A Building Renovation Concept Based on a Low-Temperature Geothermal Loop With Decentralized Plug-And-Play Heat Pumps

Sara Bordignon – University of Padova, Italy – sara.bordignon@unipd.it
Jacopo Vivian – University of Padova, Italy – jacopo.vivian@unipd.it
Agnese Tagliaferri – Manens SpA, Italy – atagliaferri@manens.com
Davide Quaggiotto – R2M Solution, Italy – davide.quaggiotto@r2msolution.com
Michele De Carli – University of Padova, Italy – michele.decarli@unipd.it

Abstract

This article proposes a renovation concept for multi-family houses and apartment blocks based on a groundwater loop with heat pumps supplied by groundwater. The study applies the proposed concept to a multi-family building in the province of Milan. The analysis relies on dynamic energy simulations of the building and thermo-hydraulic simulations of the low-temperature distribution circuit. Energy, economic, and environmental indicators are evaluated to compare the proposed solution against a benchmark retrofit with individual condensing gas boilers. The study demonstrates that the proposed renovation concept leads to increased Energy Efficiency Class compared to the benchmark renovation scenario, as well as to lower operating costs and CO_2 emissions. The proposed concept is promising, especially for areas where groundwater is easily available, and no local legal restrictions are present.

1. Introduction

Over the past few decades, the utilization of shallow geothermal energy has increased across Europe due to its remarkable energy efficiency potential and encouraged through Renewable Energy policies and European Directives. Groundwater (or water-to-water) heat pumps can efficiently supply heating and cooling to buildings on small or large scales (Sezer et al., 2024). In some regions, like the Milan area (Italy), the use of water-to-water heat pumps is extremely interesting, due to the availability of exploitable aquifers next to the ground surface (Città Metropolitana di Milano, 2023). Such systems can be used to further increase the renewable share in the heating and cooling sector and have a potential in the energy retrofit of buildings (Schibuola & Tambani, 2022), as an alternative to conventional, fossil-fueled energy plants such as condensing boilers. This paper presents the energy and cost analysis of a retrofit solution for the heating system of an apartment block in the province of Milan, which building envelope was recently retrofitted.

2. Building Retrofit Description

This paper presents energy retrofit actions to be performed both on the building envelope and on the heating and cooling system. The latter will be analyzed on a multi-apartment block, described hereafter. This section also includes details about the sizing of the components.

2.1 Case Study Building

The building is a five-story (Fig. 1) condominium of 26 apartments located on the outskirts of Milan. Being in the climatic zone “E”, according to Italian regulation, the heating period goes from October 15th to April 15th. The annual average air temperature is around 14.7 °C, with 2404 heating degree days. The ground floor houses garages and cellars and is not heated. Each floor has three stairwells (A, B, C). Most apartments have a floor area of about 100 m^2, except for four with 200 m^2 and five with around 50 m^2. The net floor area of the building is 2556 m^2, and the net heated volume is 7305 m^3.

Part of
Pernigotto, G., Ballarini, I., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). 2025. Building simulation applications BSA 2024. bu,press.
https://doi.org/10.13124/9788860462022

BY-SA

Fig. 1 – North-West façade (above) and bird's eye view of the case study building (below)

2.2 Retrofit of the Building Envelope

The retrofit of the building envelope consisted of thermally insulating the external walls, the floor slabs towards unheated spaces, and the roof. Table 1 summarizes the stratigraphy of opaque building components pre and post retrofit.

On balcony façades, the width of the insulation layer is 4 cm instead of 8 cm. Similarly, the 10 cm EPS layer below the slab of the first floor is used only above cellars, whereas above the atrium, it is replaced with a 2 cm aerogel layer to save space (height) in the condominium hall.

Table 1 – Building components stratigraphy pre and post retrofit

Building component	**Original stratigraphy**	**Additional layers**
Ext. walls U_{pre} = 1.03 W/(m² K) U_{post} = 0.17 W/(m² K)	2 cm - Gypsum plaster 8 cm - Hollow brick 10 cm - Airgap 8 cm - Hollow brick 2 cm - Gypsum plaster	Air gap filled with glass-wool (10 cm) 8 cm - Rockwool 1 cm - External coating
Floor slab U_{pre} = 1.04 W/(m² K) U_{post} = 0.24 W/(m² K)	1 cm - Ceramic tiles 4 cm - Lean concrete 5 cm - Cement 18 cm - Brick slab 2 cm - Gypsum plaster	10 cm - Graphite EPS 2 cm – Ext. Insulation
Roof U_{pre} = 1.17 W/(m² K) U_{post} = 0.24 W/(m² K)	3 cm - Clay tiles 4 cm - Airgap 4 cm - Lean concrete 5 cm - Cement 18 cm - Brick slab 2 cm - Gypsum plaster	14 cm - Rockwool panel

In the building, the most common glazed components present wooden frames and a thermal transmittance between 2.74 and 2.91 W/(m² K). They were not replaced.

2.3 Retrofit of the HVAC System

In the original configuration, each apartment has an independent system for cooling, heating, and domestic hot water (DHW) production. For space heating and DHW production, the apartments have conventional gas boilers, except for one apartment with a condensing gas boiler, and two with electric boilers. Gas boilers are located in the kitchen and all the apartments have radiators. The apartments have direct expansion air conditioning units for cooling. The annual natural gas consumption, simulated using Edilclima, is 34236 Nm³, while the annual electrical energy consumption, related to heating, cooling, and DHW production, is 38406 kWh. The proposed retrofit solution consists of distributed water-to-water heat pumps, using groundwater as a heat source during the heating season and as a heat sink during the cooling season. The groundwater does not circulate in the building's hydronic system, but exchanges heat via a heat exchanger. Although less efficient than direct coupling, this solution reduces problems of corrosion and fouling. The hydronic system supplies heat at low temperature to reversible water-to-water heat pumps (one in a balcony of each flat) that extract heat from the network during the heating season and reject heat into the network in the cooling season. During summer, heat can be also extracted to produce DHW. Radiators must be replaced with fan coils to supply cooling during summer. Fig. 2 reports a general scheme of the network. The extraction well that draws the groundwater is placed outside the building. The connection pipes reach a technical room in the basement, where the heat exchanger, the circulation pump, and the manifolds are located. The horizontal pipes run on the ceiling to reach the base of the six risers, which distribute the water to the heat pumps. A reverse return distribution was chosen for the risers to achieve a self-balanced hydronic circuit. The pipes were sized with constant pressure drop (target 30 mmwc/m) and a maximum velocity of 1 m/s to avoid noise issues. The supply and return temperatures depend on the temperature of the aquifer, assumed equal to the annual average temperature of the outdoor air. For environmental reasons, the difference between the supply and return temperature to the aquifer cannot exceed 5 °C: the return temperature was set to 10 °C in the heating operation (winter) and 20 °C in the cooling operation (summer). A temperature difference of 2 °C was considered in the heat exchanger between the outlet technical water temperature and the inlet groundwater temperature. The heat exchanger was sized to ensure proper heat transfer with these temperatures. The decentralized water-to-water heat pumps were chosen from the catalog of a local heat pump manufacturer (Table 2). The variable-speed multi-functional heat pumps use scroll compressors and R410a as refrigerant. Each unit, including a 200-liter thermal storage for DHW production (at 45 °C), is contained in a box.

Table 2 – Characteristics of the chosen heat pumps

Heat pump	Type 1	Type 2
Heating capacity [kW]	12.4	8.1
Cooling capacity [kW]	9.8	6.3
Rated COP [-] (T_{source}=10 °C - T_{load}=35 °C)	5.49	5.99
COP in operating conditions [-] (T_{source}=13 °C - T_{load}=45 °C)	4.43	4.83
Rated EER [-] (T_{sink}=15 °C - T_{load}=7 °C)	4.69	4.91
EER in operating conditions [-] (T_{sink}=17 °C - T_{load}=7 °C)	4.49	4.70

The instantaneous DHW production capacity is 25 l/min. The size of each apartment's heat pump was chosen based on the space heating, cooling, and DHW demand. For the four largest apartments (floor areas from 165 to 209 m^2), the heat pump Type 1 was chosen. The heat pump of Type 2 was selected for the remaining 22 apartments (floor area below 100 m^2). The unit's box includes two variable-speed circulators, for the user's and source circuits, which can regulate the water flow according to the apartment's thermal load. The volume flow rate of the source-side circulators is 0.29 l/s for Type 1 and 0.19 l/s for Type 2.

3. Method

The proposed retrofit solution with water-to-water heat pumps was analyzed using economic, energy, and environmental indicators and compared with a conventional energy retrofit solution. The latter consists of replacing existing traditional gas boilers with condensing boilers.

3.1 The Building Thermal Loads

The building's dynamic simulations were carried out using Edilclima EC700 (Edilclima, n.d.), a widely used software within the Italian building engineering community to calculate buildings' energy performance. The underlying model is based on the dynamic hourly method of ISO 52016-1 Standard (International Organization for Standardization,

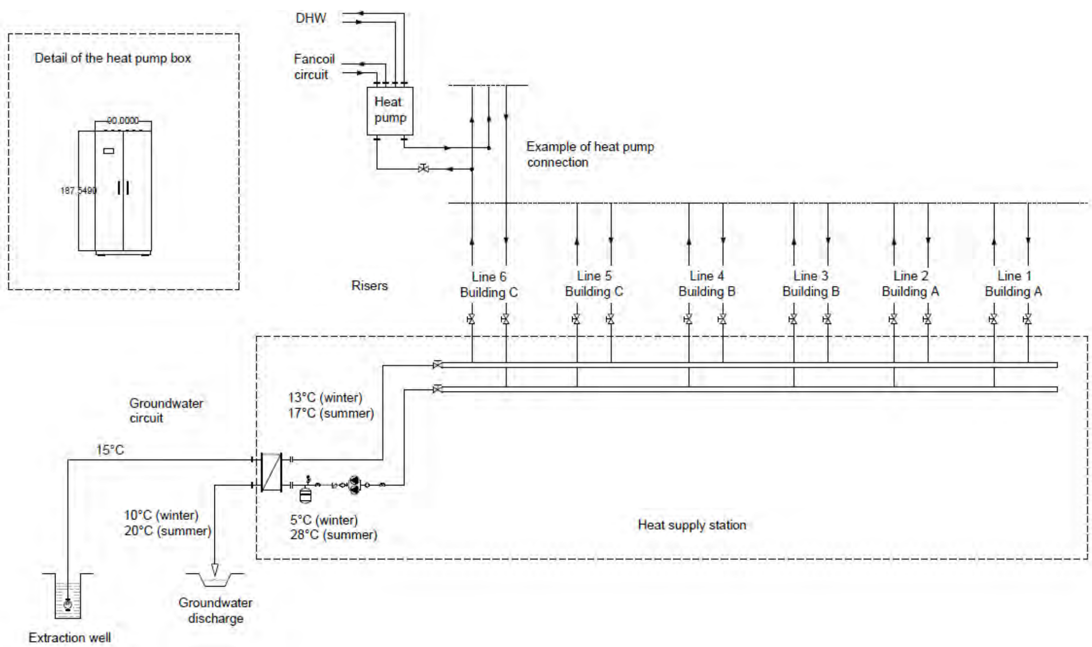

Fig. 2 – Schematic of the proposed system

2017). Domestic hot water load profiles were calculated for each apartment using DHWcalc (Jordan & Vajen, 2005), a software for the generation of stochastic profiles of DHW draw-offs. They were generated by setting a volume of 50 liters/(person day). The heat emission efficiency was set to 95%, while the heat distribution efficiency was set to 99.2%. Ambient temperature control was assumed, with a regulation efficiency of 98%. The emission efficiency for the direct expansion air conditioning units for space cooling was considered equal to 97%, with zone regulation efficiency of 97%.

3.2 Simulations of the Hydronic Network

NeMo is a code written in MATLAB that, given the supply temperatures and users' flow rates, makes it possible to calculate flow rates, pressures, and temperatures in a thermal network.

The network is represented by a set of nodes and oriented branches, and an adjacency matrix determines their mutual connections.

The velocity of the heat carrier fluid is considered uniform in the radial direction (one-dimensional model) and does not depend on the temperature distribution. Therefore, the mass flow rates on the branches and pressures on the nodes of the network can be calculated in a first step, and used as inputs to find temperatures on the nodes. The heat transfer in the radial direction considers the convection between the heat carrier fluid and the inner pipe surface, the pipe's thermal insulation, and the thermal resistance of the surrounding ground. Due to the incompressible nature of the heat carrier fluid, the hydraulic problem can be described using only two equations: the continuity and the momentum equations. NeMo solves these equations using the SIMPLE method. The heat propagation in the network is then described by the energy balance performed on the water volume of the heat carrier fluid around the network nodes.

NeMo can solve the transient heat propagation problem either with MATLAB's ODE solver or by the Gauss elimination method after linearizing the system of Equations (one for each node). A schematic of the hydronic network simulated with NeMo is shown in Fig. 3.

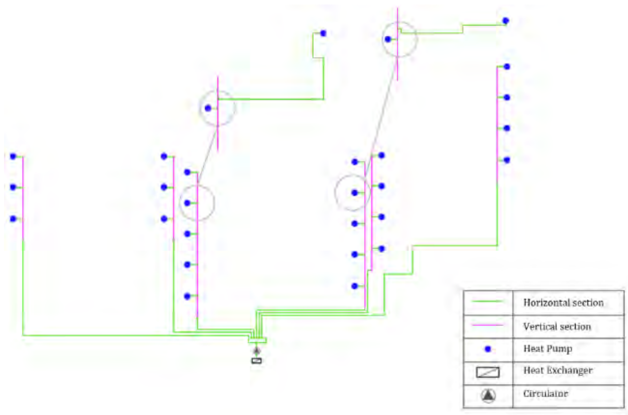

Fig. 3 – Topology of the supply network

3.3 Economic Parameters

The results of the techno-economic analysis of the proposed building renovation depend on the cost assumptions on the initial investment and the energy prices used to calculate the operating costs. The investment costs were computed considering the costs related to the installation of the thermal insulation layer on the building envelope and the costs associated with the retrofit of the HVAC system.

The operating costs depend on the energy carrier used in the installed energy system and its efficiency. The electrical energy cost was assumed to be equal to 0.24 EUR/kWh (ARERA, 2021), while for natural gas, the cost is equal to 0.814 EUR/Nm^3 (ARERA, 2021).

3.4 Key Performance Indicators

To characterize the energy performance of the retrofit solutions, the energy efficiency class of the building was defined using Edilclima. The renewable and non-renewable fractions of the primary energy consumption were calculated for both proposed retrofit scenarios. Concerning electrical energy as the energy carrier, a conversion factor applied to the final electrical energy of 0.47 was assumed to calculate the renewable ratio and 1.95 for the non-renewable part. In addition, the thermal energy extracted from the ground by the heat pump operating in heating mode is considered renewable (groundwater is considered the energy vector). The conversion factor (non-renewable) for natural gas is 1.05. The CO_2 emission factor for natural gas is assumed to be equal to 0.202 kg$_{CO2}$/kWh (IPCC, 2006), while the emission factor for electrical energy is assumed to be 0.260 kg_{CO2}/kWh (ISPRA, 2021).

4. Results

This section presents the analysis of the retrofit solutions with water-to-water heat pumps and the solution with condensing boilers and direct expansion air conditioning. Both solutions include external wall insulation.

4.1 Building Loads

The annual thermal energy loads per apartment for space heating, cooling, and DHW production are reported in Fig. 4. The yearly overall demand for space heating for the multi-family house is 84.17 MWh, while the heat demand for DHW production is 54.14 MWh, and the cooling demand is 63.2 MWh.

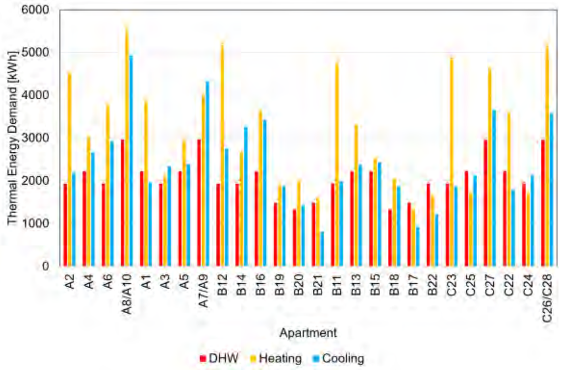

Fig. 4 – Annual thermal energy demand of the insulated building for heating, cooling, and domestic hot water production

The application of the emission, distribution, and regulation efficiency reported in Section 2.1 allows us to calculate the apartments' final thermal energy demand. The total annual final thermal energy is 90.4 MWh for heating and 67.9 MWh for cooling.

Concerning the retrofit solution with water-to-water heat pumps, Fig. 5 shows the electrical energy demand related to heating, cooling, DHW production, and the auxiliaries (circulators) per apartment. The annual electricity consumption of the building, calculated considering the heat pumps operating at full load, amounts to 55.4 MWh, 23% of which is related to DHW production, 35% to heating, 26% to cooling, and 16% to the circulators.

On the other hand, concerning the retrofit solution with condensing boilers and direct expansion air conditioning, Fig. 6 shows the estimated electrical and gas consumption per apartment and year. The total gas consumption is 14434 Nm³, while the electrical consumption is 15.4 MWh.

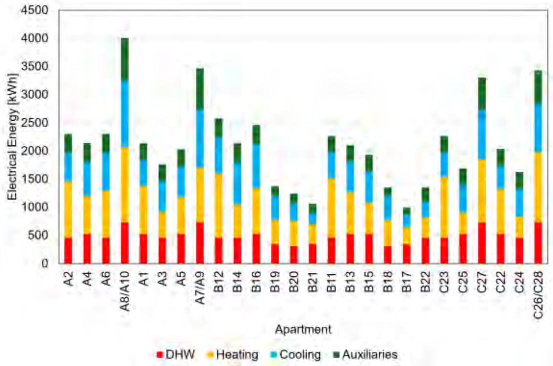

Fig. 5 – Annual electrical energy consumption for the water-to-water heat pump solution

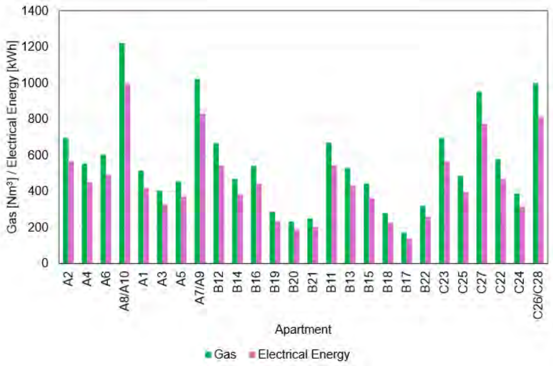

Fig. 6 – Annual electrical energy and natural gas consumption for the condensing boiler and direct expansion air conditioning solution

4.2 Hydronic Network

Thanks to the hydronic network model, it is possible to calculate the return temperature and water flow rate to the heat exchanger and, therefore, the total thermal power exchanged with the aquifer. The simulation was carried out for 365 days with a timestep of 10 minutes. Fig. 7 shows the difference between the supply and return water temperature, at the load side, during a cold winter week. The temperature difference at the heat exchanger is around 7°C during the day, when most of the water-to-water heat pumps are on. The minima refer to the timesteps in which the demand for heating or domestic hot water is low, generally occurring at night. In addition, Fig. 7 shows the thermal power supplied to the hydronic circuit: the peaks typically occur during the morning due to the simultaneous demand of space heating and DHW and correspond to a higher circulating water flow rate. In the same way, Fig. 8 shows the temperature difference between supply and return lines and the corresponding thermal power exchanged at the heat exchanger during a warm summer week. At night, the thermal power related to the DHW demand is close to zero. In the early morning, the DHW demand is higher than the cooling demand: a positive peak in thermal power and temperature difference can be seen because the water temperature in the supply pipe is higher than in the return. During the afternoon, the cooling demand increases, and so does the return water temperature.

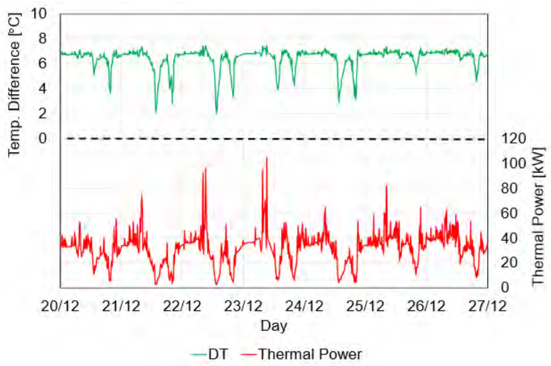

Fig. 7 – Temperature difference and thermal power exchanged at the heat exchanger during a winter week

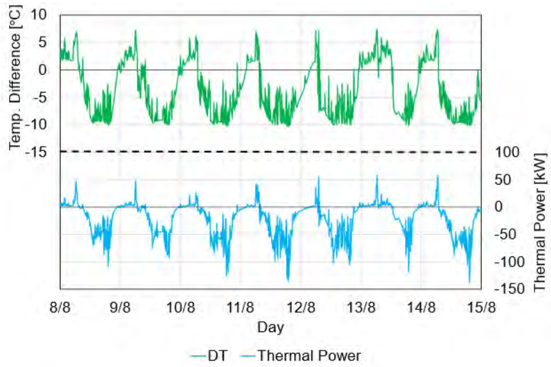

Fig. 8 – Temperature difference and thermal power exchanged at the heat exchanger during a summer week

4.3 Economic Analysis

4.3.1 Investment costs

The estimated investment costs for the solution with water-to-water heat pumps, summarized in Table 3, involve the cost of piping at the source side of the heat exchanger, the heat exchanger, the circulators, the manifolds, the costs related to the installation of the extraction well and the costs associated with the insulation of the envelope.

The overall cost on the source side of the heat exchanger is mainly related to the pipes' length and diameter, as well as the installation costs for the pipes trench and other construction works. Two heat exchangers were considered, installed in parallel for safety reasons, whose costs include the installation costs and the cost of the ancillary components like valves and pipe fittings. The extraction well cost includes drilling, installing piping and filters, cementation, chemical analysis of the groundwater, etc. The costs for the thermal insulation of the envelope include the interventions presented in paragraph 1.2.

Table 3 – Investment costs for the solution with heat pumps.

Intervention	**Cost [EUR]**
External walls insulation	600,300 (83.6%)
Source side piping	60,384 (8.4%)
Extraction well	22,000 (3.1%)
Heat exchanger	14,750 (2.1%)
Groundwater pump	12,234 (1.7%)
Circulator	7,322 (1.0%)
Manifold	1,000 (0.1%)
Total	717,990

Considering the installation of the water-to-water heat pumps, each apartment owner is supposed to cover the costs for the decentralized heat pump (overall cost of 8,054 EUR for the Type 1 heat pump and 7,952 EUR for the Type 2 heat pump), the substitution of the radiators with fan coils (around 1,000 EUR each), piping (150 EUR/m). The related cost for a single apartment ranges from around 15,000 EUR for the apartments with only three fan coils and a surface of 36 m² to around 37,600 EUR for the flats with 14 fan coils and a surface of 218 m². The total cost of the proposed retrofit solution amounts to 1,301,350 EUR, which, considering the apartments' heated floor area, is 521 EUR/m².

On the other hand, the overall cost of replacing the old traditional boiler with the new condensing boiler is estimated to be 4,000 EUR. If the installation of the thermal insulation is considered, the costs of this retrofit scenario amount to 704,300 EUR, i.e., 282 EUR/m².

4.3.2 Operating costs

For the heat pump solution, the total electricity consumption brings the operating costs to 13,289 EUR/year. Therefore, the average operating cost per flat is 511 EUR/year. Considering the total natural gas and electrical energy consumption for the scenario with the condensing boilers, the annual operating costs amount to 15,445 EUR. For each apartment, the mean operating cost is 594 EUR/year. Fig. 9 presents an overview of the operating costs compared to the original case study. Overall, the operating costs are reduced to 40% with the water-to-water heat pump solution and 47% with the condensing boiler and direct expansion air conditioning system solution.

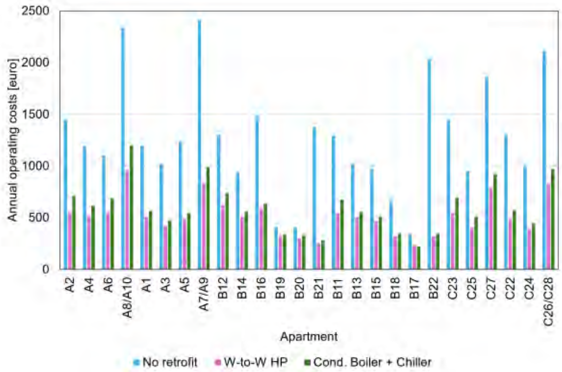

Fig. 9 – Operating cost for the original case, retrofit with heat pumps, with condensing boilers and direct expansion air cond

4.4 System's Performance

4.4.1 Energy performance class

The analysis performed with Edilclima software showed that the building's efficiency class E and the primary energy consumption was 169 kWh/(m^2 y) before the retrofit. If the same energy system (traditional boilers) is considered, combined with the installation of the external wall insulation, the efficiency class is enhanced to B (88 kWh/(m^2 y)).

On the other hand, the combination of the external wall insulation and installation of decentralized condensation boilers, with heating capacity ranging from 26 kW to 35 kW and efficiency equal to 94%, leads to an energy efficiency class A1 (72 kWh/(m^{2}y)). The retrofit scenario with envelope insulation and water-to-water heat pumps leads to the efficiency class A3, with 47 kWh/(m2 y).

4.4.2 Primary energy consumption

Table 4 shows the specific primary energy consumption related to the retrofit solutions with water-to-water heat pumps and condensing boilers. Using water-to-water heat pump systems leads to a higher renewable share, up to 55%, compared to the condensing boilers (less than 4%). This is due to the high renewable share in heating and DHW production of the water-to-water heat pump, which reaches 66%.

Table 4 – Specific renewable, non-renewable, and total primary energy (PE)

	PE ren kWh/(m^2 y)	PE non-ren kWh/(m^2 y)	PE tot kWh/(m^2 y)
W-to-W heat pumps	53.5	43.2	96.7
Heating	30.2	14.9	45.1
Cooling	2.8	11.4	14.1
DHW	18.9	10.1	29.0
Auxiliaries	1.6	6.8	8.4
Condensing boiler	2.9	72.3	75.2
Heating	0.3	43.9	44.2
Cooling	2.5	10.5	13.0
DHW	0.1	17.9	18.0

4.4.3 CO_2 emissions

The retrofit solution with water-to-water heat pumps produces 14.13 tons/year of CO_2, only 42% compared to the solution with condensing boilers and direct expansion air conditioning which produces 33.07 tons/year of CO_2.

5. Conclusions

This paper investigated a retrofit solution for a multi-family building near Milan, including the installation of a groundwater heat pump coupled with fan coils and thermal insulation of external walls. The hydraulic network was sized and simulated with a dynamic model. The solution with water-to-water heat pumps was compared with a benchmark retrofit solution based on individual gas boilers, in terms of investment and operating costs, energy efficiency class, primary energy consumption, and CO_2 emissions. The estimated installation costs for the solution with heat pumps lead to a mean value of 521 EUR/m², including the envelope retrofit, the substitution of the radiators with the fan coils, the extraction wells, the heat pumps and the whole distribution system. The investment cost for the second retrofit scenario is around 282 EUR/m².

Correspondingly, the average annual operating costs for the end users amount to 511 EUR/apartment for the first solution and 594 EUR/apartment for the second one. This means that the solution with water-to-water heat pumps can be competitive if incentives are applied to cut the investment costs for the apartment owners.

The results show that the existing case study (energy efficiency class E) reaches class A3 with the water-to-water heat pumps solution and class A1 with the solution with condensing boilers and direct expansion air conditioning. This achievement is mainly related to the high renewable share in primary energy of the water-to-water heat pump solution (55%) compared to the one with condensing boilers (4%). Overall, the heat pump solution reduces CO_2 emissions to 42% compared to the condensing boilers solution, showing that the groundwater loop can be a valuable technology for multifamily buildings to decrease the environmental impact of the heating and cooling systems.

Acknowledgements

The authors would like to thank Alberto Salmistraro from Hiref Sp.A. and Cecilia Hugony from TEICOS Group Srl for their technical support.

References

ARERA. 2021. "ARERA Dati e Statistiche." April 12, 2021. https://www.arera.it/dati-e-statistiche?ambito=55&keyword=&settore=4&orderby=

Città Metropolitana di Milano - Area ambiente e tutela del territorio - Settore risorse idriche e attività estrattive. 2023. "Scarichi Degli Impianti a Pompa Di Calore Nella Città Metropolitana Di Milano." www.cittametropolitana.mi.it

Edilclima. n.d. "Edilclima." 2024. Accessed April 12, 2024. https://www.edilclima.it/

International Organization for Standardization. 2017. "ISO 52016-1:2017, Energy Performance of Buildings – Energy needs for Heating and Cooling, Internal temperatures and Sensible and Latent Heat Loads - Part 1: Calculation Procetures."

ISPRA Istituto Superiore per la Protezione e la Ricerca Ambientale. 2023. "National Inventory Report 2023 – Italian Greenhouse Gas Inventory 1990-2021." 2023. https://emissioni.sina.isprambiente.it/inventario-nazionale/#Report

Jordan, Ulrike, and Klaus Vajen. 2005. "DHWcalc: Program to Generate Domestic Hot Water Profiles with Statistical Means for User Defined Conditions." Solar World Congress 2005: Bringing Water to the World 3: 1525–30

IPCC. 2006. "2006 IPCC Guidelines for National Greenhouse Gas Inventories." 2006. https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html

Schibuola Luigi, and Chiara Tambani. 2022. "Environmental Impact and Energy Performance of Groundwater Heat Pumps in Urban Retro-fit." https://doi.org/10.1016/j.enbuild.2022.111964

Sezer, Taha, Abubakar Kawuwa Sani, Rao Martand Singh, Liang Cui, David P Boon, and Michael Woods. 2024. "Numerical Investigation of a District Scale Groundwater Heat Pump System: A Case Study from Colchester, UK." *Applied Thermal Engineering* 236: 1359–4311. https://doi.org/10.1016/j.applthermaleng.2023.121915.