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Heat pumps in existing heating and hot water systems: an evaluation of primary energy savings and reduction of CO_2 produced

Alberta Carella[a,*], Luca Del Ferraro[b], Annunziata D'Orazio[a]

[a]Dipartimento di Ingegneria Astronautica, Elettrica ed Energetica, Sapienza Università di Roma, Via Eudossiana 18, Rome, 00184, Italy
[b]Daikin Applied Europe S.p.A., Via Piani di S.Maria 72, Ariccia, 00072, Italy

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Abstract

In a previous work we recorded a significant contribution to urban air pollution attributable to heating systems powered by fuel. Thus, we propose the replacement of existing boilers for heating and domestic hot water (DHW) production systems with high temperature air-to-water heat pumps as an intervention to improve urban air quality and energy use. We analyze replacement scenarios within the entire residential building stock of two Italian cities, Milan and Salerno, belonging to different climate zones and with their own thermophysical characteristics.
For each of them, the consequences of the replacement intervention in terms of primary energy savings and lower CO_2 production are evaluated.
The results show a reduction of primary energy consumption by 34% in Milan and 43% in Salerno, and of CO_2 production by 30% in Milan and 39% in Salerno.

Keywords: Urban air quality; Heat pumps; Primary energy; CO_2 emissions.

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1. Introduction

In a previous work [1], a significant contribution to urban air pollution, related 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 thermal systems, we propose to replace these systems with high temperature air-to-water heat pump systems of a suitable size that can supply the existing radiator systems.

The proposed measure is studied for two different Italian cities, Milan and Salerno, characterised by different outdoor air temperatures and with different thermophysical characteristics of the building stock.

In particular, replacement scenarios are analysed in the case of an outdoor temperature equal to the design temperature and for heat pump power generation equal to the current mix.

The evaluation of the intervention, while considering some approximations and working hypotheses, confirms to varying degrees for both cities a substantial reduction in both primary energy and CO_2 production needs, thanks to the highest generation efficiencies obtainable in the large thermoelectric power plants and the abatement systems present there.

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.

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[*] Corresponding author. Tel.: +39 3347684769
E-mail address: alberta.carella@uniroma1.it

2. Materials and methods

2.1. Climatic characterization

Two Italian cities were considered, belonging to two different climate zones according to national legislation. Milan, in Lombardy, located in the north-west of the Italian peninsula and characterised by an external design temperature [2] of -5 °C, and Salerno, a city in central-southern Italy facing the Tyrrhenian Sea and having an external design temperature of 2 °C.

2.2. Characterization of building stocks

According to ISTAT [3], Milan is outlined as a city made up of approximately 70% of buildings constructed between 1919 and 1970. Only 5% of the buildings were built after 1990. Most (66%) are four and more storeys above ground, while only 7% are one storey. This is confirmed by the fact that more than half of them (55%) have more than eight interiors.

Although less evident also 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 2 or 3 storeys above ground with 37% consisting of 1 or 2 interiors.

In order to characterise the building stock of the city of Milan from an energy point of view, the CENED +1.2 database [4] of the Lombardy Region was taken into consideration, which contains information useful for drawing up energy certificates.

From the database it was possible to obtain the average values of the thermal transmittances of the dwellings in the Municipality of Milan for each period of construction. Figure 1 shows the trend of the thermal transmittances of the windows and vertical opaque envelope, the basement and the roof.

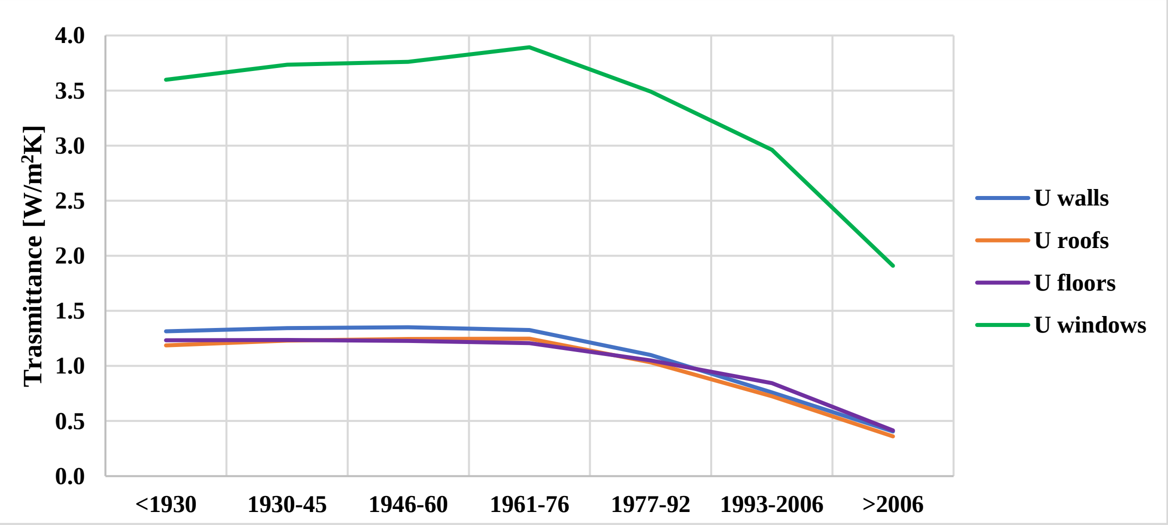

Fig. 1. Trend of the average thermal transmittances of the walls, floors, roofs and windows of the average flat in Milan by age of construction

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 for private buildings carried out in the Municipal Energy Plan of the Municipality of Salerno [5] shows the trend of average thermal transmittances of opaque components and windows shown in Figure 2.

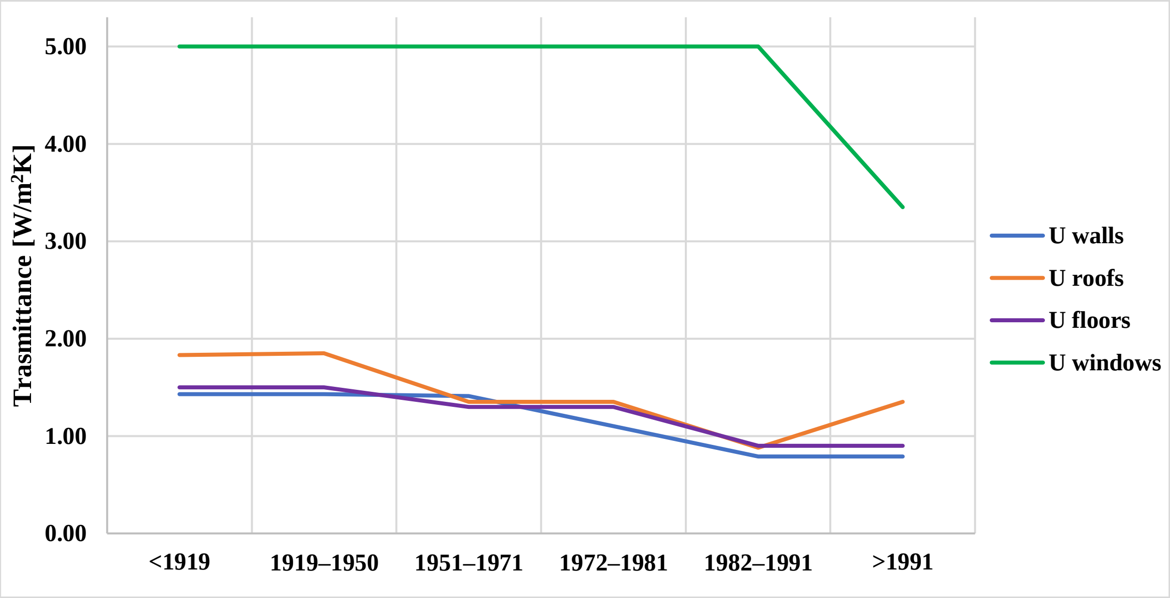

Fig. 2. Trend of the average thermal transmittances of the walls, floors, roofs and windows of the average flat in Salerno by age of construction (data from [5])

It can be seen that up to the 1970s, the average thermal transmittance of all components remained fairly constant, but then decreased, again due to the passing 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 [5].

2.3. Thermal energy needs associated with building stocks

In order to evaluate the average thermal requirements for heating associated with the flats in the Municipality of Milan, from the entire CENED +1.2 database the certificates of dwellings with destination of use E.1(1) [D.P.R. 412/93] were taken into consideration, 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 simplicity's sake, it was decided to consider only the inter-floor building units, identifiable in the database as those without a numerical transmittance value of the basement and roof, indicating the absence of these dispersing elements.

From the values of the transmittances and the 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 11300-1-2:2014 [6], by summing the monthly heating needs, relative to the period of the winter season, for twenty-four hours 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 [7].

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

The thermal energy requirements for domestic hot water Q_w were obtained according to UNI TS 11300-1-2:2014 [6], considering a 24-hour daily use period extended to the entire year (1).

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

Where:

ρ_w is the density of the water, which is approximately 1000 [kg/m^3];
c_w is the specific heat of water equal to 1,162 [Wh/kgK];
V_w is the volume of water required during the calculation period [m^3];
θ_{er} is the hot water supply temperature [°C];
θ_0 is the cold water inlet temperature [°C];
G the number of days in the calculation period considered [d].

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 outside air temperatures taken from UNI 10349. The required volumes of water V_w are obtained according to table 30, reported in [6] 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 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 the Table 1.

In order to represent and compare the data of the two different 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 needs related to the time periods of the ISTAT database were obtained by taking into account the degrees of temporal overlapping between the two periodization systems and using them as weights for the computation of the weighted average.

Table 1. Thermal energy requirements for winter heating and DHW production per year of construction CY for the city of Milan; Portion of the buildings stock %BS.

CY	%BS	Thermal energy needs kWh$_t$ / year for the city of Milan		
		Heating	DHW	Heating and DHW
<1918	8,8%	7744	1140	8883
1919-45	16,3%	7733	1130	8863
1946-60	25,0%	7933	1151	9084
1961-70	28,1%	8709	1209	9919
1971-80	11,2%	8564	1233	9797
1981-90	4,2%	8346	1269	9615
>1991	6,3%	5791	1159	6950

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

In order to evaluate the average heating requirements associated with the flats in the Municipality of Salerno, the dispersing surfaces were first obtained.

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

These are shown in succession, according to the number of floors above ground 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.

From Annex D, 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. The latter ones were subtracted from the lateral surfaces to obtain the side opaque surfaces.

From each building typology reported, characterised by a certain number of floors and interiors, the individual flats of which each building typology is composed were approximated, focusing attention, as in Milan, on the inter-floor building units. Their characteristic dimensions correspond to a weighted average of the various inter-floor flat sizes available in the building stock.

Once the heating requirements for each of them had been calculated, a weighted average was made on the basis of 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.

Similarly for Milan, thermal energy requirements for domestic hot water were then calculated according to UNI TS 11300-1-2:2014 [6] and reported in Table 2.

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

Table 2. Thermal energy requirements for winter heating and DHW production per year of construction CY for the city of Salerno; Portion of the buildings stock %BS

CY	%BS	Thermal energy needs kWh_t / year for the city of Salerno		
		Heating	DHW	Heating and DHW
<1918	8,1%	4778	1239	6017
1919-45	9,8%	4782	1239	6022
1946-60	24,1%	4205	1375	5580
1961-70	31,4%	3916	1443	5359
1971-80	12,9%	3304	1443	4746
1981-90	9,4%	2774	1443	4217
>1991	4,3%	2525	1443	3968

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

2.4. Heating systems fleet

According to the ISTAT census of 2011 on the type of fuel or energy source that fuels the heating system of homes in the Municipality of Milan [8], methane gas is the most widely used source (81.92%), followed by diesel (12.12%) and electricity (3.10%).

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

According to the "Catasto Unico Regionale degli Impianti Termici", the regional register of the thermal plants, (CURIT) [9], the number of heating systems in the Municipality of Milan is composed of approximately 153.000 autonomous systems with a capacity of less than 35 kW and 27.000 centralised systems with a capacity of more than 35 kW and typically serving more than one property unit.

According to the 2011 ISTAT census on the type of fuel or energy source that fuels the heating system of homes in the Province of Salerno [8], the most used source (53.88%) is methane, followed by solid fuel such as wood or coal (24.92%) and LPG (10.29%).

The percentage of dwellings using electricity (6.64%), diesel (2.14%), fuel oil (0.07%) or other types of fuel or energy is lower.

The census on the number of dwellings equipped with a heating system [10] shows that there are approximately 38.000 autonomous and 3.000 centralised heating systems in the municipality of Salerno.

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

In order to calculate the average global efficiency, the tables contained in UNI TS 11300-2 of 2014 [6] are used to estimate the distribution, regulation 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 is 0.8.

From the 2014 UNI TS 11300-2 prospectuses [6], the average global efficiency of the generator for the production of domestic hot water is also estimated at 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.

Since we do not have data on the efficiency of the thermal plants in the Municipality of Salerno, we assume the same efficiency value for winter air conditioning equal to 0.8 and for the production of domestic hot water equal to 0.7. As in the case of the Municipality of Milan, Salerno's thermal plants are mainly made up of autonomous plants (over 90%) that use methane gas as their main fuel.

2.5. Heat pumps identified in the proposal

Considering the scenario of replacing the entire thermal systems of the two cities with high-temperature air-water heat pumps, the nominal capacities are evaluated.

Considering a configuration based on the logic of prioritizing DHW production overheating, and since the two thermal needs are never satisfied simultaneously, the sizing is carried out on the basis of the thermal load for winter heating.

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

$$NP = (H_o \times S_o + H_w \times S_w) \times (t_i - t_p) \qquad (2)$$

Where H_o and S_o are respectively the transmittance and the dispersing surface of opaque walls, H_w and S_w the transmittance and the dispersing surface of windows, t_i the desired internal temperature equal to 20°C, t_p the design external temperature, equal to -5°C for Milan and +2 for Salerno. Tables 3 and 4 show the nominal powers NP of the heat pumps (HPs) at the design external temperature by year of construction.

In particular, air-water heat pumps are considered to be those that can work with radiators, the most common terminals in the existing building stock, and are therefore capable of producing flow water at a temperature of 70°C or higher.

The compressor of the HPs selected is a scroll type with inverter capacity control and economizers to increase the efficiency of the system. The refrigerant they use is R32, 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 machine was chosen in line with the commercial state of the art from a manufacturer's catalogue considering an outside temperature not higher than the design outside temperature and closer to this.

In order to ensure operation at high temperature, an oversizing choice is made with respect to the required heat output. The analysis carried out was related to full load performance at design conditions. The real working conditions imply different values of outdoor temperature during the heating season, with favorable consequences for HP performance, as a result of a direct thermodynamic effect and reduced heat losses from machines (with inverter) operating under partial load conditions. The present study concerned, thus, the worst-case scenario.

The plate power (PP) values of the selected heat pumps, obtained from the manufacturers' catalogues as the heating capacity at the design outdoor temperature and outlet water temperature of 70°C, are shown in Tables 3 and 4 for each requirement.

The COP of the selected HP is provided by the manufacturer as the ratio between the heating capacity and the electrical power input; the heating capacity 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 provided by the manufacturer for a value of outside air temperature and a value of water supply temperature.

To derive 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), proceed according to UNI EN 14825 [11].

Specifically, with the same outlet water flow temperature, if the design outdoor air temperature is within the range of values provided by the manufacturer, the COP is calculated by linear interpolation of the second principle efficiency values η_{II} , calculated on the basis of the known data. If the outdoor air temperature is outside the range of values provided by the manufacturer, 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 temperature difference of 5 K). The second-principle efficiency η_{II} is defined for electric heat pumps as the ratio of equation (3) between the actual efficiency of the heat pump declared by the manufacturer (COP) and the theoretically achievable maximum efficiency (theoretical maximum COP_{max}).

$$\eta_{II} = \frac{COP}{COP_{max}} = COP \, \frac{t_h - t_c}{t_h + 273{,}15} \qquad (3)$$

where t_h is the outlet water temperature (at the condenser) and t_c is the cold source temperature (at the evaporator). The COP value at conditions x is therefore obtained by the efficiency ηII interpolated to conditions x as in equation (4).

$$COP_x = \eta_{II,x} \frac{t_h + 273{,}15}{t_h - t_{c,x}} \tag{4}$$

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

Table 3 for Milan and 4 for Salerno show, for each selected HP and by year of construction of the buildings, the calculated COP values referring to the desired delivery water temperature (70°C), as it is reiterated that the current radiators are to be left as terminals, and to the external temperature of -5°C (Milan) and +2°C (Salerno).

Table 3. Nominal (NP) and plate powers (PP) and COP of the HP required for the design value of the external temperature of Milan (-5 ◦C) , per year of construction CY (outlet water temperature 70 ◦C); portion of the buildings stock %BS.

CY	%BS	NP kW	PP kW	COP (-5°C,70°C)
<1918	8,8%	3,35	8,73	1,78
1919-45	16,3%	3,34	8,73	1,78
1946-60	25,0%	3,43	8,73	1,78
1961-70	28,1%	3,76	8,73	1,78
1971-80	11,2%	3,70	8,73	1,78
1981-90	4,2%	3,61	8,73	1,78
>1991	6,3%	2,50	8,73	1,78

Table 4. Nominal (NP) and plate powers (PP) and COP of the HP required for the design value of the external temperature of Salerno (2 ◦C), per year of construction CY (outlet water temperature 70 ◦C); portion of the buildings stock %BS.

CY	%BS	NP kW	PP kW	COP (2°C,70°C)
<1918	8,1%	3,40	9,13	2,00
1919-45	9,8%	3,41	9,13	2,00
1946-60	24,1%	3,03	9,13	2,00
1961-70	31,4%	2,85	9,13	2,00
1971-80	12,9%	2,68	9,13	2,00
1981-90	9,4%	2,53	9,13	2,00
>1991	4,3%	2,46	9,13	2,00

2.6. Impact of replacement interventions

In order to assess the overall impact, in terms of primary energy consumed, tonnes of CO_2 produced and pollutants emitted, that replacing the boilers currently most used in homes in Milan and Salerno with HPs would entail, the 153.000 autonomous systems with a power output of less than 35 kW and the approximately 27.000 centralised systems are considered for the Municipality of Milan.

The latter, considering a condominium composed of an average of 12 flats, are considered equivalent to 324.000 autonomous systems. Therefore, 480.000 HPs are considered installed, with the characteristics described above, distributed in number as summarised in Table 7.

For the Municipality of Salerno, given the 38.000 autonomous systems and 3.000 centralised systems, considered as 36.000 autonomous systems, we have a total of 74.000 HPs installed, distributed as in Table 8.

In the following evaluations, the methane gas/primary energy conversion factor and the renewable electricity conversion ratio are considered unitary; the efficiency of the existing boilers is 0.8 for heating and 0.7 for DHW production, the distribution losses in the electricity grid are 10% [12][13]. Concerning electricity generation, a 35% renewable fraction and a fuel fraction of 65% are considered, the latter mainly composed of natural gas (Terna source [12][13]). The fossil-to-electric conversion efficiency for 2021 is assumed equal to 48%. The COP considered is that relative to the external air temperature conditions of the project, -5 °C for Milan and +2 °C for Salerno.

The useful coefficient for the calculation of CO_2 emissions related to the consumption of methane used to fuel the boilers is found in the table of the UNFCCC national inventory of CO_2 emission coefficients [14] for which the result is 202.36 g CO_2 /kWh thermal. The coefficient useful for the calculation of CO_2 emissions related to the production of electricity used to fuel the boilers is found in the ISPRA report on emissions in the electricity sector [14] for which the result is 449.1 g CO_2 /kWh electricity for the current mix of fuels relative to the non-renewable fraction.

Tables 5 and 6 show, by building construction period, the thermal needs for heating and DHW production and the relative primary energy needs for the current boilers and for the selected HP for the current energy mix for the cities of Milan and Salerno.

Table 5. Total heat requirement and primary energy requirement for boilers (**η_h=0,8; η_w=0,7**) and for selected HPs, per year of construction CY of buildings of the city of Milan (generation fraction from renewable energies 35%, grid losses 10%, COP at design temperature of -5°C)

CY	Thermal Energy needs for heating and DHW production 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	11307	7434
1919-45	8863	11281	7417
1946-60	9084	11560	7602
1961-70	9919	12614	8300
1971-80	9797	12467	8199
1981-90	9615	12245	8046
>1991	6950	8894	5816

Table 6. Total heat requirement and primary energy requirement for boilers (**η_h=0,8; η_w=0,7**) and for selected HPs per year of construction CY of buildings of the city of Salerno (generation fraction from renewable energies 35%, grid losses 10%, COP at design temperature of 2°C)

CY	Thermal Energy needs for heating and DHW production 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
1919-45	6022	7748	4485
1946-60	5580	7220	4156
1961-70	5359	6957	3991
1971-80	4746	6190	3535
1981-90	4217	5529	3141
>1991	3968	5218	2955

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

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

Primary energy requirements when using HPs are always lower than those of boilers, both for Milan and Salerno and for all years of construction.

The overall primary energy consumption from fossil fuels, in the case of the current boilers and the proposed replacement HPs, are shown in Tables 7 and 8. Results are presented in terms of percentage ratio, between heat pumps and boilers, of global primary energy from fossil fuel and CO_2 production.

Table 7. Distribution by year of construction CY of the buildings of Milan of the 480.000 selected HPs, percentage ratio of global primary energy requirement from fossil fuel and CO_2 emissions of heat pumps to that of boilers (generation fraction from renewable energies 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	Global primary energy from fossil fuel HPs / global primary energy from fossil fuel boilers	CO_2 HPs / CO_2 boilers
<1918	8,8%	3,35	42328	66%	70%
1919-45	16,3%	3,34	78379	66%	70%
1946-60	25,0%	3,43	119867	66%	70%
1961-70	28,1%	3,76	134816	66%	70%
1971-80	11,2%	3,70	53821	66%	70%
1981-90	4,2%	3,61	20379	66%	70%
>1991	6,3%	2,50	30410	65%	70%
TOTAL			480000	66%	70%

Table 8. Distribution by year of construction CY of the buildings of Salerno of the 74.000 selected HPs, percentage ratio of global primary energy requirement from fossil fuel and CO_2 emissions of heat pumps to that of boilers; (generation fraction from renewable energies 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	Global primary energy from fossil fuel HPs / global primary energy from fossil fuel boilers	CO_2 HPs / CO_2 boilers
<1918	8,1%	3,40	6022	58%	62%
1919-45	9,8%	3,41	7255	58%	62%
1946-60	24,1%	3,03	17860	58%	61%
1961-70	31,4%	2,85	23226	57%	61%
1971-80	12,9%	2,68	9546	57%	61%
1981-90	9,4%	2,53	6934	57%	61%
>1991	4,3%	2,46	3158	57%	60%
TOTAL			74000	57%	61%

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 replacement of the entire boiler fleet, considering the external design conditions, implies a reduction in primary energy consumption of 34% for Milan and 43% for Salerno and a reduction in emissions of 30% for Milan and 39% for Salerno.

The greater reductions obtained in the case of the city of Salerno are probably associated with the more favourable external design temperature conditions for the use of HP, which assume higher COP values in those conditions.

3. Conclusions

Starting from the results obtained in a previous work [1] on the analysis of pollutant concentrations and from the identification of the weight of heating systems as an emissive source, the replacement of boilers in current heating and domestic hot water production systems with high temperature air/water heat pumps was proposed as an intervention to improve urban air quality.

The study was mainly dedicated to assessing whether the proposed replacement of the approximately 480.000 autonomous methane gas boilers for the city of Milan and 74.000 for the city of Salerno, all with the same efficiency of 80% for heating and 70% for the production of DHW, of which, to a first approximation, the entire thermal systems of the municipalities of Milan and Salerno can be considered to be made up, implying a significant reduction in polluting emissions in the urban area, would on the other hand entail additional energy (and therefore environmental) costs. Replacing the current boilers would eliminate individual local emission sources, concentrating emissions at a thermal power plant, located in suburban areas, characterised by the highest generation efficiencies, equipped with pollutant abatement systems (sulphur oxides, nitrogen oxides, particulate matter, CO_2), with a discharge into the atmosphere at significant heights compared to those in urban areas.

The study demonstrated the validity of the proposal in terms of reducing primary energy needs and CO_2 emissions for the two different cities considered, in particular for an external temperature at design conditions and for electricity generation mixes that in the future will be modified in favour of increasing shares of renewable sources. The proposal analysed is also in line with the electrification targets set in recent years, essential to achieve the energy transition and aimed at a sustainable development model.

The results obtained are a useful indication for overall incentive measures, given the low invasiveness of the interventions for individual citizens, and cannot be considered a feasibility study of the 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 the individual intervention, which will also have to take into account the real overall dimensions (with on average little space available for old buildings, for which the use of centralised heat pump systems could be considered).

It is worth noted that full load operating condition at design temperature are not the most frequent. The real working conditions characterize by different external temperature and partial load performance imply greater advantage in terms of COP.

A more in-depth analysis will be carried out in a future work, to evaluate the behavior of the systems in real operating conditions. Future works will also investigate more favorable/unfavorable climatic conditions related to different Italian and European cities.

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