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Air/Water Heat Pumps in Existing Heating and Hot Water Systems for Better Urban Air Quality and Primary Energy Savings: Scenarios of Two Italian Cities

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Abstract: In a previous work, a significant contribution to urban air pollution, related to fuel-fired heating systems, was recorded. Thus, the replacement of existing boilers for space heating and domestic hot water (DHW) production systems with high-temperature air/water heat pumps (which can operate with radiators, the most common terminals in the existing building stock), is proposed for the improvement of the urban air quality. Scenarios of substitution within the entire residential building stock of two Italian cities, Milan and Salerno, belonging to different climate zones and with their own thermophysical characteristics, were analyzed. For each of them, the consequences of the replacement intervention on emission reduction, primary energy savings and lower CO_2 production were evaluated. The results show that reduction of primary energy consumption, evaluated at design outdoor temperature and for the present generation mix, varied between 34% and 54% in Milan and between 43% and 60% in Salerno, for two values of renewable fraction in electricity generation. The reduction of CO_2 production was in the range 30–52% in Milan and 39–58% in Salerno, respectively. The only unfavorable case occurred for Milan for a completely non-renewable electricity generation scenario. The replacement intervention, which implies a significant decrease of emissions of pollutants in urban areas, is unobtrusive to citizens, since the heat pumps (HPs) are coupled with current radiators, without the internal distribution system being modified.

Keywords: urban air quality; heat pumps; primary energy; CO_2 emissions

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1. Introduction

The restraints implemented to limit the spread of COVID-19 at the peak of the pandemic has allowed us to quantify the contribution of several polluting factors. In a previous work by Carella et al. [1], a significant contribution due to fuel-fired heating systems was recorded. Based on an analysis of the heating and domestic hot water (DHW) requirements of the residential building stock of two different Italian cities and the installed heat generators, the substitution of these heat generators with high-temperature air/water heat pumps of suitable size that can supply the current radiator systems is presented. This intervention is thus unobtrusive for citizens and is devoted to a better urban air quality.

The centralized use of air/water heat pumps has been studied by Minuto et al. [2] for a condominium in northwestern Italy to evaluate different retrofit scenarios. The air/water HP contributes to a reduction of total primary energy need by 26% and CO_2 emissions by 30%. The authors concluded that a storage system is essential to mitigate the adverse effects of the intermittence of the photovoltaic (PV) system.

The decarbonization potential of air heat pumps was also analyzed by Borge-Diez et al. [3] for the Spanish scenario. The proposal probably refers to low water outlet temperature, since the authors considered the intervention strictly coupled with adequate insulation interventions in homes.

The study by Gojak et al. [4] presents a thermodynamic sustainability assessment of various energy sources for residential buildings heating in Serbia. The authors concluded that the use of HPs, cogeneration or waste heat from thermal processes for heating implies advantages with respect to use of fossil fuels directly or for electricity production.

Zator et al. [5] presented the impact of a heat storage on the Coefficient of Performance (COP) of the HP, the self-consumption of energy from the PV system, and the energy cost in a single-family house in Poland.

The study by Jadwiszczak et al. [6] considered low-temperature HPs for heating and hot water production. Results showed that the CO_2 emissions are determined by the specific energy mix (55.2%), the COP (33.9%) and by the climate change (10.9%).

In [7], Campos et al. analyzed individual heat pumps and energy efficiency measures in Hungarian rural settings. They considered low-temperature HPs for heating and DHW, coupled with hot water storage tanks.

Teskeredzic et al. [8] examined the case of HPs for existing radiators and new underfloor heating systems in a single-family home in Bosnia and Herzegovina.

The study by Canova et al. [9] proposed two different scenarios of an energy community based on Renewable Energy Sources (RES): PV for the electricity demand of apartments, and an added HP for the building's heating needs. The authors demonstrated the economic affordability and environmental sustainability of a collective self-consumption system based on RES.

Baibolov et al. [10] create a zoning of the Kazakhstan territory based on the average temperature of the heating period for the selection of HP.

The importance of multiple parameters, such as climatic conditions for selecting the best HP technology, was also studied by Mouzeviris et al. [11], for the case of low water outlet temperatures. Authors provided the Seasonal Coefficient of Performance (SCOP) for different air/water heat pumps available in the Greek market for four Greek climate zones (A, B, C, D). Numerical results showed the influence of heat pump technology (compressor) and water outlet temperature, and highlighted the relevance of climate data on seasonal performance.

The recent literature has largely focused on the study of the coupling of low-temperature heat pumps with other systems, from an energy and/or economic perspective, or on the comparisons of different heating systems at different levels (for example, district heating [12]).

Proposed actions were studied for two different Italian cities, Milan and Salerno, characterized by different outdoor air temperatures and with different thermophysical characteristics of their building stock.

Replacement scenarios were analyzed for the case of an outdoor temperature equal to the design temperature (the most severe one) and for different distributions of energy production to power the HPs. More specifically, in addition to the present fraction of production from RES (related to the supplying from the Italian grid), a fraction of fossil fuel in electricity generation equal to 100% (renewable portion equal to 0% and present mix of fuels) was considered as the worst case to take in account. Furthermore, a 2030 future scenario based on the 2021 Development Plan of Terna [13] (the Italian national electricity transmission grid operator) was considered, which targets a 55% contribution by renewables to electricity production.

The assessment of the replacement, while taking into account a few approximations and working hypotheses, confirmed for both cities a significant abatement of primary energy needs, CO_2 production and pollutant emissions, due to the highest generation efficiencies achieved in the large thermoelectric power plants and to their pollutant reduction systems.

It represents an important contribution for a better air quality in the cities, both for the lower emission levels and for the most effective capture and neutralization interventions, and for more efficient emissions of fumes at the chimney.

Finally, it can be minimally invasive for citizens (since the existing radiator systems are not modified) to reduce air pollution in the long term, since it implies a significant decrease of emissions of pollutants in urban areas, with reduced energy (and, therefore, environmental) costs, towards environmentally sustainable cities.

At present in Italy, there are aid programs for thermal modernization of buildings implemented by residents/building owners, but they are available for limited periods and not mandatory for old and inefficient buildings. The impact of these retrofits on the global efficiency of the national building stock is not yet known. A more efficient building allows for the installation of low-temperature heat pumps, but with invasive and, in general, long-term retrofits. The same aid programs promote the replacement of the heating systems with HPs, but necessarily coupled with other improvements to building efficiency.

In this paper, a replacement is proposed for quick implementation, under the present conditions of existing thermal installations and focused on air quality improvement.

For the same reason, in our study, possible benefits or more favorable scenarios such as localized generation from photovoltaic [14] were not considered, because the focus was on an easy intervention that is not invasive and not too expensive, such as the simple substitution of the heat generator.

2. Materials and Methods

Two Italian cities, belonging to two different climate zones according to Italian national legislation, were considered [15]. In particular, the Italian territory is divided into six climate zones (A, B, C, D, E, F), based on average temperature and independent of geographical location, as shown in Figure 1.

Figure 1. Map of Italy divided into climate zones and location of the cities of Milan and Salerno.

Milan, in Lombardy, located in the northwestern region of the Italian peninsula, belonging to the cold-temperate zone E and characterized by an external design temperature [16] of −5 °C, was considered. The other analyzed city was Salerno, a city in central-southern Italy facing the Tyrrhenian Sea, belonging to mid-temperate zone C and having an external design temperature of 2 °C.

The two cities belong to distinct and different zones (E and C), both widespread in Italy; the choice of two extreme zones such as A and F would have concerned limited cases with respect to the entire territory.

In addition, for these two cities, data were available on the thermophysical characterization of their building stocks.

According to the National Institute of Statistics ISTAT [17], Milan is outlined as a city in which approximately 70% of buildings were constructed between 1919 and 1970. Only 5% of the buildings were built after 1990. Most (66%) are four or more stories above ground, while only 7% are one story. This was confirmed by the fact that more than half of them (55%) have more than eight interiors.

Although less evident in Salerno, the majority (55%) of residential buildings were built between 1919 and 1970. Only 7.5 % of the buildings were built after 1990. Most (46%) are two or three stories above ground, with 37% consisting of one or two interiors.

In order to characterize the building stock of the city of Milan from an energy point of view, the CENED +1.2 database [18] of the Lombardy Region was taken into consideration; this database contains information useful for drawing up energy certificates.

From the database, it was possible to compute the average values of the thermal transmittance by dwellings in the Municipality of Milan for each period of construction. Figure 2 shows the trends in thermal transmittance by the windows and vertical opaque envelope, the basement and the roof.

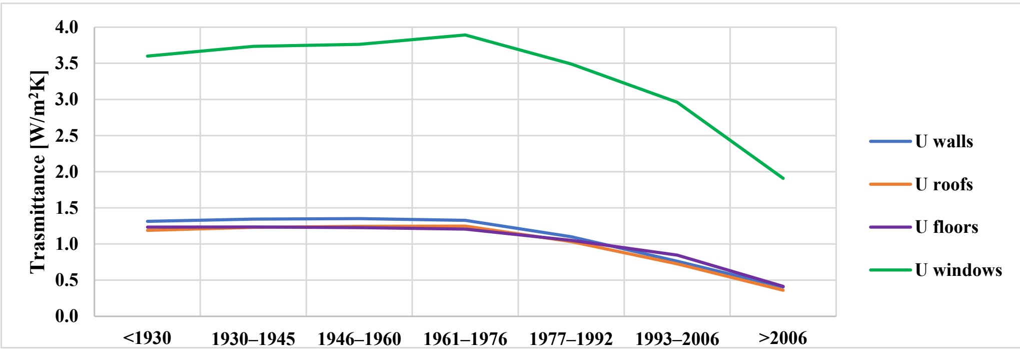

Figure 2. Trend in average thermal transmittance by walls, floors, roofs and windows of the average flat in Milan, by age of construction.

It can be seen that up to 1976, the average thermal transmittance of all components remained fairly constant and then decreased, probably due to the approval of Law 373 of 1976 on energy efficiency and Law 10 of 1991.

The energy analysis of private buildings carried out in the Municipal Energy Plan for the Municipality of Salerno [19], whose authors declared that the values of transmittance were taken from UNI/TS 11300-1:2008 [20], identified the trends in average thermal transmittance by opaque components and windows, as shown in Figure 3.

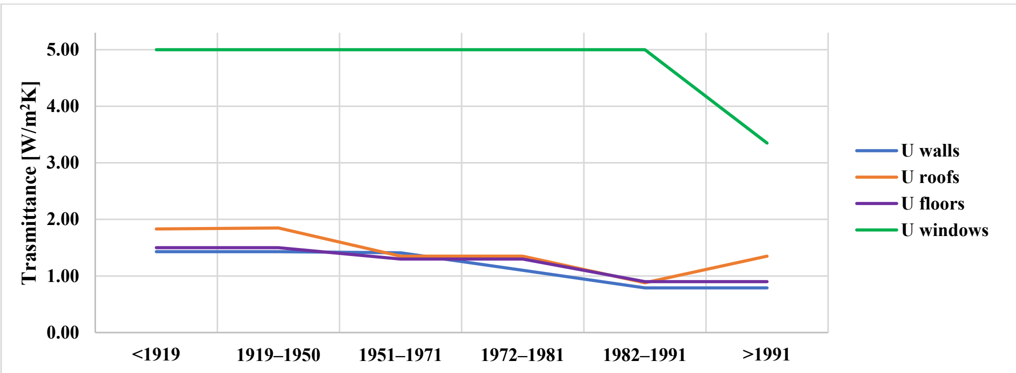

Figure 3. Trend in average thermal transmittance by walls, floors, roofs and windows of the average flat in Salerno, by age of construction (data from [19]).

It can be seen that up to the 1970s, the average thermal transmittance by all components remained fairly constant, but then decreased, again due to passage of Law 373 of 1976 on energy efficiency and Law 10 of 1991. In the case of roofs, on the other hand, an anomalous increase was noted for the data available in [19].

In order to evaluate the average thermal requirements for heating, associated with flats in the city of Milan, the certificates of dwellings with destination of use E.1(1) (D.P.R. 412/93) were taken into consideration from the entire CENED +1.2 database. They were dwellings used as residences with a continuous character, relative to a single sub-terrain, so as to exclude those referring to entire blocks of flats.

For the sake of simplicity, it was decided to consider only the inter-floor building units, identifiable in the database as those without a numerical transmittance value for the basement and roof, indicating the absence of these dispersing elements.

From the values for the transmittances and dispersing surfaces, the heat requirement for heating was thus calculated, assumed as a first approximation to be equal to the heat dispersion by transmission through the vertical opaque envelope and windows.

The simplified calculation of the heating heat requirement was carried out in line with what was adopted by UNI/TS 11300-1:2014 [21], by summing the monthly heating needs, relative to the period of the winter season, for 24 h per day.

An internal temperature t_i of 20 °C was assumed, and an external temperature equal to the monthly average value of the daily average external temperature, obtained from UNI 10349:1994, was used [22].

The calculation was applied to all of the certificates present in the Cened +1.2 database, from which the average characteristic values relative to each period of construction shown in Table 1 were then obtained.

Table 1. Thermal energy needs for space heating and DHW preparation per construction year CY for the city of Milan and portion of the buildings stock %BS.

CY	%BS	Thermal Energy Needs in kWh$_t$/Year for the City of Milan		
		Heating	DHW	Heating and DHW
<1918	8.8%	7744	1140	8883
1919–1945	16.3%	7733	1130	8863
1946–1960	25.0%	7933	1151	9084
1961–1970	28.1%	8709	1209	9919
1971–1980	11.2%	8564	1233	9797
1981–1990	4.2%	8346	1269	9615
>1991	6.3%	5791	1159	6950

The thermal energy requirements for domestic hot water were obtained according to UNI/TS 11300-2:2014 [23], considering a 24 h daily use period extended to the entire year (1).

$$Q_w = \rho_w \times c_w \times Vw \times (\theta_{er} - \theta_0) \times G \quad (1)$$

The domestic hot water supply temperature θ_{er} is assumed to be 40 °C, and the cold-water inlet temperature θ_0 is assumed to be equal to the annual average of the monthly average outdoor temperatures of the air taken from UNI 10349. The required volumes of water were obtained according to Table 30, reported in [23] as a function of the useful surface area of the dwelling, which is present as data in the Cened +1.2 certificates.

The formula was applied to all of the certificates present in the Cened +1.2 database, from which the average characteristic values for each period of construction were then derived. The results are shown in Table 1.

To represent and compare the data of the two cities, coming from two different databases with different periodization, it was decided to use the subdivision of construction periods adopted by ISTAT. The average values of thermal requirements related to the time periods of the ISTAT database were obtained by considering the degrees of temporal overlapping between the two periodization systems and using them as weights for the computation of the weighted average.

The results show higher thermal requirements associated with the average intermediate flat after the 1960s, probably associated with higher average transmittance by windows and walls together with higher dispersing surfaces.

With regard to the city of Salerno, in order to evaluate the average heating requirements associated with the flats, at first the dispersing surfaces were obtained.

In particular, reference was made to Annexes A and B of the Municipal Energy Plan of Salerno, where the recurrent architectural types in the building stock are represented.

These are shown in succession, in relation to the number of above-ground floors and the number of interiors present. From the diagrams shown, it was possible to deduce the net floor area and the lateral area of the buildings.

On the other hand, the values of the net heights, the surfaces of the walls and the windows, and the surfaces dispersing towards the stairwell were obtained from Annex D. The latter ones were subtracted from the lateral surfaces to obtain the side opaque surfaces.

From each building typology reported, characterized by a certain number of floors and interiors, the typical individual flats for each building typology were approximated, focusing attention, as in Milan, on the inter-floor building units.

Once the heating requirements for each typical individual flat had been calculated, a weighted average was made based on ISTAT data on the number of buildings by number of interiors and above-ground floors, in order to obtain a representative average value for each period of construction. Table 2 shows the results obtained in summary.

Table 2. Thermal energy needs for space heating and DHW preparation per construction year CY for the city of Salerno and portion of the building stock %BS.

CY	%BS	Thermal Energy Needs in kWh$_t$/Year for the City of Salerno		
		Heating	DHW	Heating and DHW
<1918	8.1%	4778	1239	6017
1919–1945	9.8%	4782	1239	6022
1946–1960	24.1%	4205	1375	5580
1961–1970	31.4%	3916	1443	5359
1971–1980	12.9%	3304	1443	4746
1981–1990	9.4%	2774	1443	4217
>1991	4.3%	2525	1443	3968

Similarly to Milan, thermal energy requirements for domestic hot water were then calculated according to UNI/TS 11300-2:2014 [23] and reported in Table 2.

For Salerno, the division of construction periods adopted by ISTAT was also used.

From the data obtained, a progressive decrease in thermal requirements could be observed as the years progressed.

Once the thermal requirements of the building stocks were known, the present stocks of installed thermal systems were analyzed. According to the ISTAT census of 2011 on the type of fuel or source of energy supplying the heating systems of homes in Milan [24], the most widely used source was methane gas (81.92%), followed by diesel (12.12%) and electricity (3.10%).

The portion of homes using fuels such as wood or coal (0.47%), LPG (0.57%), oil (0.15%) or other types of fuel or energy were lower.

Following the regional register of thermal plants (Catasto Unico Regionale degli Impianti Termici CURIT) [25], the number of heating systems in the city of Milan consisted of approximately 153,000 autonomous systems with an average capacity of less than 35 kW and 27,000 centralized systems with an average capacity of more than 35 kW and typically serving more than one property unit.

According to the 2011 ISTAT census on the types of fuel or source of energy used to fuel the heating systems of homes in the Province of Salerno [24], the most used source was methane (53.88%), followed by solid fuel (24.92%) and LPG (10.29%).

The percentages of dwellings using electricity (6.64%), diesel (2.14%), oil (0.07%) or other types of fuel or energy for heating were lower.

The census on the number of dwellings equipped with a heating system [26] showed that there were approximately 38,000 autonomous and 3000 centralized systems of heating in the city of Salerno.

With regard to the combustion efficiency for winter air conditioning of the systems present in Milan, an average value of 0.9 was deduced from CURIT.

In order to calculate the average global efficiency, the tables contained in UNI/TS 11300-2:2014 [23] were used to estimate the distribution, control and emission efficiency values, assumed to be 0.98, 0.95 and 0.94, respectively. The average global efficiency value obtained from the product of the four efficiencies was 0.8.

With regard to the efficiency for DHW production, reference was made to the UNI/ TS 11300-2:2014 prospectuses [23], from which the average global efficiency of the generator was estimated to be equal to 0.7 (obtained from the product of the efficiencies of generation equal to 0.8, supply equal to 1, and distribution equal to 0.9).

Because data on the efficiency of thermal plants in Salerno were not available, the same efficiency values as those in the previous cases were assumed (0.8 for winter air conditioning and 0.7 for DHW production). In fact, as in the case of Milan, Salerno's thermal plants were mainly made up of autonomous plants (over 90%) that used methane gas as their main fuel.

In order to replace the entire thermal systems of the two cities with high-temperature air/water heat pumps, and analyzing the different scenarios, selection of sizes and types of HPs were made.

The sizing of the HPs was done related to the thermal load for winter space heating by considering a configuration based on the logic of prioritizing DHW production over heating and taking into account the fact that the two thermal needs are never satisfied simultaneously.

In particular, for both cities, from the values for the transmittances and dispersing surfaces, the winter heat load at the external design temperature was calculated (2); as a first approximation, it was assumed equal to the heat dispersion by transmission through the vertical opaque envelope and the windows, as follows:

$$q_h = (H_o \times S_o + H_w \times S_w) \text{ x } (t_i - t_p) \quad (2)$$

where H_o and S_o are, respectively, the transmittance and dispersing surface of opaque walls, H_w and S_w the transmittance and dispersing surface of windows and walls, t_i the desired indoor temperature of 20 °C, and t_p the design outdoor temperature, equal to −5 °C for Milan and 2 °C for Salerno.

Tables 3 and 4 show the nominal powers of the HPs by year of construction.

Table 3. Nominal power (NP), plate power (PP) and COP of the HP appropriate for the design value of the outdoor temperature of Milan (−5 °C), per construction year CY (outlet water temperature 70 °C) and portion of the building stock %BS.

CY	%BS	NP kW	PP kW	COP (−5 °C/70 °C)
<1918	8.8%	3.35	8.73	1.78
1919–1945	16.3%	3.34	8.73	1.78
1946–1960	25.0%	3.43	8.73	1.78
1961–1970	28.1%	3.76	8.73	1.78
1971–1980	11.2%	3.70	8.73	1.78
1981–1990	4.2%	3.61	8.73	1.78
>1991	6.3%	2.50	8.73	1.78

Table 4. Nominal power (NP), plate power (PP) and COP of the HP appropriate for the design value of the outdoor temperature of Salerno (2 °C), per construction year CY (outlet water temperature 70 °C) and portion of the building stock %BS.

CY	%BS	NP kW	PP kW	COP (2° C/70 °C)
<1918	8.1%	3.40	9.13	2.00
1919–1945	9.8%	3.41	9.13	2.00
1946–1960	24.1%	3.03	9.13	2.00
1961–1970	31.4%	2.85	9.13	2.00
1971–1980	12.9%	2.68	9.13	2.00
1981–1990	9.4%	2.53	9.13	2.00
>1991	4.3%	2.46	9.13	2.00

In particular, air-water HPs are considered suitable to operate with radiators, the most frequent terminals in the current stock of building, and are, thus, capable of producing water flow at a temperature of 70 °C or higher.

The heat pumps selected in this study had scroll compressors with inverter capacity control and economizers to increase the efficiency of the system. They used the R32 refrigerant, which offers a low global warming potential (GWP) compared to standard refrigerants and ensures higher energy efficiency and lower CO_2 emissions.

The size of the HP was selected from a catalogue of a manufacturer taking into account an outdoor temperature close to and not higher than the design outdoor temperature.

In order to ensure high-temperature operation, a choice to oversize was made with respect to the required heat output. The choices previously described were related to design conditions. Real operating conditions imply different values of external temperature during the heating season, with favorable consequences for HP performance, due to a direct thermodynamic effect and to reduced heat losses from machines (with inverter) working under partial load conditions. The present analysis concerned, therefore, the worst-case scenario.

The nominal power (NP) values of the selected heat pumps, obtained from the manufacturers' catalogues, at the design outdoor temperature and flow temperature of 70 °C, are shown in Tables 3 and 4 for each energy needs.

The COP of the selected heat pumps is given by the HPs makers as the ratio between the heating capacity and the electrical power input. The first is defined as the integrated power between the power for heating and the power used between the start of one defrosting cycle and the start of the next, also given by the HP maker for a pair of outside air and outlet water temperature values.

The COP at design conditions, if not present in the values declared by the manufacturer (as in the case of Milan with an external design temperature of −5 °C), was obtained following UNI EN 14825 [27] (see Appendix A).

Table 3 for Milan and Table 4 for Salerno show, for each selected HP and by construction year of the buildings, the calculated COP values for the selected delivery water temperature (70 °C), reiterating that the current radiators were to be left as terminals, and the outdoor design temperatures were −5 °C (for Milan) and 2 °C (for Salerno).

3. Results and Discussion

To evaluate the overall impact, with regard to primary energy consumed and tons of CO_2 produced, that the substitution of the boilers currently most common in Milan and Salerno with HPs would entail, the entire heating system stock of the cities was considered. Results are summarized in Tables 5 and 6, together with Tables 7 and 8 and finally in Tables 9 and 10. According to Milan, there are approximately 153,000 autonomous systems, each with output power of less than 35 kW, and 27,000 centralized systems. The latter, with regard to a condominium composed of an average of 12 flats, were considered equivalent to 324,000 autonomous systems. Therefore, 480,000 HPs were considered to be installed, with the characteristics previously described, distributed in number as reported in Table 7.

Table 5. Total heating needs and primary energy requirements for boilers (η_h = 0.8; η_w = 0.7) and selected HPs, per building construction year CY in the city of Milan (generation fraction from RES 35%, grid losses 10%, COP at design temperature of −5 °C).

CY	Thermal Energy Needs for Heating and DHWPreparation, kWh_t/Year	Primary Energy Requirement for Single Boiler, kWh_t/Year	Primary Energy Requirement for HP (COP −5 °C/70 °C) from Fossil Fuels, kWh_t/Year
<1918	8883	11,307	7434
1919–1945	8863	11,281	7417
1946–1960	9084	11,560	7602
1961–1970	9919	12,614	8300
1971–1980	9797	12,467	8199
1981–1990	9615	12,245	8046
>1991	6950	8894	5816

Table 6. Total heating needs and primary energy requirements for boilers (η_h = 0.8; η_w = 0.7) and selected HPs, per building construction year CY in the city of Salerno (generation fraction from RES 35%, grid losses 10%, COP at design temperature of 2 °C).

CY	Thermal Energy Needs for Heating and DHW Preparation, kWh_t/Year	Primary Energy Requirement for Single Boiler, kWh_t/Year	Primary Energy Requirement for HP (COP 2 °C/70 °C) from Fossil Fuels, kWh_t/Year
<1918	6017	7743	4482
1919–1945	6022	7748	4485
1946–1960	5580	7220	4156
1961–1970	5359	6957	3991
1971–1980	4746	6190	3535
1981–1990	4217	5529	3141
>1991	3968	5218	2955

Table 7. Distribution, by building construction year CY in Milan, of the 480,000 selected HPs, percentage ratio of global primary energy from fossil fuels (GPE) and CO_2 emissions of heat pumps to that of boilers (generation fraction from RES 35%, grid losses 10%, COP at design temperature of −5 °C), portion of building stock %BS, nominal power NP.

CY	%BS	NP kW	Number of HPs	GPE HPs/GPE Boilers	CO_2 HPs/CO_2 Boilers
<1918	8.8%	3.35	42,328	66%	70%
1919–1945	16.3%	3.34	78,379	66%	70%
1946–1960	25.0%	3.43	119,867	66%	70%
1961–1970	28.1%	3.76	134,816	66%	70%
1971–1980	11.2%	3.70	53,821	66%	70%
1981–1990	4.2%	3.61	20,379	66%	70%
>1991	6.3%	2.50	30,410	65%	70%
TOTAL	8.8%	3.35	480,000	66%	70%

Table 8. Distribution, by year of building construction CY in Salerno, of the 74,000 selected HPs, percentage ratio of global primary energy from fossil fuels and emissions of CO_2 of heat pumps to that of boilers; (generation fraction from RES 35%, grid losses 10%, COP at design temperature of 2 °C), portion of building stock %BS, nominal power NP.

CY	%BS	NP kW	Number of HPs	GPE HPs/GPE Boilers	CO_2 HPs/CO_2 Boilers
<1918	8.1%	3.40	6022	58%	62%
1919–1945	9.8%	3.41	7255	58%	62%
1946–1960	24.1%	3.03	17,860	58%	61%
1961–1970	31.4%	2.85	23,226	57%	61%
1971–1980	12.9%	2.68	9546	57%	61%
1981–1990	9.4%	2.53	6934	57%	61%
>1991	4.3%	2.46	3158	57%	60%
TOTAL	8.1%	3.40	74,000	57%	61%

Table 9. Percentage ratio of global primary energy from fossil fuels (GPE) and emissions of CO_2 of heat pumps to that of boilers per building construction year CY in the city of Milano (generation fraction from RES 0% and 55% (2030), grid losses 10%, COP at design temperature of −5 °C).

CY	GPE HPs/GPE Boilers		CO_2 HPs/CO_2 Boilers	
	Generation Fraction from Renewable Energies, 0%	Generation Fraction from Renewable Energies, 55%	Generation Fraction from Renewable Energies, 0%	Generation Fraction from Renewable Energies, 55%
<1918	101%	46%	108%	48%
1919–1945	101%	46%	108%	48%
1946–1960	101%	46%	108%	48%
1961–1970	101%	46%	108%	49%
1971–1980	101%	46%	108%	49%
1981–1990	101%	45%	108%	48%
>1991	101%	45%	107%	48%
TOTAL	101%	46%	108%	48%

Table 10. Percentage ratio of global primary energy from fossil fuels (GPE) and CO_2 emissions of heat pumps to that of boilers per building construction year CY in the city of Salerno (generation fraction from RES 0% and 55% (2030), grid losses 10%, COP at design temperature of 2 °C).

CY	GPE HPs/GPE Boilers		CO_2 HPs/CO_2 Boilers	
	Generation Fraction from Renewable Energies, 0%	Generation Fraction from Renewable Energies, 55%	Generation Fraction from Renewable Energies, 0%	Generation Fraction from Renewable Energies, 55%
<1918	89%	40%	95%	43%
1919–1945	89%	40%	95%	43%
1946–1960	89%	40%	94%	42%
1961–1970	88%	40%	94%	42%
1971–1980	88%	40%	94%	42%
1981–1990	87%	39%	93%	42%
>1991	87%	39%	93%	42%
TOTAL	88%	40%	94%	42%

For the city of Salerno, given its 38,000 autonomous systems and 3000 centralized systems (equivalent to 36,000 autonomous systems), a total of 74,000 HPs were considered to be installed, distributed as in Table 8.

In the following evaluations, the conversion factor to primary energy, for methane gas and electricity from renewable source, was assumed equal to unity; the efficiency of the existing boilers was 0.8 for heating and 0.7 for DHW production, the distribution losses in the electricity grid were 10% [28,29], and the fossil-to-electric conversion efficiency for 2021 was 48%.

Concerning electricity generation, two cases were considered regarding the renewable fraction: the present one, referring to 2021 ((equal to 35%), available from Terna source [28,29]), and 0%, referring to the worst case. Furthermore, a 2030 target scenario was considered, which targeted a 55% contribution by renewables to total electricity generation.

The considered COP was that related to the design value of outdoor temperature of the air, equal to −5 °C for Milan and 2 °C for Salerno. The useful coefficient to calculate the emissions of CO_2, with regard to the methane burnt for the boilers, was taken from the table of the national inventory of CO_2 emission coefficients of the United Nations Framework Convention on Climate Change (UNFCCC) [30], and was equal to 202.36 g CO_2/kWh_t. The coefficient useful to compute the emissions of CO_2 related to the production of electricity supplying the HPs was found in a report on emissions in the electricity sector by the Italian institute for environmental protection and research (Ist. Sup- per la Protezione e la Ricerca Ambientale ISPRA) [30], and it was equal to 449.1 g CO_2 /kWh of electricity for the current mix of fuels relative to the non-renewable fraction.

Tables 5 and 6 show, by year of construction CY of the building, the thermal requirements for heating and DHW preparation and the corresponding primary energy needs for the existing boilers and selected heat pumps in the current energy distribution scenarios for the cities of Milan and Salerno.

As expected, the heat requirements, and corresponding primary energy needs were significantly higher for the older buildings in Salerno.

In Milan, on the other hand, the thermal needs, and consequently the primary energy needs, were higher if associated with the average intermediate flats built after the 1960s, probably due to the higher average transmittance of windows and walls, together with higher dispersing surfaces.

Primary energy requirements in the case of HPs were always lower than those of boilers, both for Milan and Salerno and for all years of construction.

For the same generation scenario (35% from RES), the percentage ratios of global primary energy consumption from fossil fuels (GPE), in the case of existing boilers and proposed HPs, are reported in Tables 7 and 8 for the entire building stock of the city of Milan and Salerno, respectively.

Results are presented in terms of the percentage ratio, between heat pumps and boilers, of global primary energy from fossil fuel and of CO_2 production.

One can see that the percentage ratios, representative of the reduction in consumption and CO_2 production, were irrespective of the year of construction; this was due to the fact that the same machine, with a certain COP under design conditions, was selected to ensure operation at high temperatures (70 °C) with radiators.

The substitution of the whole boiler fleet, taking into account the external design conditions, implied a decrease of primary energy consumption of 34% and 43% and an abatement of the emissions of CO_2 of 30% and 39% for Milan and Salerno, respectively.

The greater reductions obtained in the case of the city of Salerno were probably associated with the more favorable external design temperature conditions, for which the COP of the HPs assumed higher values.

A similar analysis was performed for the case of electricity generated both from fossil fuels alone (0% RES fraction) and 55% from renewable sources (the 2030 target goal). The results are reported in Tables 9 and 10 for the city of Milan and Salerno, respectively.

In the most unfavorable scenario (electricity generation exclusively from fossil fuels with the present mix of fuels), one can see that a reduction occurred for the case of Salerno (related to milder design external conditions), while for the case of Milan, characterized by more unfavorable design temperature, an advantage was not observed. The same results were obtained for CO_2 emissions.

In the future scenario (2030) [13], reductions at design conditions were significant: in primary energy consumption of 54% for Milan and 60% for Salerno, and in CO_2 emissions of 52% and 58% for Milan and Salerno, respectively.

An analysis performed with parameters evaluated at the most frequent external conditions, different from the design ones (for example, by means of SCOP), would yield different results, also due to different water outlet temperatures.

Under these more realistic conditions, it is likely that the results in terms of obtained advantages, related to the cities under consideration, will be different. The present results, for the less favorable scenario, implied minimum values of achievable benefit.

4. Conclusions

Starting from the findings of a previous work by Carella et al. [1] on the analysis of pollutant concentrations and from the identification of the weight of heating systems as an emissive source, the substitution of boilers in current heating and DHW preparation systems with air/water HPs was proposed as an intervention to increase the urban air quality level.

The study was mainly dedicated to assessing whether the proposed substitution of the approximately 480,000 autonomous methane gas boilers in the city of Milan and 74,000 in the city of Salerno, which implies a significant reduction in emissions of pollutants in the urban area, would, on the other hand, entail additional energy (and, therefore, environmental) costs. Replacing the current boilers would eliminate the individual local sources of emission, displacing emissions at thermal power plants located in suburban areas, characterized by the highest generation efficiencies and equipped with trapping and reaction systems (for sulfur and, nitrogen oxides, particulate matter, CO_2), with release into the atmosphere, which occurs at relevant heights, with respect to those in urban zones.

The study demonstrated the validity of the proposal in terms of reducing primary energy needs and CO_2 emissions in the two cities under consideration, for the case of an external temperature at design conditions and for some electricity generation mixes that will be changed in the future, in favor of increasing shares of RES.

The results obtained are a useful indication for overall incentive measures, given the low invasiveness of the interventions for individual citizens (since internal heat distribution systems using radiators are not involved), and cannot be considered a feasibility study for an individual intervention. It should be remembered that the assumptions made (average efficiency of boilers) and selections performed (the machines) were a first approximation, and, therefore, cannot be used for the evaluation of an individual intervention. Each individual intervention will also have to take into account the real overall dimensions (with, on average, little space available in ancient and old buildings, for which the option of centralized HPs systems could be taken in consideration).

It is worth pointing out that design conditions are not the most frequent. In the case of different external temperature, the higher COP of the HPs and the fact that they work at partial load conditions imply a greater advantage. A more in-depth analysis will be performed in a future work, to assess the behavior of the systems in real operating conditions. More specifically, the seasonal COP (SCOP) declared by the manufacturer will be taken into account, representing the weighted seasonal average of COPs at various load and temperature conditions, according to a standard profile. In addition, a specific SCOP, constructed according to the characteristic external temperature profiles of each city under consideration, will be assessed as an average value, both in time and frequency (BIN method).

This preliminary analysis was carried out to verify that the substitution of boilers with high-temperature heat pumps in order to achieve better air quality in urban areas does not imply a price to pay in terms of primary energy consumption and production of CO_2.

Future works will also investigate more favorable/unfavorable climatic conditions related to different Italian and European cities.

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Appendix A

For the same outlet water flow temperature, for the case of a design outdoor air temperature within the range of values given by the HP makers, the COP is computed by linear interpolation of the second principle efficiency values η_{II}, computed on the basis of the known data. If the outdoor air temperature is outside the range of values given by the HP makers, but within a maximum deviation of 5 K, the efficiencies η_{II} calculated on the basis of the nearest possible known data can be extrapolated (i.e., η_{II} is considered to remain constant up to a difference of temperature of 5 K). The second principle efficiency η_{II} is calculated for electric HPs as the ratio of Equation (A1), between the actual efficiency of the heat pump, declared by the HP maker, and the theoretically attainable maximum efficiency (theoretical maximum COP).

$$\eta_{II} = \frac{\text{COP}}{\text{COP}_{max}} = \text{COP}\,\frac{t_h - t_c}{t_h + 273.15} \tag{A1}$$

where t_h is the outlet water temperature (at the condenser), and t_c is the temperature at the cold source (evaporator). The COP value at condition x is, thus, derived from the efficiency ηII interpolated to condition x, as in Equation (A2).

$$\text{COP}_x = \eta_{II,x}\,\frac{t_h + 273.15}{t_h - t_{c,x}} \tag{A2}$$

Since the COP values for the desired value of the design external temperature of Milan (−5 °C) were not available from the HP makers, we proceeded by analogy with the interpolation of the second-principle efficiencies of the known data.

References

1. Carella, A.; D'Orazio, A. The heat pumps for better air quality. *Sustain. Cities Soc.* **2021**, *75*, 103314. [CrossRef] [PubMed]
2. Minuto, F.D.; Lazzeroni, P.; Borchiellini, R.; Olivero, S.; Bottaccioli, L.; Lanzini, A. Modeling technology retrofit scenarios for the conversion of condominium into an energy community: An Italian case study. *J. Clean. Prod.* **2021**, *282*, 124536. [CrossRef]
3. Borge-Diez, D.; Icaza, D.; Trujillo-Cueva, D.F.; Açıkkalp, E. Renewable energy driven heat pumps decarbonization potential in existing residential buildings: Roadmap and case study of Spain. *Energy* **2022**, *247*, 123481. [CrossRef]
4. Gojak, M.; Bajc, T. Thermodynamic sustainability assessment for residential building heating comparing different energy sources. *Sci. Technol. Built Environ.* **2021**, *28*, 73–83. [CrossRef]

5. Zator, S.; Skomudek, W. Impact of DSM on Energy Management in a Single-Family House with a Heat Pump and Photovoltaic Installation. *Energies* **2020**, *13*, 5476. [CrossRef]
6. Jadwiszczak, P.; Jurasz, J.; Kaźmierczak, B.; Niemierka, E.; Zheng, W. Factors Shaping A/W Heat Pumps CO_2 Emissions—Evidence from Poland. *Energies* **2021**, *14*, 1576. [CrossRef]
7. Campos, J.; Csontos, C.; Harmat, Á.; Csüllög, G.; Munkácsy, B. Heat consumption scenarios in the rural residential sector: The potential of heat pump-based demand-side management for sustainable heating. *Energ. Sustain Soc.* **2020**, *10*, 40. [CrossRef]
8. Teskeredzic, A.; Blazevic, R.; Dzino, S. Application of Air-Water Heat Pump in Refurbished Building with Existing Radiator System. In Proceedings of the 31ST DAAAM International Symposium on Intelligent Manufacturing and Automation., Vienna, Austria, 21–24 October 2020. [CrossRef]
9. Canova, A.; Lazzeroni, P.; Lorenti, G.; Moraglio, F.; Porcelli, A.; Repetto, M. Decarbonizing residential energy consumption under the Italian collective self-consumption regulation. *Sustain. Cities Soc.* **2022**, *87*, 104196. [CrossRef]
10. Baibolov, A.; Sydykov, S.; Alibek, N.; Tokmoldayev, A.; Turdybek, B.; Jurado, F.; Kassym, R. Map of zoning of the territory of Kazakhstan by the average temperature of the heating period in order to select a heat pump system of heat supply: A case study. *Energy Sources A: Recovery Util. Environ. Eff.* **2022**, *44*, 7303–7315. [CrossRef]
11. Mouzeviris, G.A.; Papakostas, K.T. Seasonal heat performances of air-to-water heat pumps in the Greek climate. *IOP Conf. Ser.: Earth Environ. Sci.* **2020**, *410*, 012043. [CrossRef]
12. Nardecchia, F.; Bisegna, F.; Zanghirella, F. A review of Italian district heating. In Proceedings of the 2022 IEEE International Conference on Environment and Electrical Engineering and 2022 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Prague, Czech Republic, 28 June–1 July 2022. [CrossRef]
13. Terna Driving Energy, 2021 Development Plan. Available online: https://download.terna.it/terna/Piano_Sviluppo_2021_8d94126f94dc233.pdf (accessed on 4 September 2022).
14. Nematchoua, M.K.; Sadeghi, M.; Reiter, S. Strategies and scenarios to reduce energy consumption and CO_2 emission in the urban, rural and sustainable neighbourhoods. *Sustain. Cities Soc.* **2021**, *72*, 103053. [CrossRef]
15. President of Republic, Decree August 26, 1993 n. 412 (italian language) Presidente della Repubblica, Decreto 26 agosto 1993 no.412, GU n.96 del 14-10-1993, Rome. 1993. Available online: https://www.anit.it/wp-content/uploads/2015/03/DPR_412_93.pdf (accessed on 7 September 2022).
16. *UNI EN 12831*; Design Heat Load Calculation Method. UNI—Ente Italiano di Normazione: Milan, Italy, 2006.
17. ISTAT, National Institute of Statistics. Residential Buildings by Age of Construction-ISTAT Census 2011 (Italian Language) ISTAT, Edifici Residenziali per Epoca di Costruzione. 2011. Available online: http://dati-censimentopopolazione.istat.it (accessed on 5 February 2022).
18. Cened Data. Available online: https://www.cened.it/opendata-cened-1.2 (accessed on 28 January 2022).
19. Municipality of Salerno, University of Salerno, Proposed Municipal Energy Plan for the Municipality of Salerno (PEC), Energy Analysis for Private Buildings, Annexes A, B, C, D. Available online: http://www.dimec.unisa.it/PEC_Salerno/materiali.asp (accessed on 2 February 2022).
20. *UNI/TS 11300-1:2008*; Energy Performance of Buildings Part 1: Evaluation of Energy Need for Space Heating and Cooling. UNI—Ente Italiano di Normazione: Milan, Italy, 2008.
21. *UNI/TS 11300-1:2014*; Energy Performance of Buildings Part 1: Evaluation of Energy Need for Space Heating and Cooling. UNI—Ente Italiano di Normazione: Milan, Italy, 2014.
22. *UNI 10349:1994*; Heating and Cooling of Buildings, Climate Data. UNI—Ente Italiano di Normazione: Milan, Italy, 1994.
23. *UNI/TS 11300-2:2014*; Energy Performance of Buildings Part 2: Evaluation of Primary Energy Need and of System Efficiencies for Space Heating, Domestic Hot Water Production, Ventilation and Lighting for Non-Residential Buildings. UNI—Ente Italiano di Normazione: Milan, Italy, 2014.
24. ISTAT, National Institute of Statistics. Houses with Heating System by Type of Fuel or Energy Supplying the Heating System—ISTAT Census 2011 (Italian Language) ISTAT, Abitazioni con Impianto di Riscaldamento per tipo di Combustibile o Energia che Alimenta l'impianto di Riscaldamento. Available online: http://dati-censimentopopolazione.istat.it (accessed on 7 February 2022).
25. Curit, Catasto Unico Regionale degli Impianti Termici. Available online: https://www.curit.it/consulta-i-dati (accessed on 25 February 2022).
26. ISTAT, National Institute of Statistics. Dwellings Occupied by Residents—Dwellings by Availability of Services-ISTAT Census 2011 (Italian Language) ISTAT, Abitazioni Occupate da Persone Residenti—Abitazioni per Disponibilità di Servizi. 2011. Available online: http://dati-censimentopopolazione.istat.it (accessed on 6 February 2022).
27. *UNI EN 14825: 2019*; Condizionatori d'aria, refrigeratori di liquido e pompe di calore, con compressore elettrico, per il riscaldamento e il raffrescamento degli ambienti—Metodi di prova e valutazione a carico parziale e calcolo del rendimento stagionale. UNI—Ente Italiano di Normazione: Milan, Italy, 2019.
28. TERNA National Electricity Grid, Production Data (Italian Language), Rome. 2021. Available online: https://download.terna.it/terna/5%20-%20PRODUZIONE_8da7ab6394701ad.pdf (accessed on 4 September 2022).

29. TERNA National Electricity Grid, Generation Data (Italian Language), Rome. 2021. Available online: https://download.terna.it/terna/3%20-%20IMPIANTI%20DI%20GENERAZIONE_8da7ab6ef9ad0ea.pdf (accessed on 4 September 2022).
30. Caputo, A. *Indicators of Efficiency and Decarbonisation of the National Energy System and the Electricity Sector, (Italian Language) Istituto Superiore per la Protezione e la Ricerca Ambientale ISPRA, Indicatori di Efficienza e Decarbonizzazione del Sistema Energetico Nazionale e del Settore Elettrico*; Higher Institute for Environmental Protection and Research ISPRA: Rome, Italy, 2022; pp. 1–108.