

European Heat Pump Association, Heat Pumps in Europe - Key Facts & Figures, 2023b. Available at ⟨https://www.ehpa.org/wp-content/uploads/2023/06/Heat-Pump-Key-Facts-May-2023_compressed.pdf⟩.

Fabrizio, E., Filippi, M., Virgone, J., 2009. Trade-off between environmental and economic objectives in the optimization of multi-energy systems. Build. Simul. 2 (1), 29–40.

Fedrizzi, R. Overview Article - Integrating Heat Pumps in Existing Residential Buildings. BUILD-UP - The European portal for energy efficiency and renewable energy in buildings, 2024. ⟨https://build-up.ec.europa.eu/en/resources-and-tools/articles⟩.

Ferrara, M., Fabrizio, E., 2023. Optimized design and integration of energy storage in solar-assisted ground-source heat pump systems. Build. Simul. 16, 1933–1948. https://doi.org/10.1007/s12273-023-1030-4.

Ferrara, M., Fabrizio, E., Virgone, J., Filippi, M., 2015. Appraising the effect of the primary systems on the cost optimal design of nZEB: A case study in two different climates. Energy Procedia 78, 2028–2033. https://doi.org/10.1016/j.egypro.2015.11.200.

Ferrara, M., Sirombo, E., Fabrizio, E., 2018. Energy-optimized versus cost-optimized design of high-performing dwellings: the case of multifamily buildings. *Sci. Technol.*

Built Environ. (Switz.) 24 (5), 513–528. https://doi.org/10.1080/23744731.2018.1448656.

Guidetti, E., Ferrara, M., 2023. Embodied energy in existing buildings as a tool for sustainable intervention on urban heritage. *Sustain.* Cities Soc. 88, 104284.

IEA TCP Annex 62, Heat pumps for multi-family residential buildings in cities, Project results and updates available at ⟨https://heatpumpingtechnologies.org/annex62/⟩.

Le, K.X., Huang, M.J., Shah, N.N., Wilson, C., Mac Artain, P., Byrne, R., Hewitt, N.J., 2019. Techno-economic assessment of cascade air-to-water heat pump retrofitted into residential buildings using experimentally validated simulations. Appl. Energy 250, 633–652.

W.J. Ljunggren P Optimum performance of radiator space heating systems connected to achieve low as possible DH return temperature, de 10th International Symposium on District Heating and Cooling, Lund, 2006.

Nawaz, K., Shen, B., Elatar, A., Baxter, V., Abdelaziz, O., 2017. R290 (propane) and R600a (isobutane) as natural refrigerants for residential heat pump water heaters. Appl. Therm. Eng. 127, 870–883.

Nowak, T., 2021. European Heat Pump market. Rehva J. 4, 40–43.

Østergaard, D., Svendsen, S., 2018. Are typical radiators over-dimensioned? an analysis of radiator dimensions in 1645 Danish houses. Energy Build. 178, 206–215.

I. Pothof, T. Vreeken, M. van Meerkerk. Field measurements on lower radiator temperatures in existing buildings, WarmingUP project, 2022.

Roca Reina, J.C., Toleikyte, A., Volt, J., Carlsson, J., 2024. Alternatives for upgrading from high-temperature to low-temperature heating systems in existing buildings: challenges and opportunities. Energy Build. 323, 114798. https://doi.org/10.1016/j.enbuild.2024.114798.

Saffari, M., Keogh, D., De Rosa, M., Finn, D.P., 2023. Technical and economic assessment of a hybrid heat pump system as an energy retrofit measure in a residential building. Energy Build. 295, 113256.

Schito, E., Conti, P., Testi, D., 2023. Substitution of heating systems in the Italian buildings panorama and potential for energy, environmental and economic efficiency improvement. Energy Build. 295, 113273. https://doi.org/10.1016/j.enbuild.2023.113273.

Tang, W., He, G., Zhou, S., Sun, W., Cai, D., Mei, K., 2018. The performance and risk assessment of R290 in a 13 kW air source heat pump. Appl. Therm. Eng. 144, 392–402.

Tilche, A., Basile, F., Torsello, M., 2022. Le città a impatto climatico zero: strategie e politiche. MIMS Ministero delle Infrastrutture e della Mobilità Sostenibili.

UNI - Italian Unification Body, UNI/TS 11300-2:2019 - Prestazioni energetiche degli edifici - Parte 2: Determinazione del fabbisogno di energia primaria e dei rendimenti per la climatizzazione invernale, per la produzione di acqua calda sanitaria, per la ventilazione e per l'illuminazio, 2019.

Zhuang, C., Choudhary, R., Mavrogianni, A., 2023. Uncertainty-based optimal energy retrofit methodology for building heat electrification with enhanced energy flexibility and climate adaptability. Appl. Energy 341, 121111.