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The heat pumps for better urban air quality

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ABSTRACT

Strict restrictions to halt the spread of COVID-19 provided an opportunity to quantify the contribution of different pollution agents. We analyze the concentrations of pollutants recorded in Rome during the lockdown periods for the containment of the spread of Covid 19, compared with those of other periods and years. We recorded a significant contribution attributable to heating systems powered by fuel. Thus, we propose the replacement of existing boilers for heating and drinking hot water (DHW) production systems, with air / water heat pumps, as an intervention to improve urban air quality. We analyze the replacement scenarios, within the entire residential building stock in the Municipality of Rome, in terms of emissions reduction, primary energy savings and reduced CO2 production. Results show significant reductions in concentrations. Reduction in primary energy consumption varies between 12% and 56% for various scenarios, different for outdoor temperatures and mix of electricity generation. The intervention on the urban scale can reduce air pollution on a long-term basis, implying significant reductions of polluting emissions in urban areas, and entailed reduced energy (and therefore environmental) costs, with a significant step towards sustainable cities.

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1. Introduction

The confinement measures to contain the spread of Covid 19 in 2020 resulted in sudden and significant changes in anthropogenic activities in the urban area. This gives rise to the possibility of better understanding and evaluating the weight of these anthropogenic activities, in particular with regard to air quality, and the consequences of any changes [1, 3, 4, 14, 23, 29].

We analyzed the concentrations of pollutants, recorded in Rome thanks to the Air Quality Network of Regional Agency for Environmental Protection (ARPA Lazio), and compared with those of different periods of the year and/or previous years. We consider the contribution to the concentration of the various pollutants that can be attributed to vehicular traffic and that related to heating systems powered by fuel. In fact, we focused the attention on the periods of confinement and on those of ignition of heating systems. Since a significant contribution related to heating systems is recorded (ranging from 10% for NOx, 24% for NO, 40% for Benzene, to 44% for NO2, 47% for CO, 71% for both PM2.5 and PM10 and 83% for SO2 as detailed in the following), we propose the replacement at the urban scale of existing boilers for heating and hot water production systems, with air / water heat pumps, as an intervention to improve urban air quality.

The centralized use of air / water heat pump has been simulated by [9] for a condominium in the North-West of Italy. The study aims to investigate what technology used in combination in different retrofit scenarios can help achieve the European Union climate target and benefit the energy system, the electric grid, and the citizen who will invest in the retrofit. The air-water heat pump helps in reducing the total primary energy demand by 26% and the CO2 emission by 30%. Nevertheless, the load volatility introduced by the air-water HPs it resulted in being more harmful to the electric grid than the intermittence of the PV system. The authors found out that a storage system is a key to smooth down such undesired effects.

The study in [13] presents a thermodynamic sustainability assessment of different energy sources for residential building heating. Various options of energy sources were studied, namely: coal, natural gas, electricity, district heating, air-water heat pump, biomass and district heating with a cogeneration, to compare the energy and exergy flows and the impact of different energy sources for heating on the environment, by considering a new residential building with ‘C’ energy efficiency rating, in accordance with the Serbian rule book (Ministry CTI 2012). The authors conclude that utilization of heat pumps, cogeneration or waste heat from thermal processes for heating is much more beneficial than the direct usage of fossil fuels and electricity from fossil

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fuels.

In [31], the authors presented the impact of using a heat accumulator on the Coefficient of Performance (COP) of the heat pump, the self-consumption of energy from the photovoltaic system, and the cost of purchasing energy in a Single-Family House in Poland.

In the analysis of [15], the emissions associated with heat pump operation result from a combination of power system energy mix, weather conditions and heat pump technology. They consider low temperature HP, for heating and hot water production. Their results revealed that for a scenario where an air-to-water (A/W) heat pump is supposed to cover space and domestic hot water load, its CO2 emissions are shaped by country-specific energy mix (55.2%), heat pump technology (coefficient of performance) (33.9%) and, to a lesser extent, by changing climate (10.9%).

In [5], individual heat pumps and energy efficiency measures are analyzed in four scenarios to investigate their role in cleaner and sufficient heating in rural settings in Hungary. They consider low temperature HP, for heating and hot water production, coupled with the hot water storage tank.

In [27] authors analyzed the case of HP for the existing radiator heating system and the case of HP with new underfloor heating system installed. They refer to an existing single-family house in Bosnia and Herzegovina, and they conclude that in this particular case the installation of a heat pump with radiators is not energy efficient, but that, however, there is no general conclusion which can be used in all practical situations.

Recent literature is focused for the most part on the coupling of low temperature HPs with other systems, to identify the most promising combinations of technologies from an energetic and/or economic point of view. We focus our attention, at the urban scale for a historical city as Rome, on the replacement of existing installed systems with high temperature HPs, to obtain a better urban air quality with a minimally invasive and small impact modification for the citizens. We demonstrate that the advantages stay in the improved local urban air quality and at the same time in the reduced energy consumption and CO2 emissions.

At the best knowledge of the authors, this is the first time that this intervention is proposed and analyzed in these terms at urban scale and in particular for a city as Rome, a large historical city. It is characterized by an old or aging building stock, with few new energy-performing buildings. Much can be done to upgrade the energy efficiency of buildings, but it is difficult to imagine that all existing systems can be replaced with low-temperature heat pump systems in a short period of time. We therefore propose the replacement of boilers with high temperature heat pumps coupled to existing radiator systems.

In the following, we analyze the thermal needs for heating and domestic hot water production, of the residential buildings in the Municipality of Rome, together with the installed thermal systems, and we describe the replacement of these systems with air/water heat pumps of suitable size to supply the existing radiator systems. The proposed measure is studied for different scenarios, as regards both the external air temperature, in addition to the design temperature (the most severe one), and for the generation of the electricity supply to the heat pumps. In particular, in addition to the current fraction of production from renewable sources (in the supply from the national grid), a fraction of fossil fuel in the production of electricity equal to 100% (renewable portion equal to 0%) was considered as a limit evaluation condition. Furthermore, in the fraction relating to fossil fuels, both the mix currently used and the exclusive use of methane gas were considered, since this gas is usually used to supply the boilers currently present.

The evaluation of the intervention, while considering some approximations and working hypotheses, confirms a substantial reduction in both primary energy requirements and CO2 production and pollutant emissions, thanks to the high electricity generation yields obtainable in large thermoelectric plants and the abatement systems present therein. The replacement proposed in the case of the Municipality of Rome represents a case study that can be extended at a national level (with all due evaluations). It constitutes a significant contribution for the improvement of urban air quality, even if we do not consider a localized generation from photovoltaic [22], both for the reduced emissions, both for the most effective abatement interventions, and for the best conditions for expelling the fumes from the chimney. We can conclude that this can be an intervention to reduce air pollution on a long-term basis, implying a significant reduction of polluting emissions in urban areas, and at the same time reduced energy (and therefore environmental) costs, with a significant step towards environmentally sustainable cities.

2. Urban air quality - Effects of lockdown on the main pollutants

The concentration values of pollutants are obtained from the 13 monitoring units present within the Municipality of Rome, belonging to the ARPA Lazio Air Quality Network. The units are placed by type of station according to the criteria of the European environment agency (EEA) [2]. In particular, the monitoring stations can be of type T (Traffic), located in such a way that the level of pollution is mainly influenced by emissions from traffic of medium-high intensity, of type B (Background) and of type I (Industrial), located so that the level of pollution is mainly influenced by single industrial sources or neighboring industrial areas. The stations can be installed in the Urban area (U), i.e. in continuously or at least predominantly built-up area, in the Suburban area (S), i.e. in largely built-up area with built-up areas and non-urbanized areas, and in a Rural area (R), i.e. in non-urban and non-suburban contexts (if the station is located more than 50 km from the emission sources the station is defined as remote rural).

By evaluating the trend over time of the average concentration value of the measurements of the 13 monitoring units (one-dimensional approach), or in some cases that of the concentrations in an area of interest, the following pollutants were evaluated: NO, NO2, NOx, C6H6, CO, SO2, PM10, PM2.5. For each pollutant, the considered trends are the annual ones (both with a daily step and proceeding with weekly and fortnightly averages) for the year 2020, compared with the years from 2016 to 2019. The year 2020 is characterized by the adoption of various measures of containment, one that runs from March 10 to May 3 (phase I), that from May 4 to June 14 (phase II) and that from June 15. The recognized values of interest are those up to 31 December of each year. For each year, the period in which the heating systems are switched on, from November 1st to April 14th, must be taken in account. Fig. 1a shows, as an example, the trends in the NO2 concentration in the considered years, together with the time intervals of the containment phases and those of plant operation. In Fig. 1b, the time interval considered is that relating to confinement (phases I and II).

The reduction of concentration, compared to the previous 4 years, is evident as regards phase I. This reduction is more significant for the 4 UT (Urban - Traffic) stations, for which, compared to the average value of the years 2016–2019, a decrease from 52% to 64% occurs; the reduction in the UB (Urban – Background) stations is lower, with values ranging from 26% to 33%. The study, of which the details are not reported, also took into account meteorological events, such as the transport of PM10 particulate matter from desert and sandy areas occurred on 29 and 30 March 2020, as well as from 13 to 18 May (data from the Copernicus Atmosphere Monitoring Service). For some pollutants, the reduction occurred during the containment period was more significant. In particular, that of nitrogen monoxide (NO), compared to the years from 2016 to 2019 of the same period, is approximately 70%. That of NO2 is approximately 60%. A reduction between 40% - 50% was observed for benzene and NOx. The abatement is less marked for PM10 and PM2.5, with reductions under 10%. In some cases, average concentrations detected during the confinement period result higher than those of some previous four years, due to factors other than vehicular traffic, also related to meteorological events. For sulphur dioxide (SO2) and carbon monoxide (CO) a reduction of about 30% was observed. If we focus on the confinement period, and therefore on the influence of vehicular traffic, we note that the monitoring units for which the greatest
that of the heating systems still powered on is considered, as a first
confinement measures were in place Eq. (3).

to derive the contribution of the plants in previous years, for which no
constant over the various years considered. This makes it possible to
approximation, constant. The obtained contribution of vehicular traffic
contribution linked to vehicular traffic can be considered negligible and
concentration within phase I (10 March-14 April), for which the
abatement was found were urban traffic ones (compared to those of
urban and rural background).

As regards the concentrations of CO, NO, NO2, C6H6, NOx, PM2.5,
PM10, it is noted that during the heating period the concentration values
are higher than when it is switched off, while for O3 an opposite trend is
observed, as high temperatures and solar radiation favour the formation
of ozone.

3. Contributions related to vehicular traffic and heating systems

The trends recorded during the periods of containment highlight the
contribution of vehicular traffic to the concentrations of the various
pollutants [30]. The average concentration C\textsubscript{jan-feb} in the period
January-February 2020 (from 01/01/20 to 29/02/20), is assumed to be
due in first approximation only to vehicular traffic (T\textsubscript{2020}) and heating
systems in operation (R\textsubscript{2020}). It is compared with the average C\textsubscript{jan-feb}
concentration within phase I (10 March-14 April), for which the
contribution linked to vehicular traffic can be considered negligible and
that of the heating systems still powered on is considered, as a first
approximation, constant. The obtained contribution of vehicular traffic
T (from Eq. (1)) is equal to a fraction k of that of heating systems R (see
Eq. (2)) which, with a certain amount of arbitrariness, can be considered
constant over the various years considered. This makes it possible to
derive the contribution of the plants in previous years, for which no
confinement measures were in place Eq. (3).

\begin{equation}
C\textsubscript{phase I} = R\textsubscript{2020} \Rightarrow C\textsubscript{jan-feb 2020} - C\textsubscript{phase I} = T\textsubscript{2020}
\end{equation}

\begin{equation}
\frac{T\textsubscript{2020}}{R\textsubscript{2020}} = k
\end{equation}

\begin{equation}
C\textsubscript{jan-feb} - T = R \Rightarrow C\textsubscript{jan-feb} = R(1 + k)
\end{equation}

from which the concentrations of pollutants from vehicular traffic and
heating systems are obtained for each year. With this approach, a sig-
nificant contribution related to heating systems is recorded for all pol-
lutants, to different degrees. This is particularly high for SO2 (about
83%), and for particulate matter PM10 and PM2.5 (about 71% for each),
while for NO, NOx and benzene the contribution associated with
vehicular traffic stands out (with a contribution from heating systems
respectively equal to 24%, 10% and 40%). As regards NO2 and CO, there
are less marked differences between the two pollution factors (with a
contribution from heating systems respectively equal to 44% and 47%).

If one proceeds by evaluating the variation in the average concen-
tration between the periods of switch-on and the periods of non-
operation of the plants, can obtain the contribution to the concentra-
tion of heating systems only (by considering the contribution of vehic-
lar traffic almost constant in the two periods, a more questionable
hypothesis for the 2020, if the lockdown is taken into account). The
cumulative averages are calculated either on the entire considered pe-
riods (from 01 November to 14 April and from 15 April to 31 October),
or only in the periods within the confinement phase (from 10 March to
14 April and from 15 April to 3 May); in this second case (entire period
of phase I) the contribution of vehicular traffic is considered almost nil.
Here the results are shown for 2020 and for a typical year, the average
of the years from 2016 to 2019. Fig. 2 shows the trends of pollutants in
2020 compared with the average trend between 2016 and 2019.

Considering the values of the contribution of heating systems,
general lower in the case of the calculation in the confinement period,
it should be remembered that in Rome the months of January and
February are the coldest, while those of March and April are mild and
therefore the systems tend to be switched off. For some pollutants (SO2,
PM2.5, PM10), an increase occurred in concentrations in some years,
when the plants were off. This suggests the intervention of other factors,
such as the atmospheric phenomena mentioned above. The approach
that uses the difference between the cumulative averages of the periods,
with and without heating systems, shows high percentages related to
heating systems (over 45%), even for the pollutants more related to
vehicular traffic [12] such as NO, NOx and benzene.

Both approaches are affected by a high degree of arbitrariness, and
therefore they are not suitable for detailed evaluations. However, it can
be concluded from the obtained results that a measure related to the
contribution of heating systems would certainly have a significant

4. Energy characterization of the residential building stock in
the municipality of rome

The feedback provided by the data, about the non-negligible

Fig. 1. annual trend of the weekly average NO2 concentration from 2016 to 2020 (ARPA Lazio data [2]): full year at the top, lockdown phases at the bottom.
contribution of pollution associated with the heating of buildings, leads to focus the attention on the consumption of thermal energy and on the heating systems currently in use in homes of Rome, with the aim of replacing them with HPs. For the energy characterization, the composition of the building stock was assessed by age of construction, starting from what was reported by National Institute of Statistics (ISTAT), which results in a city made up for about 60% of buildings built in the post-war period to the 1980s. Among these, the buildings built before 1976, the year of the enactment of the first law on the energy regulation of plants, account for more than 60% of the total. Only about 6% is made up of newly built homes, from 2002 to 2009.

Since we have not a direct source on the thermal energy needs of the residential building stock in Rome, the study was based on data relating to the primary energy needs of the residential building stock in Rome divided by construction period [24]. In particular, starting from the study in [8] on the morphological characteristics and thermal transmittance of each portion of the building envelope, based on the construction period, we show in table 1, for the different periods, the specific energy requirement index of primary energy for winter heating (Epi) and that of global primary energy for winter heating and DHW production (EPgl). It should be noted that the overall heating energy requirement in 2009, just over 9600 GWh/year, almost 80% is attributable to buildings built before 1976, with an evident dispropportion between the number of these buildings and the related needs; in particular, compared to the current standard of less than 40 kWh/m² year, values close to 130 kWh/m² year are recorded for less efficient buildings. The average value is around 106 kWh/m² year.

To describe our logical path, based on the available data, Fig. 3 shows a diagram related to the tables presented in the following.

5. Heating systems fleet of the municipality of rome

From the census of ISTAT (2011) on the fuel type or energy source powering the heating system of the houses in the Municipality of Rome [21], methane is the most used source (for about 81%), followed by diesel (8.44%) and electricity (5.85%).

The percentages of homes that use solid fuel, such as wood or coal (1.92%), LPG (1.75%), fuel oil (0.16%), or other types of fuel or energy, are much lower.

The park of thermal systems for heating uses, falling within the territory of the Municipality of Rome, is made up of 23,466 centralized

Table 1
Energy characterization of buildings in the Municipality of Rome by construction period CY (SEAP 2012 [24]); portion in the buildings stock%BS, winter air conditioning: WAI; winter air conditioning and DHW production WAI·DHW.

| CY     | %BS | Needs and emissions: WAI·DHW | Energy rating Epi | EPgl |
|--------|-----|-----------------------------|-------------------|------|
|        |     | GWh/year | TOE/year | kE/year | kWh/m² year | GWh/year | TOE/year | kE/year | kWh/m² year |
| < 1919 | 5.90% | 699 | 69,388 | 162 | 130 | G |
| 1919–45 | 9.60% | 1132 | 112,309 | 263 | 130 | G |
| 1946–61 | 21.10% | 2480 | 246,087 | 575 | 129 | G |
| 1962–71 | 22.00% | 2262 | 224,395 | 525 | 117 | G |
| 1972–81 | 18.70% | 1600 | 158,737 | 371 | 94 | F |
| 1982–91 | 11.30% | 878 | 87,140 | 204 | 86 | F |
| 1992–01 | 5.50% | 326 | 32,374 | 76 | 65 | E |
| 2002–06 | 3.80% | 373 | 36,999 | 86 | 75 | E |
| 2007–09 | 2.00% | 219 | 21,711 | 51 | 63 | D |
| TOTAL | 100.00% | 9637 | 956,069 | 2235 | 106 | G |

Fig. 2. Annual trend of the weekly average concentration of pollutants detected in 2020 (solid line) and in the average-year between 2016 and 2019 (dotted line) - (ARPA Lazio data [2]).
systems (total of verifiable systems) and about 600,000 autonomous thermal systems [19]. Centralized heating systems (which use the fuels in table 2) have a power greater than 35 kW and are typically at the service of several real estate units; the so-called autonomous ones are the individual ones with a power lower than 35 kW. In addition to the centralized systems relating to private building property, the calculation includes the systems owned by the Municipality of Rome, approximately 2700 boilers (98% running on natural gas and 2% on ecological diesel).

Methane is used for 79% of the boilers with power above 35 kW and for almost all the autonomous systems.

As regards the combustion efficiency, for the centralized heating systems we consider the percentage distribution relative to 2003 [19], for which the efficiency is for 5.15% of the boilers less than 0.85, for 26.97% between 0.85 and 0.9, for 62.87% between 0.90 and 0.95 and for 5% above 0.95. For individual systems, table 3 shows the data of [11], for boilers maintained and not, by year of installation.

On the basis of the available data, a methane boiler with efficiency 0.9 is considered as a representative heating system of those in use in the Municipality of Rome for the heating and DHW production.

6. Heat pumps identified in the proposal

Taking in account, for the heated useful surface (pursuant to Italian Ministerial Decree 22/11/2012, Annex A paragraph 50 [18]), also that of environments without emission terminals, in the case of a volume of these under 10% of the total net heated volume, we considered for all types of dwelling a heated useful surface corresponding to the average of an apartment in the Municipality of Rome. According to data of [20], this average area is equal to 91 m². This does not take in account the fact that the surfaces and volumes of the older apartments are greater than the more recent ones. Starting from the available data on the primary energy needs of table 1, we obtained the average thermal energy needs for heating (reported in table 4) by multiplying by the overall average efficiency of the system (assumed equal to 0.9).

To meet these requirements, air-water heat pumps are considered, replacing the current boilers. The HPs are combined with existing radiator systems, without system modifications, such as, for example, the possible replacement of the terminals with fan coils or the passage to an underfloor heating system. The configuration considered for smaller powers is that of a three-way valve and storage for DHW, with temperature probe on the storage for the management of the three-way valve and priority to DHW production over the heating; for higher powers, the configuration is that with double heat exchanger, always with priority over DHW production. Since the two thermal requirements

| CY | %BS | Thermal energy needs kWh / year Heating and DHW |
|----|-----|---------------------------------------------|
| < 1919 | 5.9% | 10,647 | 12,121 |
| 1919–45 | 9.6% | 10,647 | 12,121 |
| 1946–61 | 21.1% | 10,565 | 12,039 |
| 1962–71 | 22.0% | 9255 | 10,565 |
| 1972–81 | 18.7% | 7699 | 8845 |
| 1982–91 | 11.3% | 7043 | 8026 |
| 1992–01 | 5.5% | 5323 | 6143 |
| 2002–06 | 3.8% | 4504 | 5160 |
| 2007–09 | 2.0% | 3030 | 3440 |

the primary energy needs of table 1, we obtained the average thermal energy needs for heating (reported in table 4) by multiplying by the overall average efficiency of the system (assumed equal to 0.9).

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(winter heating and DHW production) are never satisfied at the same time, the sizing is carried out based on the requirements for winter heating. The nominal power $P$ of the heat pump is selected according to the usual energy balances (equations 4), related to the annual heat requirement of the building $F_{heating}$ considering all the days when the system is switched on for which the internal temperature is higher than the external one, and to the generator power required in the face of winter dispersion:

$$F_{\text{heating}} = \sum_{j=1}^{N} HA(t_j - t_{e,\text{design}}) n$$

$$P = HA(t_e - t_{e,\text{design}})$$

$$P = \frac{F_{\text{heating}} (t_e - t_{e,\text{design}})}{\sum_{j=1}^{N} (t_j - t_{e,\text{design}}) n}$$

In equations (4) $H$ is the transmittance of the building, $A$ the exchange surface, $t_e$ the desired internal temperature equal to $20 \, ^{\circ}C$, $t_c$ the daily external temperature, $N$ the number of days of the system was switched on for which $(t_i - t_{e,\text{design}}) > 0$, $n$ the number of hours of plant operation, $t_{e,\text{design}}$ the external design temperature, equal to $0 \, ^{\circ}C$ for the city of Rome. This gives Eq. (5) a nominal power $P$ for the heat pump equal to $P = HA(t_e - t_{e,\text{design}})$.

In equation (5) $P$ is the heat requirement and the terms at denominator represent by definition the DD "degree days" of the location in a given climatic zone and the maximum number $n$ of hours of ignition of the heating systems pursuant to the Italian law D.P.R. 412/93 [7]. For the city of Rome (climatic zone D), we have DD equal to 1415 (with an ignition period from 1 November to 15 April) and $n$ equal to 12. The allowed maximum of 12 h per day, enables to take into account the operating interrruptions for heating, due to the DHW production periods and the time required by the defrosting cycles.

Table 5 shows the nominal powers of the heat pumps, computed based on the various thermal requirements previously established.

Among the air/water heat pumps, we considered those that can work with radiators, the most common terminals in the existing building stock, and therefore able to produce supply water at a temperature equal to or higher than $60-65 \, ^{\circ}C$. The size of the machine was chosen in a manufacturer’s catalogue, considering an external temperature not higher than the design external one and closer to this. The inlet water temperature is $55 \, ^{\circ}C$; the supply water temperature is $65 \, ^{\circ}C$. The rated powers of the selected HPs are shown in Table 5 for each requirement.

The COP of the selected HPs is provided by the manufacturer as the ratio between the heating capacity and the absorbed electrical power. The heating capacity is understood as the integrated power between the start of one defrost cycle and the start of the next one. Also, it is provided by the manufacturer for a value of the external air temperature and a value of supply water temperature. To obtain the COP in the conditions of interest, in particular the design conditions for the city of Rome, we proceed according to UNI EN 14,825 [10] (see appendix A).

Table 5 shows, for each selected HP and by year of construction of the buildings, the COP values calculated with reference to the desired supply water temperature ($65 \, ^{\circ}C$), since, as said, we want to leave the current radiators as terminals, and to the external temperature of $0 \, ^{\circ}C$ (design), $7 \, ^{\circ}C$ and $9 \, ^{\circ}C$ (the latter being among the most frequent daily average temperatures in Rome in recent winters [17]).

7. Impact of replacement interventions

To assess the global impact, in terms of consumed primary energy, produced tons of $CO_2$ and emitted pollutants, that the replacement with HP of the boilers currently most used in Roman homes (methane boilers with an average efficiency of about 90%) would imply, we consider the 600,000 autonomous systems with power below 35 kW and the approximately 23,500 centralized systems. The latter, considering a condominium of 12 apartments on average, are thought to be equivalent to 280,000 autonomous systems. The 880,000 installed HPs are therefore taken in account, with the characteristics described above, distributed in number as summarized in Table 7.

In the following, starting from some assumptions, some scenarios relating to the COP of the selected HPs and to the generation of electricity are considered. In particular, the conversion factor of methane gas / primary energy and the transformation ratio of renewable electricity are considered unitary; the efficiency of existing boilers is equal to 0.9, the distribution losses in the electricity network are equal to 8% [25, 26].

Regarding the generation of electricity, a fraction of renewables is considered equal to both 35% (existing in 2019 and available from Terna [25,26]) and 0%. The fossil fuel generation fraction (with an efficiency of the transformation from fossil to electricity for 2021 equal to 48%) relates both to the current mix (taking in account the divestment of 26 coal-fired thermal power plants that have already taken place, to a phase out of all coal-fired power plants expected by 2025), and to the hypothesis of completely methane generation (for which the carbon impact of the current energy supply will be reduced) because of the introduction of hydrogen). The considered COP is that relating to the values of external air temperature for design conditions ($0 \, ^{\circ}C$) and for $7 \, ^{\circ}C$ and $9 \, ^{\circ}C$. The coefficient useful for calculating $CO_2$ emissions, related to the consumption of methane used to power the boilers, is found in the table of the UNFCCC national inventory of the coefficients of $CO_2$ emissions [6], for which it results in 201.43 g $CO_2$ / thermal kWh. The coefficient useful for the calculation of $CO_2$ emissions linked to the production of electricity, used to power the HP, is identified by the ISPRA report on emissions in the electricity sector [6], for which 493.8 g CO2 / kWh of electricity are identified with regard to the current mix of fuels relating to the non-renewable fraction.

Table 6 shows, by period of construction CY of the building, the thermal needs for heating and DHW production of an apartment of 91 m$^2$. The related primary energy requirements are reported for the current boilers and for the selected HPs, in the various operating conditions, for the current fraction of generation from fossil fuels. The global

Table 5

| CY | %BS | Thermal energy needs for heating requirement kWh / year | NP kW | PP kW | COP 0°C/65°C | COP 7°C/65°C | COP 9°C/65°C |
|----|-----|------------------------------------------------------|-------|------|--------------|--------------|--------------|
| < 1919 | 5.9% | 10,647 | 12.54 | 16 | 2.26 | 2.87 | 2.94 |
| 1919-45 | 9.6% | 10,647 | 12.54 | 16 | 2.26 | 2.87 | 2.94 |
| 1946-61 | 21.1% | 10,565 | 12.44 | 16 | 2.26 | 2.87 | 2.94 |
| 1962-71 | 22.0% | 9,255 | 10.90 | 14 | 2.32 | 3.00 | 3.08 |
| 1972-81 | 18.7% | 7,699 | 9.07 | 11 | 2.39 | 3.08 | 3.14 |
| 1982-91 | 11.3% | 7,043 | 8.30 | 11 | 2.39 | 3.08 | 3.14 |
| 1992-01 | 3.5% | 5,323 | 6.27 | 11 | 2.39 | 3.08 | 3.14 |
| 2002-06 | 3.8% | 4,504 | 5.31 | 8 | 1.85 | 2.30 | 2.38 |
| 2007-09 | 2.0% | 3,030 | 3.57 | 4 | 1.79 | 2.26 | 2.34 |
consumption of primary energy from fossil fuels, in the case of the current boilers and the proposed HPs as replacements, is shown in table 7 for the previous generation scenario (35% from renewable sources).

As expected, the thermal requirements, and therefore the primary energy requirements, of older buildings are much higher. In the case of use of HP, the primary energy requirement, depending on the COP, could be higher for lower thermal requirements, related to the size of the selected machine and therefore to the different performances (for example in the case of apartments built between 2002 and 2006).

The primary energy requirement in case of heat pumps is always lower than that of boilers, more markedly for buildings built between 1972 and 2006, for all the considered external conditions. The advantage is less evident in more recent buildings, for which the machine size is lower, with a consequent lower value of the COP; however, the number of such buildings is small in percentage terms and therefore their weight on the overall savings is negligible. Similar behaviour is observed for CO₂ emissions. The replacement of the entire boilers fleet, considering the design external conditions, implies a reduction in primary energy consumption by 43% (for the most frequent external temperatures in Rome, a saving of 56% is achieved) and a reduction in CO₂ emissions by 33% (and 49% for more frequent temperatures).

Proceeding to a similar analysis in the case of electricity generation both from fossil fuels alone (0% renewable fraction), for the current mix of fuels, and for the current fraction of renewable energy (35%) and exclusive use of methane gas, we obtain the results summarized in table 8.

In the most unfavourable case (production of electricity exclusively from fossil fuels with the current mix of fuels), the reduction in needs, compared to the use of boilers, remains, even in the case of design conditions for the external temperatures, and it is equal to 12%. For recent buildings, the advantage is not recorded (once again due to the reduced COP of the smaller sizes) but, as already mentioned, their weight is small. For an external temperature of 9 °C, the reduction in fossil primary energy requirements rises to 33%. The result about CO₂ emissions is not unique across the entire heating systems fleet: in the most severe case (design value of external temperature) an increase occurs, while for the less severe (and more frequent) case, there is a reduction of 21%. With a fraction of renewable energies of 35% and a production from fossil fuels related to methane alone, the emission reductions vary from 72% to 79%.

8. Conclusions

An analysis of concentrations of pollutants recorded in Rome during the lockdown periods for the containment of the spread of Covid 19 has

| CY | Thermal Energy needs for heating and DHW production kWh/yr | primary energy requirement for single boiler kWh/yr | primary energy requirement for HP (COP = 6/7°C) from fossil fuels kWh/yr | primary energy requirement for HP (COP = 5/5°C) from fossil fuels kWh/yr | primary energy requirement for HP (COP = 4°C) from fossil fuels kWh/yr |
|----|-------------------------------------------------------|-----------------------------------------------|-----------------------------------------------------------------|-----------------------------------------------------------------|-----------------------------------------------------------------|
| < 1919 | 12,121 | 13,468 | 7844 | 6177 | 6030 |
| 1919-45 | 12,121 | 13,468 | 7844 | 6177 | 6030 |
| 1946-61 | 12,039 | 13,377 | 7791 | 6135 | 5980 |
| 1962-71 | 10,565 | 11,739 | 6660 | 5150 | 5017 |
| 1972-81 | 8845 | 9828 | 5413 | 4200 | 4120 |
| 1982-91 | 8026 | 8918 | 4991 | 3811 | 3738 |
| 1992-2001 | 6143 | 6825 | 3759 | 2917 | 2861 |
| 2002-2006 | 5160 | 5733 | 4079 | 3281 | 3171 |
| 2007-2009 | 3440 | 3822 | 2810 | 2226 | 2150 |

Table 6

total heat requirement and primary energy requirement for boilers (efficiency 0.90) and for selected HPs for various COPs, per year of construction CY of the buildings (generation fraction from renewable energies 35%, grid losses 8%).

Table 7

distribution by year of construction CY of the buildings of the 880,000 selected HPs, global primary energy requirement from fossil fuel and CO₂ emissions for various COPs (boiler efficiency 0.9, generation fraction from renewable energies 35%, grid losses 8%); portion of the buildings stock%BS, plate power PP.

| CY | %BS | PP kW | Number of HPs | global primary energy from fossil fuel HPs | global primary energy from fossil fuel HPs and global primary energy from fossil fuel boilers CO₂ HPs / CO₂ boilers (COP = 6°C) | COP = 5°C | COP = 4°C |
|----|-----|------|--------------|------------------------------------------|-----------------------------------------------------------------|---------|---------|
| < 1919 | 5.90% | 16 | 51,920 | 58% | 46% | 45% |
| 1919-45 | 9.60% | 16 | 84,480 | 58% | 46% | 45% |
| 1946-61 | 21.10% | 16 | 185,680 | 58% | 46% | 45% |
| 1962-71 | 22.00% | 14 | 193,600 | 57% | 44% | 43% |
| 1972-81 | 18.70% | 11 | 164,560 | 55% | 43% | 42% |
| 1982-91 | 11.30% | 11 | 99,440 | 55% | 43% | 42% |
| 1992-01 | 5.50% | 11 | 48,400 | 55% | 43% | 42% |
| 2002-06 | 3.80% | 8 | 33,440 | 71% | 57% | 55% |
| 2007-09 | 2.00% | 4 | 18,480 | 74% | 58% | 56% |
| TOTAL | 880,000 | | | 57% | 45% | 44% |

Table 8

global primary energy requirement and CO₂ emissions per year of construction CY of the buildings and for various COP of the selected HPs (boiler efficiency 0.9, grid losses 8%); global primary energy GPE.
been performed. Compared to previous years, a significant reduction occurred for the concentrations of pollutants that in the literature are more related to vehicular traffic, such as NO, NOx, NO2 and benzene (ranging from 40% for benzene up to 70% for NO). Greater reductions were recorded in the stations located in urban areas with a high level of vehicular traffic, compared to those located in urban areas with a background level or those in rural areas. The comparison with those of other periods and previous years, allowed the identification of the main pollutant abatement systems (sulphur oxides, nitrogen oxides, particulate matter, CO2), with a discharge into the atmosphere at significant heights compared to those in urban areas. Because of this significant contribution, we proposed as an intervention to improve urban air quality, the replacement of existing boilers for heating and hot water production systems, with air / water heat pumps. At the best knowledge of the authors, this is the first time that this intervention is proposed and analyzed in these terms for a city as Rome. The replacement of the current boilers, at the entire urban scale, would eliminate the individual localized emission sources, concentrating the emissions at a thermoelectric plant, located in peripheral areas, characterized by the highest generation efficiency, equipped with pollutant abatement systems (sulphur oxides, nitrogen oxides, particulate matter, CO2), with a discharge into the atmosphere at significant heights compared to those in urban areas.

The replacement of the about 880,000 existing methane gas boilers, constituting as a first approximation the entire heating systems fleet in the Municipality of Rome, without modifications of the existing radiator systems (the most common terminals in the existing building stock of Rome), represents a minimally invasive intervention and with a small impact for the citizens.

The replacement scenarios were analyzed in terms of primary energy savings and reduced CO2 production, to verify that an intervention dedicated to improving air quality did not imply worsening energy or environmental costs.

The study demonstrated the validity of the proposal, in terms of reduction of primary energy requirements and CO2 emissions, for the various considered scenarios. In particular, this is true for one of the lowest outdoor temperatures in the last decade (design value), and for the current mix of electricity generation, which in the future will be modified in favour of increasing fractions of renewable sources. The case even more favourable of local generation from photovoltaic panels has not been considered here.

The obtained results are based on the thermal needs of the houses, indirectly determined by the primary energy needs per unit surface area, coming from literature data, and considering a useful heated surface of 91 m² for each period of construction, and on the assumptions made on the average efficiency of the boilers. They constitute a useful indication for overall measures of incentive, and they cannot be used for the evaluation of the single intervention. The feasibility study of the single intervention must also take in account the real dimensions, because of the spaces that on average are little available for old buildings; in this case the use of centralized heat pump systems could be considered, with different plate powers and COPs, and a new analysis of the different scenarios could be performed.

Overall measures of incentive, could be oriented to heating systems improving the urban air quality, together with the replacement of the heating systems with more efficient ones [16,28].

This work constitutes a first case study regarding the proposed replacement within the entire residential building stock of the Municipality of Rome, which can be evaluated in other conditions and extended at national level. The expected results will be presumably more advantageous in the southern regions and less positive in the northern ones.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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**Appendix A**

With the same water delivery temperature, if the design value of external air temperature is in the range of values provided by the manufacturer, the COP is calculated by linear interpolation of the second principle efficiency values \( \eta_{II} \) calculated based on known data; if the external temperature is outside the range of values provided by the manufacturer, but within a maximum deviation of 5 K, it is possible to proceed with the extrapolation of the efficiencies \( \eta_{II} \) calculated based on the known data as close as possible (i.e. it is considered that \( \eta_{II} \) remains constant up to a temperature difference of 5 K). The second principle efficiency \( \eta_{II} \) is defined for electric heat pumps as the ratio of equation (A.1) between the actual efficiency of the HP, declared by the manufacturer, and the maximum theoretically achievable (theoretical maximum COP).

\[
\eta_{II} = \frac{COP}{COP_{\text{max}}} = \frac{c_{b} - t_{c}}{c_{b} + 273, 15}
\]  

(A.1)

where \( c_{b} \) is the delivery water temperature (to the condenser) and \( t_{c} \) is the temperature of the cold source (to the evaporator). The COP value under conditions \( x \) is therefore obtained by means of the efficiency \( \eta_{II} \) interpolated under conditions \( x \) as in (equation A.2).

\[
COP_{x} = \eta_{II, x} = \frac{c_{b} + 273, 15}{c_{b} - t_{c}}
\]  

(A.2)

Not having the COP values provided by the manufacturer for the desired value of the water delivery temperature (65 °C), we proceeded by analogy with the interpolation of efficiencies, following second principle, of the known data.

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