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A preliminary analysis of the potential reduction of CO_2 emissions by using high temperature heat pumps in residential buildings in Italy

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Abstract. The present research aims to provide an innovative contribution to the reduction of fossil fuels and the consequent reduction of CO_{2eq} emissions for each Italian region. Simulations have been carried out to replace space heating boilers supplied with fossil fuels with air to water heat pumps, when the environmental conditions (external temperature, temperature of the water in the emission systems, etc.) allow it. In order to estimate the potential covering of high temperature heat pumps in Italy energy profiles of buildings have been considered together with the potential COP of heat pumps working with variable climatic control supply temperature. The potential electrification for buildings' space heating has been estimated subdividing Italy into 21 territorial units. The work has shown that 83% of heating energy which can be covered by the heat pumps in Milan and almost 100% in Lecce. Overall, in Italy 146 TWh of current energy consumed by fossil fuels could be covered by heat pumps; at the same time 45 TWh of electric energy has to be generated to drive the heat pumps.

1.Introduction

The Russian invasion of Ukraine which led to serious consequences for the rest of Europe, as well as for Italy, highlighted the energy dependence on natural gas and fossil fuels in general for most of the European countries. Consequences are related to the increases in energy prices as well as to serious environmental problems linked to global warming deriving from the polluting emissions produced by the combustion of fossil fuels.

As well known, buildings are responsible for CO_2 emissions and in the last years it has been shown that there is an increasing need to replace the current fossil fuels, in particular natural gas which is the most extensively used in residential buildings. with other energy carriers for many reasons. The two energy carriers are the electricity and the hydrogen. Among them the electricity is the one that in short and long term can be applied in residential buildings. Different retrofit solutions may be applied to buildings, but,

looking in short term view, the easiest solution is to use high temperature heat pumps for heating the buildings. In fact, the most typical heating system in Italy is composed by gas boilers and radiators. Depending on the climate it is possible to replace the boiler with an air to water heat pump (in warmer climates) or to couple the high temperature heat pump with the natural gas boiler (in colder climates).
While in literature the replacement of traditional boilers considering the national scale is analyzed in Italy as a whole [1,2] and similarly in other individual countries [3, 4, 5], or even for groups of nations [6,7] or for the European Union as a whole [8,9], there are not specific works on the numerical detail of each region. For this reason, the primary objective of the present work is to identify for all territorial units both the energy values which can be supplied by heat pumps to replace fossil fuel-fired boilers for heating buildings, and the demand for electricity necessary for the operation of heat pumps and finally the net energy saved by that replacement. The secondary objective is to divide the residential energy consumption related to space heating between different energy vectors (electricity, residual heat, gas, solid fossil fuels, liquid fossil fuels, renewable sources) for each Italian region. This work is the first step of a more detailed analysis which will be carried out afterwards by going more in detail for the climatic conditions to consider even warmer and colder climates.
In the calculation method, the energy profiles of two cities, Milan and Lecce, representative of the different Italian climates were used, aiming to extend the results to all Italian regions according to average climate similarities. The replacement of the boiler based on fossil fuels with the heat pump may take place when the temperature of the supply water temperature is lower than 60°C. The coefficient of performance (COP) of the heat pump has been calculated as a function of both the supply temperature for the emission system and the outdoor temperature. The energy profile of representative cities and thus the specific energy demand for space heating, the delivered energy and the net energy saved with heat pumps were analyzed with a range of outdoor temperature of 1°C starting from the design minimum outdoor temperature value up to an outside temperature of +16°C. The environmental impact has been evaluated analysing the variations and reductions of CO_{2eq} emissions, for the 21 territorial units present in the database created.

2. Estimation of the energy need for heating in residential buildings

In the geographical subdivision of Italy into 19 regions plus 2 autonomous provinces, the classification "Nomenclature des unites territoriales statistiques" (NUTS) of EUROSTAT was used. Based on the heating degree-days (HDD) measured by various climatic stations located throughout Italy (in each territorial unit there is at least one climatic station), the following linear equation was applied to correlate HDD and specific space heating energy demand E in kWh/(m^2 year) [10]:

$$E = M * HDD + B \qquad (1)$$

where the coefficients M, B depend on the building archetype and on the location of the region among the 5 climatic zones present in Italy according to the Köppen-Geiger classification (Csa, Csb, Cfa, Cfb, Dfb). The equation was solved for each climatic station, taking the HDD value measured by the climatic station and inserting in the equation the values of M, B for the climatic zone of the region being calculated and referred to the type of building, the condition of thermal insulation which represents the most frequent situation for Italian buildings. The average surface of dwelling per inhabitant has been Considering that for Italy the average value of 42.9 m^2 of dwelling per inhabitant can be assumed, as stated by a database from a previous work [11], the energy need per capita (expressed in kWh/px) has been calculated. Using the Eurostat population database to know the number of inhabitants for each Italian region, the value of the total annual energy demand for residential heating, expressed in GWh/y, was estimated for each region, thus for the whole nation. The residential heating consumption has been divided among the different energy carriers based on data present in [11]: electricity, residual heat, gas, solid fossil fuel, liquid fossil fuels, renewable sources. This way it has been possible to subdivide the annual energy consumption for each region into these six energy carriers.

From these overall normalized consumption data by region, the map of total energy consumption for space heating of buildings for Italians regions was constructed (Fig. 1) using the QGIS procedure. As can be seen, the highest consumptions is observed in Lombardy, followed by Piedmont, Veneto and Emilia-Romagna, are due both to the large number of inhabitants of these regions and to the colder climate compared to the central-southern regions. As it can be noticed, the population plays a major role than the climate in the heating consumptions. The total national annual demand for heating of residential buildings is about 245 TWh, distributed as follows:

- 33.9% in the North-West regions,
- 23.8% for the North-East,
- 17.6% for the Centre,
- 18.2% for the South
- 6.5% for the two island regions.

The Lombardy region contributes to the 22.3% of the total national energy use. After Lombardy, Veneto is responsible of 9.9% of national consumption of fossil fuels, then Emilia-Romagna (9.2%), Lazio (7.8%), and Campania (7.3%). Starting from the data file created by adding, for each Italian region, the total consumption of energy deriving from fossil fuels, both natural gas, both solid and liquid, the values of the total consumption of fossil fuels for heating buildings are reported divided by region (Fig. 2). The consumption of fossil fuels for heating in Italy can be seen in Figure 2. The use of fossil fuels to provide space heating for buildings is high and therefore it is urgent to seek alternative solutions such as the one proposed in this research for the Italian energy and environmental situation. Two Italian cities, Milan and Lecce, have been considered representative of the different Italian climates based on geographical proximity, degree-days of climatic stations, latitude, climatic zones on the Koppen-Geiger scale. Milan is decided as the representative city of the northern regions, Lecce of the central-southern regions, considering Emilia Romagna the borderline region.

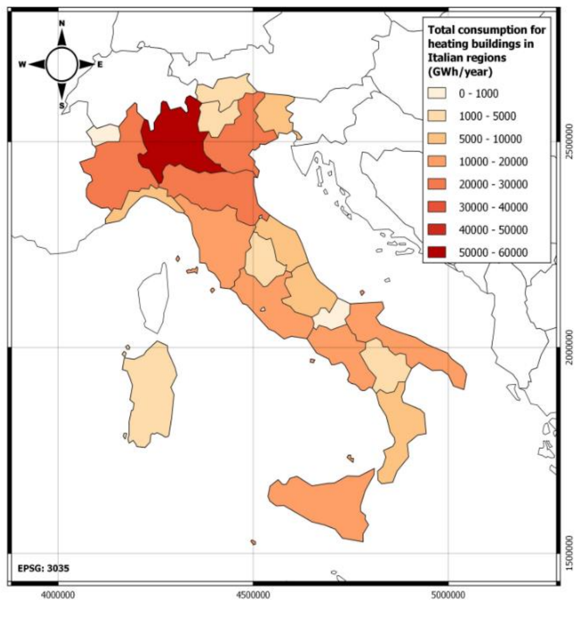


Figure 1. Total consumption for heating buildings in the Italian regions (GWh/y)

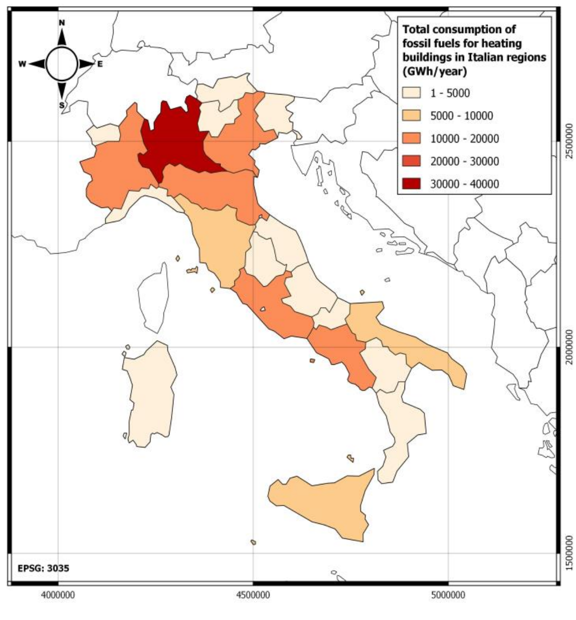
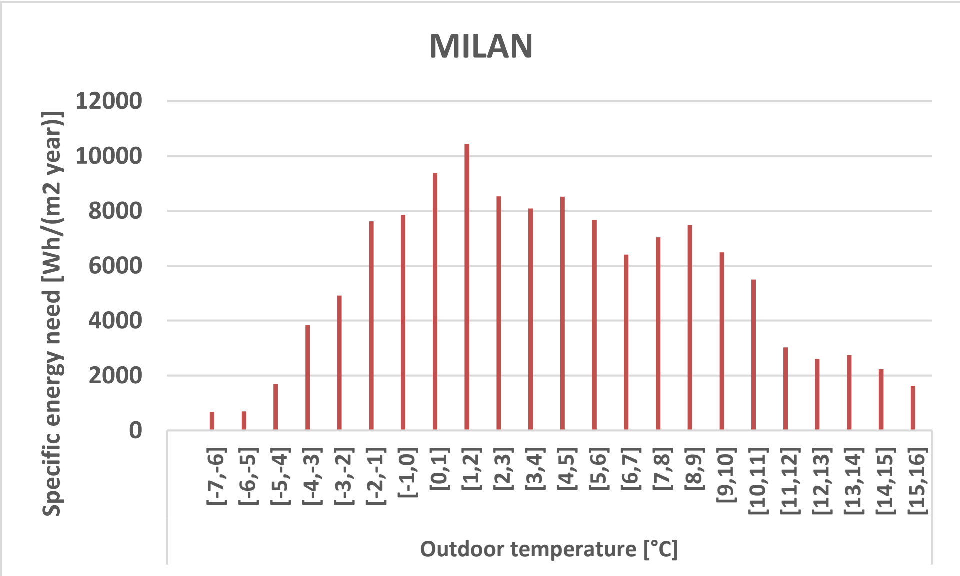


Figure 2. Total consumption of fossil fuels for heating buildings in the Italian regions (GWh/y)

3. Potential heating energy covered by high temperature heat pumps in residential buildings

As already mentioned, this work represents the preliminary step for a wider research, hence in the present paper we present the first results which focus mainly on the methodology. In the future steps of the research additional energy profiles based on other climatic conditions will be considered. Hence the work here is focused on the energy profile calculations for two climatic conditions: for this purpose Milan and Lecce have been selected and the specific power for space heating of buildings was calculated according to the methodology presented [10] The two graphs (in Fig. 3, represent the occurrence of the specific hourly loads calculated via dynamic simulations as a function of the external temperatures for the "range" of temperatures from -7°C to +16°C, considered as range of temperatures in which the heating can be considered switched on.

a



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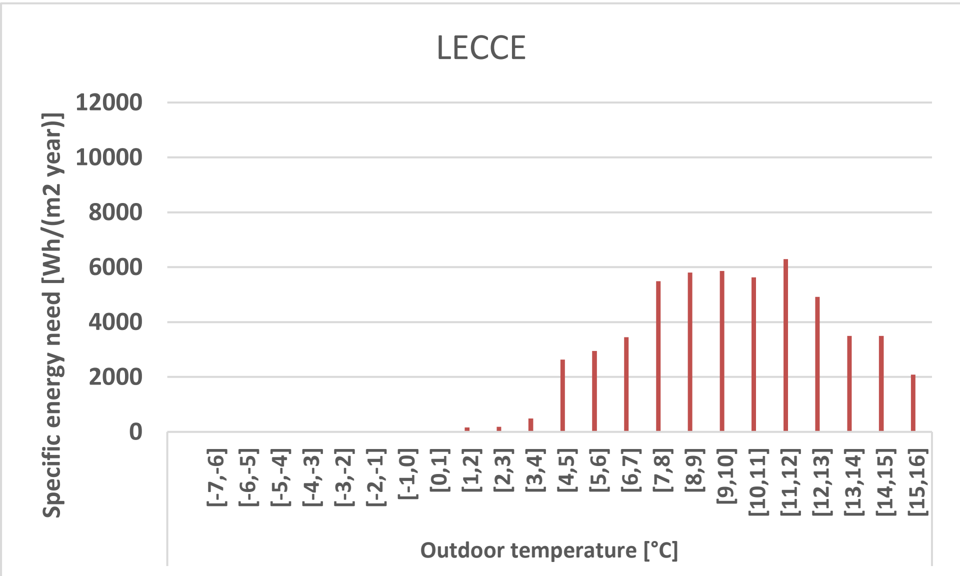


Figure 3. Yearly specific energy Vs. Outdoor temperature for Milan (a) and Lecce (b)

To estimate the potential use of heat pumps, it has been assumed to couple the heating load of the building with the outdoor temperature, including also the possibility to work with a climatic control strategy, i.e. by varying the water temperature supply as a function of outdoor air temperature. Based on

this control strategy, the lower the outdoor temperature, the greater the heat load. This behaviour can be coupled with the water supply temperature of the radiator, since it is the most diffuse emission system used in heating in existing buildings. By lowering the supply temperature of the radiators, the thermal output of the radiator will decrease.
Hence, based on the dynamic simulations results the linear function between the outdoor temperature and the specific load has been set for the two climates (see Figure 4 and 5). This way the load factor (i.e. the ratio between the actual load and the peak load) has been varied linearly versus the outdoor temperature, setting to 100% the load factor at the design temperature conditions.

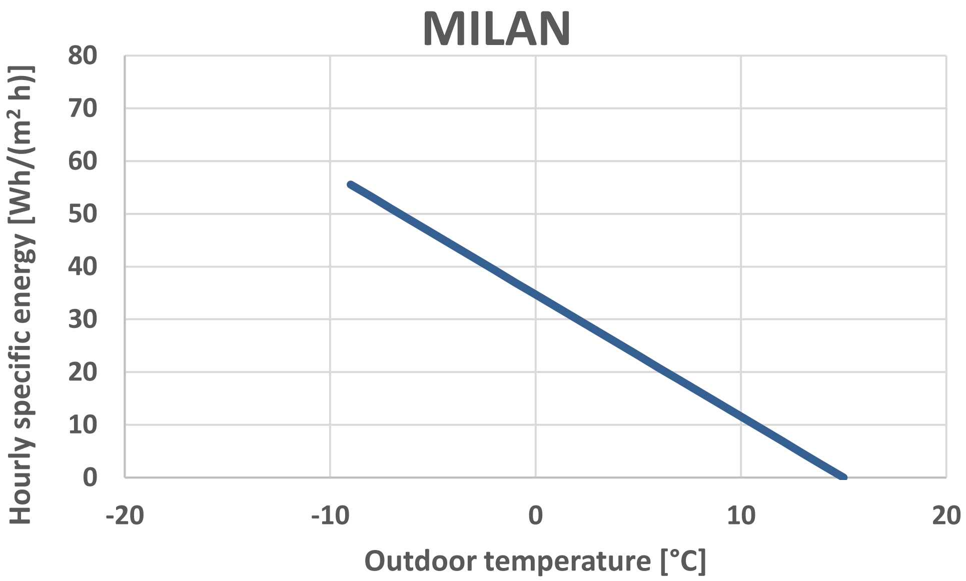


Figure 4. Interpolation via linearization of the hourly scattered diagram for Milan from dynamic simulations

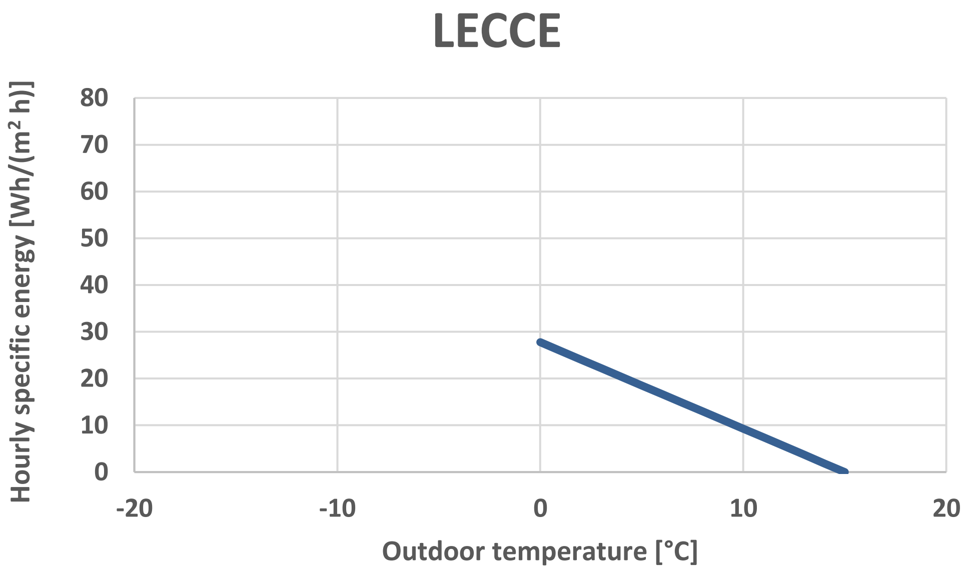


Figure 5. Interpolation via linearization of the hourly scattered diagram for Milan from dynamic simulations

The load factor has been correlated to the thermal output of the radiator (q) based on the well-known radiator efficiency formula:

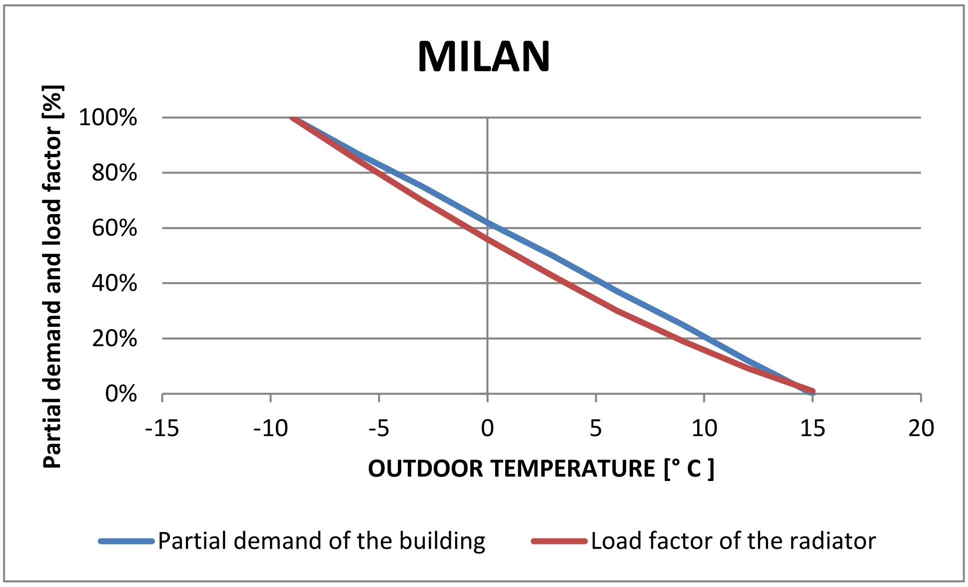
$$q = \Delta T^{n} \qquad (2)$$

where n has been set to 1.3 considered an average value among different types of radiators. This way the thermal output of the radiators has been linked to the outside temperature. As can be seen in Figure 6, the load factor together with the thermal output of the radiator as a function of the outdoor temperature can be seen. Figure 6 shows the possibility in the two climates to meet the load factor by different average temperatures in the radiators. The thermal output of the radiator has been set considering to get the maximum load factor (100%) of the radiator at the design outdoor temperature. The water supply temperature and hence the average temperature in the radiators has been changed according to outdoor temperature, so as to provide the load factor curves (the curve of the partial load of the radiators, i.e. the "Load factor of the radiator") of Figure 6.a and 6.b.

On the other hand, the calculation of the thermal output of the radiator as a function of the temperature of the water in the radiator allows to check the supply temperature to the radiators with respect to outdoor temperature. At the same time the operating conditions of a heat pump available in the market (specific technical data have been used) has been considered to check the temperature which can be supplied by the heat pump. Based on the technical data available the maximum temperature which can be provided by the heat pump is 60°C. Hence if the supply temperature is lower or equal to 60°C the heat pump works; if instead the supply temperature is greater than 60°C, the boiler works in an alternate way. It has been estimated that for Milan the cut-off temperature, i.e. the transition from to heat pump to boiler, occurs at -1°C, while for Lecce the temperature cut-off temperature is at 0°C.

Thanks to the technical data of the heat pump it was possible to obtain the COP of the heat pump at different ranges of external temperature. The COP values are evaluated as a function of the supply water temperature to the radiators variable between 35°C and 60°C, each 5 °C of interval, according to the external temperatures. Therefore, for each representative city, by entering this database , the corresponding COP value has been identified by interpolation. As expected, as the $T_{outdoor}$ increases, the COP increases, thus the heat pump is more profitable. Furthermore, the COP increases for the same $T_{outdoor}$, as $T_{w,out}$ decreases. For example, for $T_{w,out}$=60° C there is a COP=2 for $T_{outdoor}$ = 0° C, while for $T_{w,out}$=35° C and for $T_{outdoor}$=0° C the COP increases up to 3.5. Since COP values have been calculated for each 1°C interval of external temperature, the electricity requirement for the operation of the heat pump is estimated as the ratio between the energy supplied by the heat pump (which is considered equal to specific energy required for heating the building when the heat pump replaces the boiler) and the COP of the heat pump itself.
Subtracting the demand for electricity for the heat pump operation from the energy demand of the building, it has been possible to obtain the net energy saved when heat pumps replace boilers' operation. By adding the net energy values saved for all the external temperature intervals, the total net energy saved has been calculated, as well as the percentage of this saving with respect to the total specific energy request, calculated as sum of the request of all the external temperature intervals.
From the ratio between the total energy supplied by the heat pump and the total energy demand, the percentage of fossil fuel consumption saved has been estimated.
The primary energy has been also calculated, evaluating the overall primary energy saved as well as the fossil primary energy reduction, based on the national mix to produce electric energy.

a



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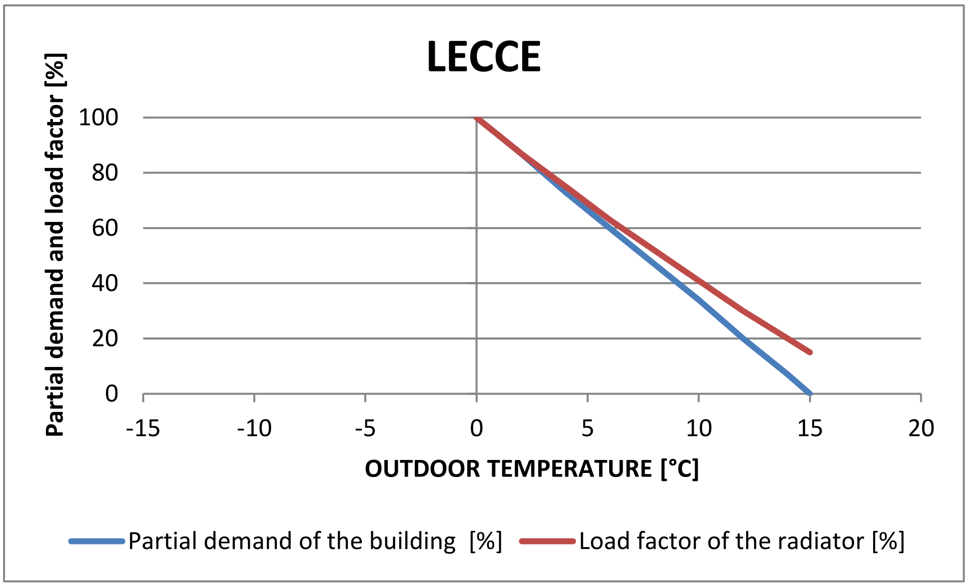

Figure 6. Partial demand of the building and Load factor of the radiator for Milan (a) and Lecce (b)

4. Results

4.1 Energy results

For the specific case study of Lecce, the saving of fossil fuels when using heat pumps is 52.8 kWh/(m^2 year) equal to 99% of current consumption. The electricity need for the operation of the heat pump is equal to 14.3 kWh/m^2. The saving of specific energy with the high temperature heat pumps is 38.5 kWh/m^2. The SPF is equal to 3.7 for Lecce. In Milan the heating demand is equal to 126.7 kWh/m^2. The saving of fossil fuels with heat pumps is equal to 105.6 kWh/m^2, corresponding to 83% of the total specific energy need. This leads to an electricity demand of 36.1 kWh/m^2. The total specific energy saving with heat pumps for Milan hence is equal to 69.8 kWh/m^2, corresponding to 55.1% compared to the current specific energy need. The SPF for Milan has been estimated to be 2.9.

By combining the results obtained for each of the two different climates the potential energy provided by the heat pump has been calculated at regional level, combining the energy results with the amount of family unit. The results are represented in the map of the energy potentially supplied by the heat pumps reported in Figure 7. The total energy which can be supplied by heat pumps is 146 TWh/y. This saving is divided into 31.3% for the North-West regions, 22% for the North-East, 19.5% for the Centre, 20% for the South, 7.2% for the Islands. Considerable potential energy savings in Italy can be achieved in Lombardy with 30 TWh, which represents the 20.6% of the total national potential. The potential savings for the other Northern regions and for Lazio and Campania are between 10 and 15 TWh for each of these regions. The total national demand for electricity for heat pumps' operation (Figure 8) would increase by 45TWh, shared between 34.5% for the North-West, 24.2% for the North-East, 17.2% for the Centre, 17.8% for the South, 6.3% for the Islands.

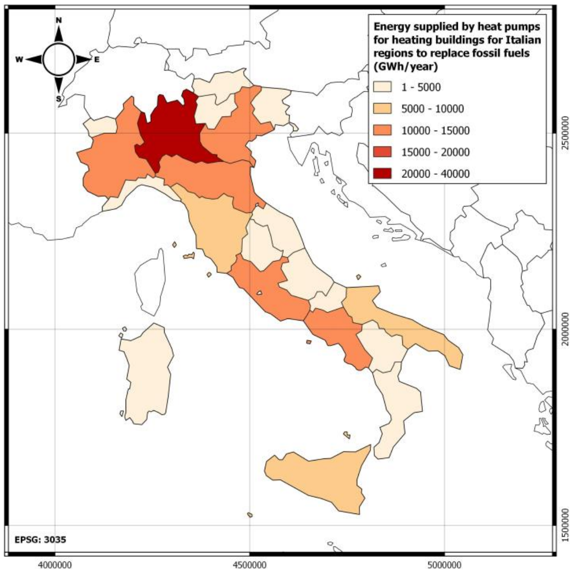

Figure 7. Thermal energy supplied by the heat pumps in the Italian regions [GWh/year]

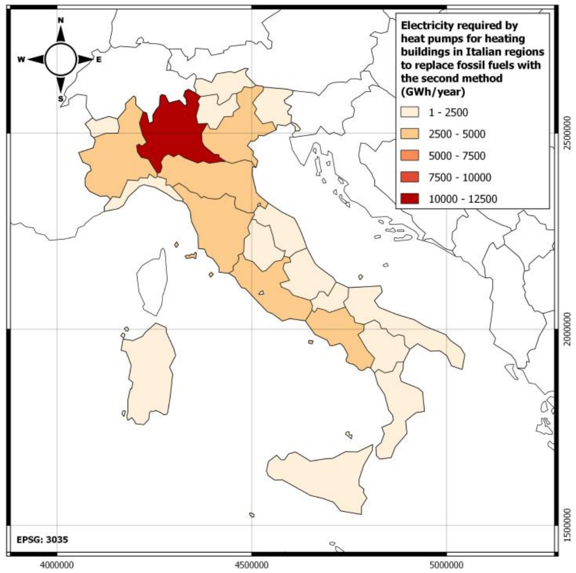

Figure 8. Electricity required by heat pumps in the Italian regions [GWh/year]

The difference between the values of the 2 previous maps gives the map of the overall energy which can be saved thanks to the heat pumps for the Italian regions (see Figure 9), which is about 101 TWh, which can replace 62.4% of the total consumption of fossil fuels for heating. The energy saved is shared into 29.8% for the North-West, 21% for the North-East, 20.5% for the Centre, 21.1% for the South, 7.6% for island regions

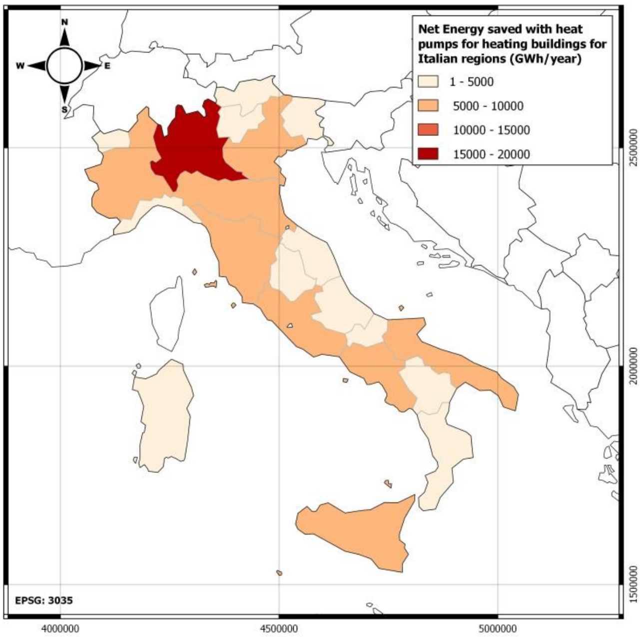

Figure 9. Net energy saved with heat pumps [GWh/year]

4.2. Environmental analysis

The environmental impact obtained by replacing fossil fuel boilers with electric heat pumps to supply space heating in Italian buildings was addressed. In particular, for all 21 Italian territorial units considered, the changes in CO_2 and other greenhouse gas emissions thanks to this energy transition strategy were obtained quantitatively, through the introduction of equivalent CO_2 emissions (CO_{2eq}) that include several greenhouse gases (in addition to CO_2, also N_2O, NH_4, PCF, SF_6, NF_3, hydrofluorocarbons). The energy of residential heating contributes in Italy to 17.7% of CO_2 emissions, as well as being responsible for 64% of the amount of $PM_{2.5}$, 53% of PM_{10} and 60% of CO released into the atmosphere [12]. To obtain this change in CO_{2eq} for each territorial unit, the operational basis is to calculate the difference between the value of CO_{2eq} emissions avoided by switching from fossil fuel boilers to heat pumps and the value of CO_{2eq} emissions deriving from the production of electric energy to power the heat pumps. To include the other greenhouse gases as well, the emissions must be considered in terms of CO_{2eq}, therefore the value of 0.237 tons CO_{2eq}./MWh was assumed for natural gas, and 0.305 tons CO_{2eq}/MWh for heating oil [13]. The CO_{2eq} avoided by saving gaseous and liquid fossil fuels was calculated for each region starting from the energy carriers. The amount of CO_{2eq} emitted, in the same region, from the production of electricity to be supplied for the operation of the heat pumps has been calculated based on the values provided by specific website[1] , which gives for Italy the average value of 372 grams CO_{2eq}/kWh electricity, higher than the European average of 279 grams CO_{2eq}/kWh electricity. In this way, the map of the net CO_{2eq} savings for the various Italian territorial units is obtained (excluding the indirect GWP of the heat pumps). Overall, there is a net reduction of 19.21 Mton CO_{2eq} per year in Italy, equal to 4.6% of total CO_{2eq} emissions of anthropic origin which for Italy accounts, for the year 2019, to 418.28 Mton [14]. This overall reduction is distributed for 28.4% in the North-West, 20% in the North-East, 21.5% in the Centre, 22.2% in the South, 7.9% in the Islands. It should be noted that there are 8 Italian regions in the CO_{2eq} abatement range between 1 and 2 Mtons. Lombardy stands out among the regions with 3.6 Mtons CO_{2eq} avoided, followed by Lazio with 1.8 Mton CO_{2eq} and Campania with 1.7 Mtons CO_{2eq}. It emerges from these data that the number of inhabitants is always the predominant factor determining the differences between one

[1] ourworldindata.org/grapher/carbon-intensity-electricity (Last seen: May 17th, 2023)

region and another in absolute terms. Considering for Italy a population of 59 million inhabitants, the reduction per person corresponds to 326 kg CO_{2eq}/px.

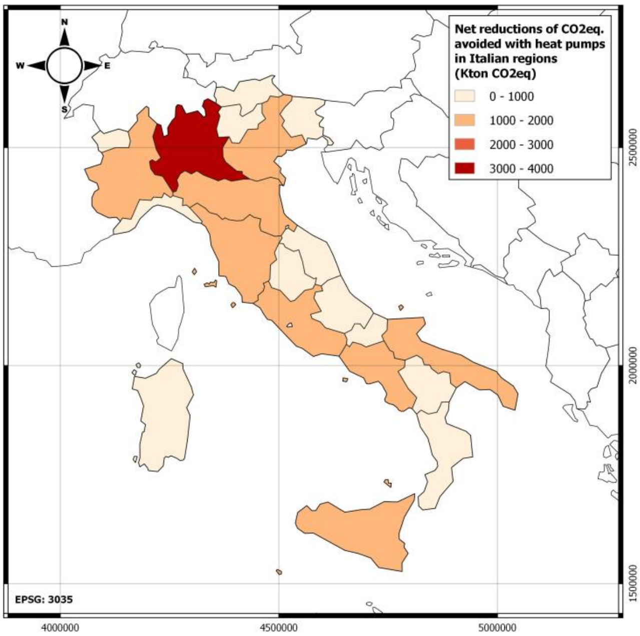

Figure 10. Net reductions of CO_{2eq} avoided with heat pumps

5. Discussion and conclusions

In this work a preliminary analysis to check the potential use of high temperature heat pumps has been analysed for the residential sector in Italy. The work has shown the energy which can be potentially covered by the heat pump in a cold climate (Milan) and in a warm climate (Lecce). The energy profiles of two typical buildings have been analysed. The occurrence of the energy demand with respect of outdoor temperature has been set. An interpolation to define a linear trend of energy demand based on outdoor temperature has been evaluated. At the same time the thermal output of a radiator with a climatic control strategy has been considered so as to find the supply water temperature related to the outdoor temperature. This has lead to 83% of heating energy which can be covered by the heat pumps in Milan and 99% in Lecce.
Based on technical data of commercial heat pumps in the market the SPF has been calculated, being 3,7 in Lecce eand 2,9 in Milan.
Based on the climatic conditions and on the population the potential energy saving of fossil fuel has been evaluated at regional level. Overall, 146 TWh of current energy consumed by fossil fuels could be covered by heat pumps. This would lead to 45 TWh of electric energy which has to be generated to produce the heating energy for the heat pumps.
Further work has to be done including a more detailed analysis to include other climates and also to check the potential scenarios with different energy mixes of electric production.

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