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The Role of Heat Pumps for the Decarbonization of European Regions

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Abstract**—**This research aims to provide a contribution to the reduction of fossil fuels and the consequent reduction of CO_{2eq} emissions for each European region. Simulations have been carried out to replace fossil fuel fired heating boilers with air-to-water heat pumps, when allowed by favorable environmental conditions (outdoor temperature, water temperature in emission systems, etc.). To estimate the potential coverage of high-temperature heat pumps in European regions, the energy profiles of buildings were considered together with the potential coefficient of performance (COP) of heat pumps operating with flow temperature with variable climatic regulation. The electrification potential for heating buildings was estimated by dividing the 38 European countries examined into 179 territorial units. The yields have been calculated in terms of energy savings and CO_{2eq} reduction.

Keywords**—**Decarbonization, Space heating, Heat pumps, Energy policies.

I. Introduction

THE Russian invasion of Ukraine which has had serious consequences for the rest of Europe has highlighted the energy dependence on natural gas and fossil fuels for most European countries. Although energy prices rapidly increased due to the war, the energy demand did not change and it is still responsible of serious environmental problems deriving from the polluting emissions produced by the combustion of fossil fuels.

As well known, buildings are responsible for CO_2 emissions and in recent years it has been demonstrated that [1] there is a growing need to replace current fossil fuels with other energy carriers. The two energy carriers most studied are electricity and hydrogen [2]. Among them, electricity is the one that can be applied in residential buildings both in the short and long term.

Considering that the most important action to save energy is not consuming it, the first retrofit action that should be taken into account is the thermal improvement of the envelope. Concerning the HVAC systems, several efficient solutions can be applied to buildings, but looking at the short term, the use of high temperature heat pumps is the most effective solution in terms of investment costs, installation times and energy benefits. In fact, since the most typical space heating system in Europe consists of gas boilers and high-temperature radiators, this type of heat pumps could avoid the replacement of the emission system, requiring a lower investment cost.

Depending on the climate, it is possible to replace the boiler with an air-water heat pump (in warmer climates) or combine the high temperature heat pump with a natural gas boiler (in colder climates).

In literature the replacement of traditional boilers has been analyzed at different scales: in Italy as a whole [1], [2] and similarly in other individual countries [3]-[5]; by groups of countries [6], [7]; for the European Union as a whole [8], [9]. The primary objective of this work is to identify for all territorial units both the energy values that can be supplied by the heat pumps to replace the fossil fuel boilers for space heating, the electric energy required to support heat pumps operation, 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 carriers (electricity, residual heat, gas, solid fossil fuels, liquid fossil fuels, renewable sources) for each European region.

This work is the first step of a more detailed analysis that will be carried out later considering more detailed climatic conditions to estimate the performance in warm and cold climates.

In the calculation method, the energy profiles of 13 European cities representative of the different European climates were used, with the aim of extending the results to all European regions according to average climatic similarities.

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The energy profiles of representative cities were analyzed, the specific energy demand for space heating, the delivered energy and the net energy saved with heat pumps operation considering an outdoor temperature range of 1 °C starting from the minimum design outdoor temperature up to an outdoor temperature of +16 °C. The environmental impact was assessed by analyzing the variations and reductions in CO_{2eq} emissions for the 179 European regions present in the database created.

II. Estimation of Energy Needs for Space Heating in Residential Buildings

In the geographical subdivision of the 38 European countries examined into 179 regions, the classification "Nomenclature des unites territorial statistiques" (NUTS) of EUROSTAT was used. Based on the heating degree-days (HDD) available for

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different weather files located throughout Europe, (1) was applied to correlate the HDD and the specific thermal energy demand in kWh/(m^2 year) [10]:

$$E = M * HDD + B \tag{1}$$

where the coefficients M, B depend on the building archetype and on the climatic region according to the Köppen-Geiger classification (Csa, Csb, Cfa, Cfb, Dfb).

Equation (1) 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 referring to the type of building and the insulation condition thermal which represents the most frequent situation for European buildings.

The average surface of dwelling per inhabitant has been assumed considering a database from a previous work [11] to calculate the energy need per capita (expressed in kWh/px).

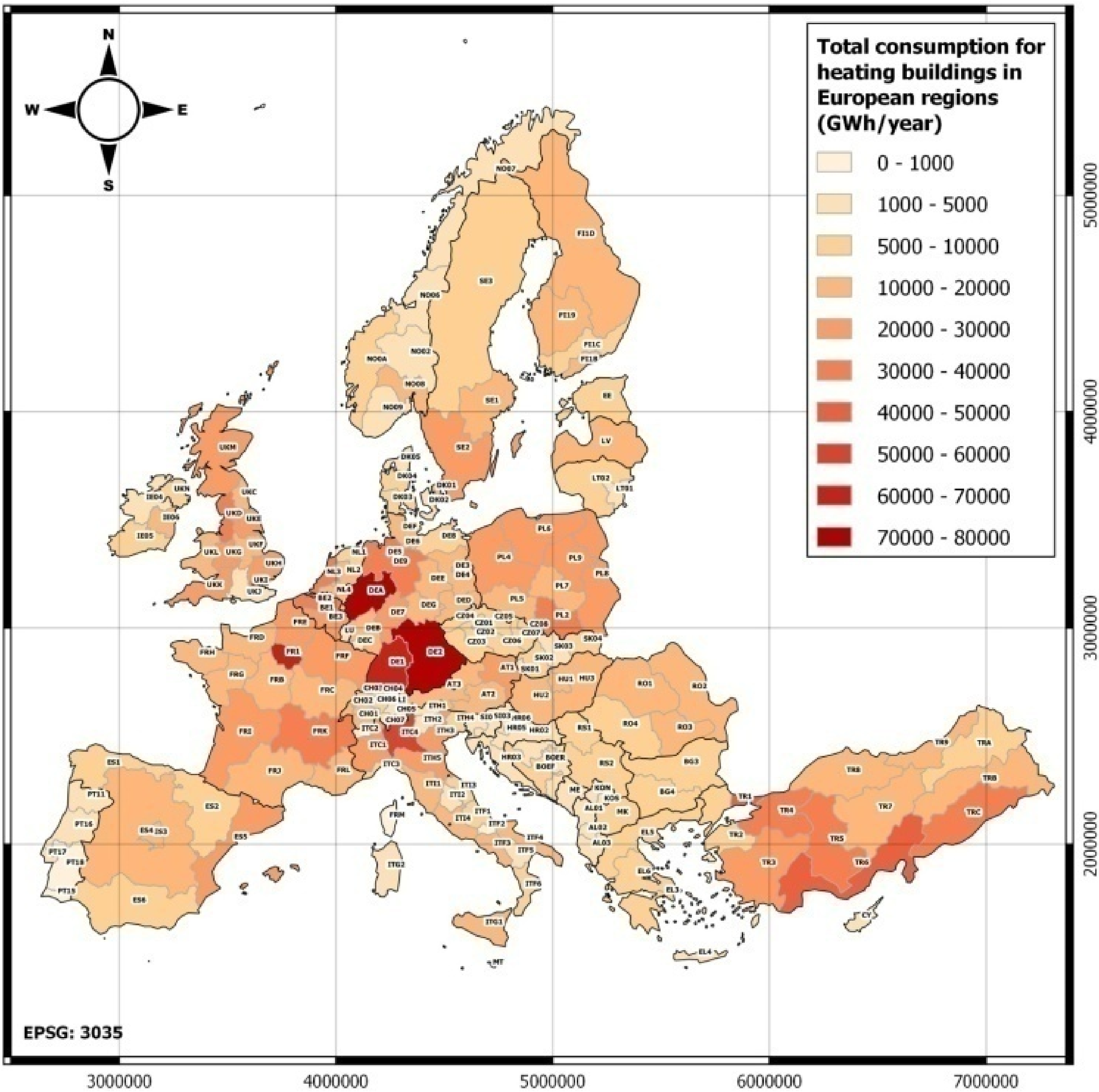


Fig. 1 Total energy consumption for heating buildings in the various European regions

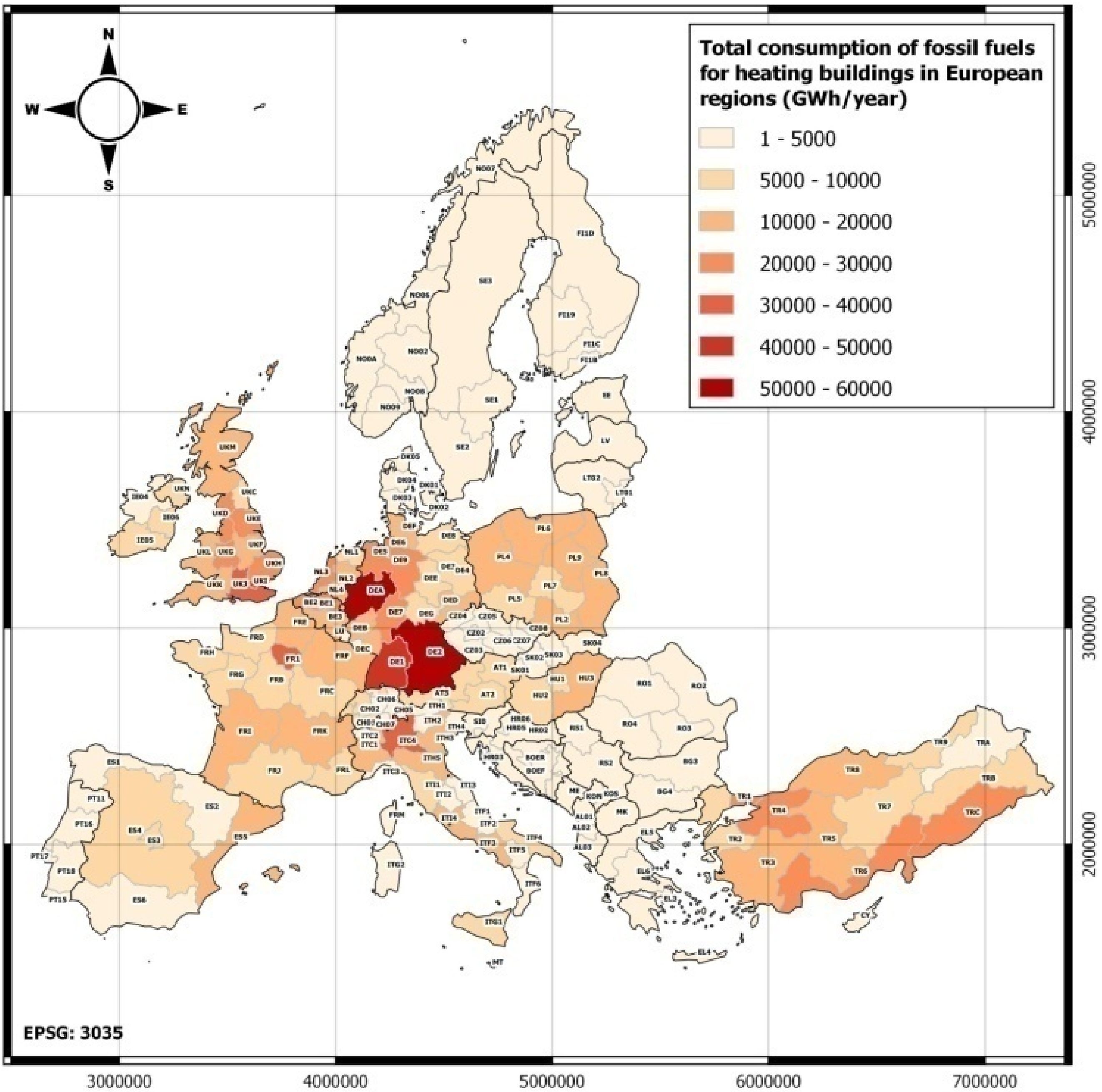


Fig. 2 Total consumption of fossil fuels for heating buildings in the different European regions

Using the Eurostat population database to know the amount of inhabitants for each European region, the value of the total annual energy demand for residential heating, expressed in GWh/year, was estimated; furthermore, the energy used has been divided into the different energy carriers (electricity, residual heat, natural gas, solid fossil fuels, liquid fossil fuels, renewable sources), based on the data present in [11], finally obtaining the subdivision of the annual energy consumption for each region into six energy carriers. From these overall normalized consumptions data by region, the map of the total energy consumption for space heating of buildings for the European regions was evaluated (Fig. 1) using the QGIS procedure. As can be seen from the map, the highest consumption for heating occurs in the southern German regions, within the Paris region and in Lombardy, mainly due to the high population density of these regions and also to the cold climatic conditions compared to southern populated locations.

The bands of highest density in European regions are those between 10 and 30 TWh/year. The total annual consumption for residential space heating of the 38 countries analyzed is 2440 TWh/year.

Fig. 2 shows the total consumption of fossil fuels (solid, liquid, gaseous) for each European region, equal to 733 TWh/year, corresponding to 30% of total consumption.

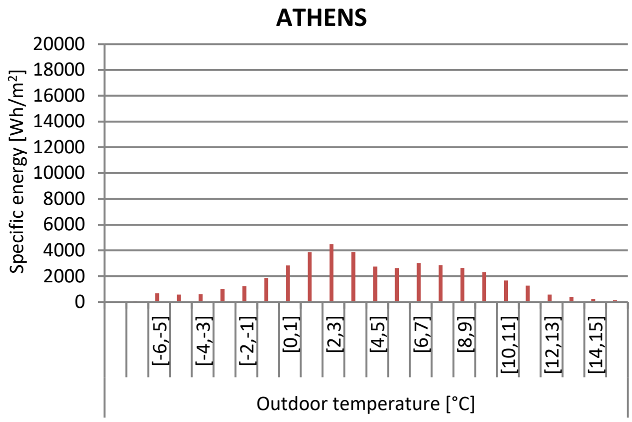
The Balkan and Scandinavian regions are those with the lowest consumption of fossil energy, due to the relative lower population density of these regions.

III. Potential Heating Energy Covered by High Temperature Heat Pumps in Residential Buildings

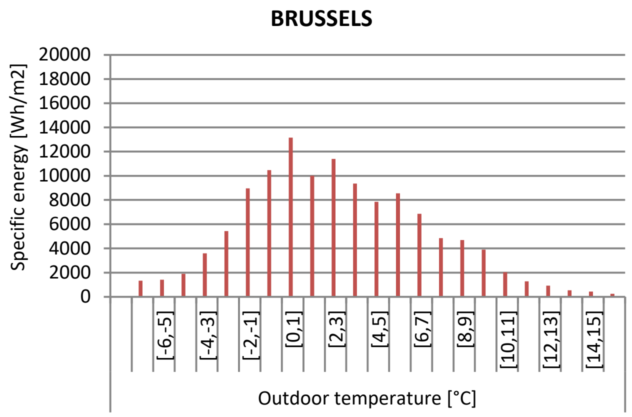
As already mentioned, this work represents the preliminary step of a wider research, hence in the present paper will be presented the first results which focus mainly on the methodology. Further energy profiles based on other climatic conditions will be considered in future works.

The results presented are based on the calculations of energy profiles for different climatic conditions: for this purpose, 13 representative cities were selected and the specific power heating of the buildings was calculated according to the presented methodology [10].

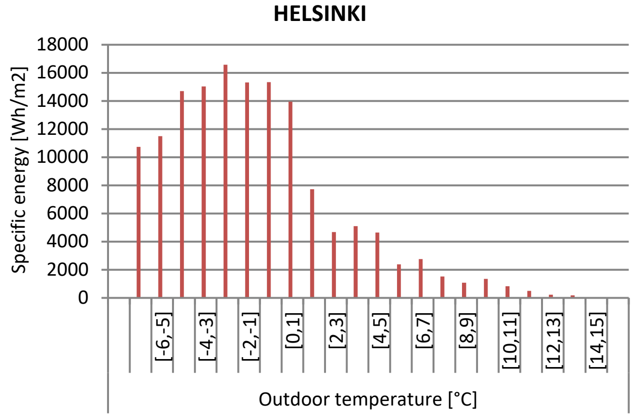
The graphs in Fig. 3 represent the occurrence of the specific hourly loads calculated via dynamic simulations as a function of the external temperatures for the "range" of temperatures from -7 °C to +16 °C, considered as range of temperatures in which the heating can be considered switched on. A significant difference can be found among the three different climates according to the energy need.



(a)



(b)



(c)

Fig. 3 Specific energy for Athens (a), Brussels (b) and Helsinki (c)

To estimate the potential use of heat pumps, it was assumed to couple the heating load of the building with the external temperature, including also the possibility of working with a climate control strategy, i.e. varying the delivery water temperature as a function of the outdoor air temperature.

Based on this control strategy, the lower the outside temperature, the higher the heat load. This behavior can be coupled with the supply water temperature of the radiator, which is the most common emission system used for space heating of buildings in Europe. By lowering the average temperature of the radiators, the thermal output of the radiator decreases.

Based on the results of dynamic simulations, the linear function between the outdoor temperature and the specific load was set for different climates (see Figs. 4-6). In this way, the load factor (that is the ratio between the effective load and the peak load) was varied linearly with respect to the outdoor temperature, setting the load factor to 100% at the design temperature conditions, and then decreasing the load factor while the outside temperature increases.

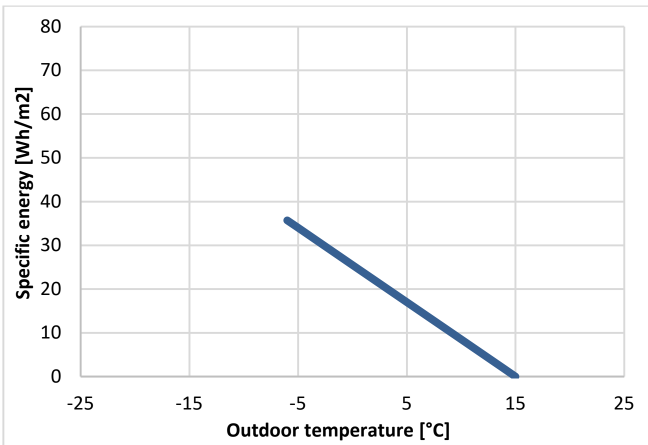


Fig. 4 Linearization of the scatter diagram for Athens

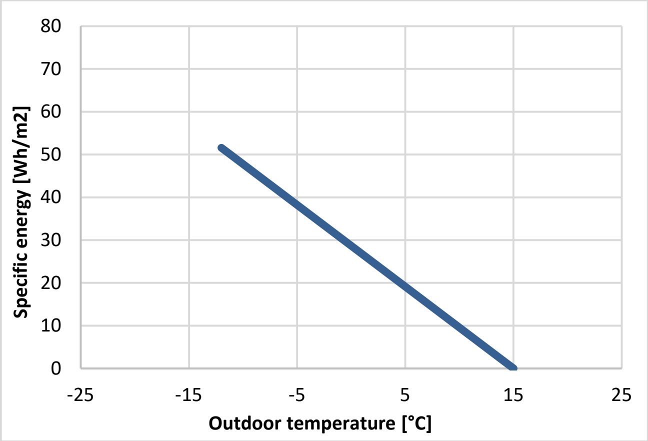


Fig. 5 Linearization of the scatter diagram for Brussels

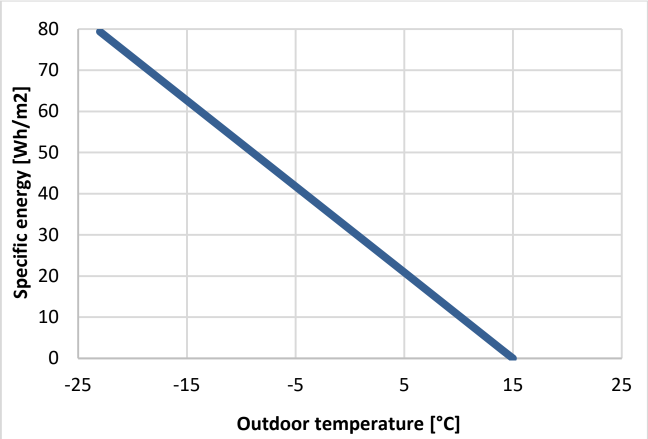


Fig. 6 Linearization of the scatter diagram for Helsinki

The load factor was related to the heat output of the radiator (q) based on the well-known radiator efficiency formula:

$$q = \Delta T^n \quad (2)$$

where n has been set to 1.3 and is considered an average value for different types of radiators.

Figs. 7-9 show the load factor together with the heat output of the radiator as a function of the outside temperature. Furthermore, the graphs show the possibility to meet the load factor in different climates by different average temperatures of the radiators combined with the maximum efficiency of the radiators.

Proportioning the subsequent values obtained, for each of the representative cities, it was also possible to meet the curve of the partial load of the radiators, named "Radiator Load Factor".

The calculation of the thermal output of the radiator as a function of the temperature of the water allowed to check the supply temperature to the radiators with respect to the outdoor air temperature. At the same time, the operating conditions of a heat pump available on the market were considered to verify the temperature that can be provided by the heat pump. Based on the technical data available, the maximum temperature that can be supplied is 60 °C. Therefore, if the supply temperature is lower than or equal to 60 °C the heat pump works; otherwise, for supply temperatures higher than 60 °C, the boiler works in an alternate way.

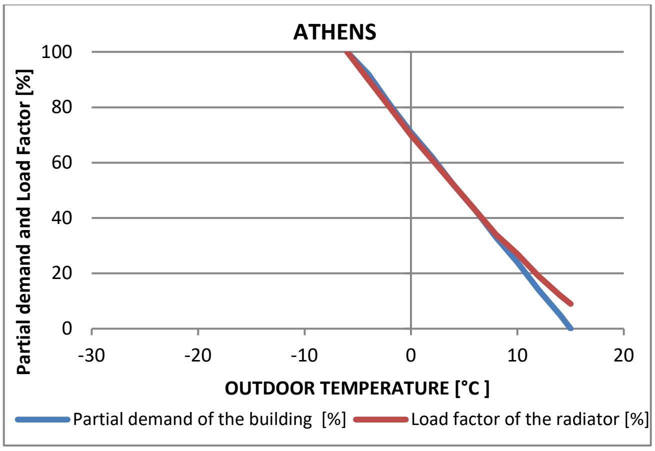


Fig. 7 Partial demand of the building and Load Factor of the radiator for Athens

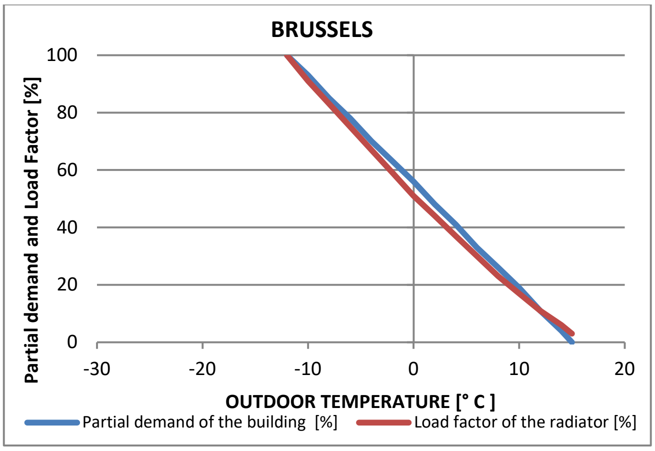


Fig. 8 Partial demand of the building and Load Factor of the radiator for Brussels

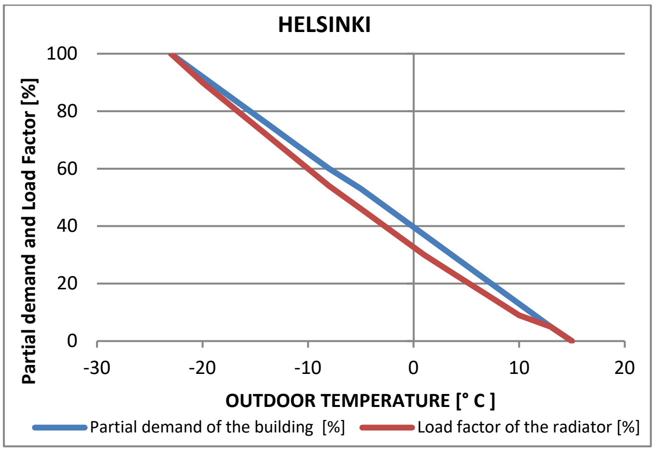


Fig. 9 Partial demand of the building and Load Factor of the radiator for Helsinki

It has been estimated that for Athens the cut-off temperature, i.e. the transition from heat pump to boiler, occurs at +1 °C, for Cordoba at +3 °C, for Lecce at +2 °C, for Milan and Brussels at -1 °C, for Madrid and London at -2 °C, for Debrecen and Kaunas at -4 °C, for Helsinki at -6 °C.

Thanks to the technical data of the heat pump, it was possible to obtain the COP at different outdoor temperature ranges. The COP values were evaluated according to the temperature of the supply water to the radiators which varies between 35 °C and 60 °C, each 5 °C interval, according to the external temperatures. Therefore, for each representative city, entering this database, the corresponding COP value was identified by interpolation.

As expected, as the $T_{outdoor}$ increases, the COP increases, the heat pump works for longer time, allowing (for warmer climates) to replace the existing boilers. Furthermore, the COP increases for the same $T_{outdoor}$, while Tw,out decreases. For example, for $_{Tw,out}$ = 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 the COP values have been calculated for each 1 °C interval of external temperature, the electricity requirement for the heat pump operation is estimated as the ratio between the energy supplied by the heat pump (considered equal to the specific energy required for heating the building when the heat pump replaces the boiler) and the COP of the heat pump itself. Subtracting the electricity demand for heat pump operation from the building's energy demand, it was possible to obtain the net energy saved when heat pumps replacing boilers' operation.

By adding the net energy saved for all the outdoor temperature intervals, the total net energy saved was calculated, as well as the percentage of this saving with respect to the total specific energy request, calculated as the sum of the request for all the temperature intervals.

Finally, the percentage of fossil fuel consumption saved was estimated from the ratio between the total energy supplied by the heat pump and the total energy requirement. The primary energy was also calculated, evaluating the total primary energy saved and the fossil primary energy reduction, based on each national mix representative of the electricity production.

IV. Results

A. Energy Results

Results have been summarized in Table I. In particular, for the specific case study of Athens, the saving of fossil fuels when using heat pumps is 32.7 kWh/m^2 equal to 78.7% of current consumption. The electricity need for the operation of the heat pumps is about 11.5 kWh/m^2, while the specific energy saved with the high temperature heat pumps is 21.2 kWh/m^2 equal to 51% of current consumption. The SPF is equal to 2.85 for Athens.

TABLE I
Results for the 13 Representative Cities

City	Specific Energy Demand Total [KWh/m^2]	Energy supplied by the Heat Pumps [%]	Specific electricity for the Heat Pump [KWh/m^2]	Net Energy saved with heat Pumps [%]
Athens	41.6	78.7	11.5	51.0
Cordoba	42.2	82.9	12.4	53.4
Lecce	53.0	99.7	14.3	72.6
Madrid	77.3	75.8	21.9	45.5
La Coruna	58.4	100.0	15.9	72.8
Lodz	159.5	55.8	32.8	35.2
London	113.8	85.8	34.8	55.2
Milan	126.7	83.3	36.1	55.1
Bilbao	71.1	98.8	20.6	69.8
Bruxelles	121.2	60.2	26.3	38.5
Debrecen	125.3	87.8	43.3	53.2
Kaunas	180.5	61.8	45.8	36.4
Helsinky	197.5	68.5	58.8	38.7

Looking at the case of Brussels, the saving of fossil fuels when using heat pumps is 72.9 kWh/m^2 equal to 60.2% of current consumption. The electricity need for the operation of the heat pumps is 26.3 kWh/m^2. Therefore, the saving of specific energy with the high temperature heat pumps is 46.6 kWh/m^2 equal to 38.5% of current consumption. The SPF is estimated equal to 2.77 for Brussels.

Finally, for Helsinki, the saving of fossil fuels when using heat pumps is 135.3 kWh/m^2 equal to 68.5% of current consumption. The electricity need for the operation of the heat pumps is about 58.8 kWh/m^2. The saving of specific energy with the high temperature heat pumps is 76.5 kWh/m^2, which corresponds to the 38.7 % of current consumption. The SPF in this case is equal to 2.3.

Combining the results obtained for each climate, the potential energy supplied by the heat pump at the regional level was calculated. The results are represented in the map of the potential potentially provided by heat pumps is shown in Fig. 10.

The total energy that can be supplied operating with heat pumps in the 38 countries has been evaluated equal to 550 TWh/year, corresponding to 75% of the energy currently supplied by fossil fuels. The most populated areas are found in the bands with the greatest energy savings.

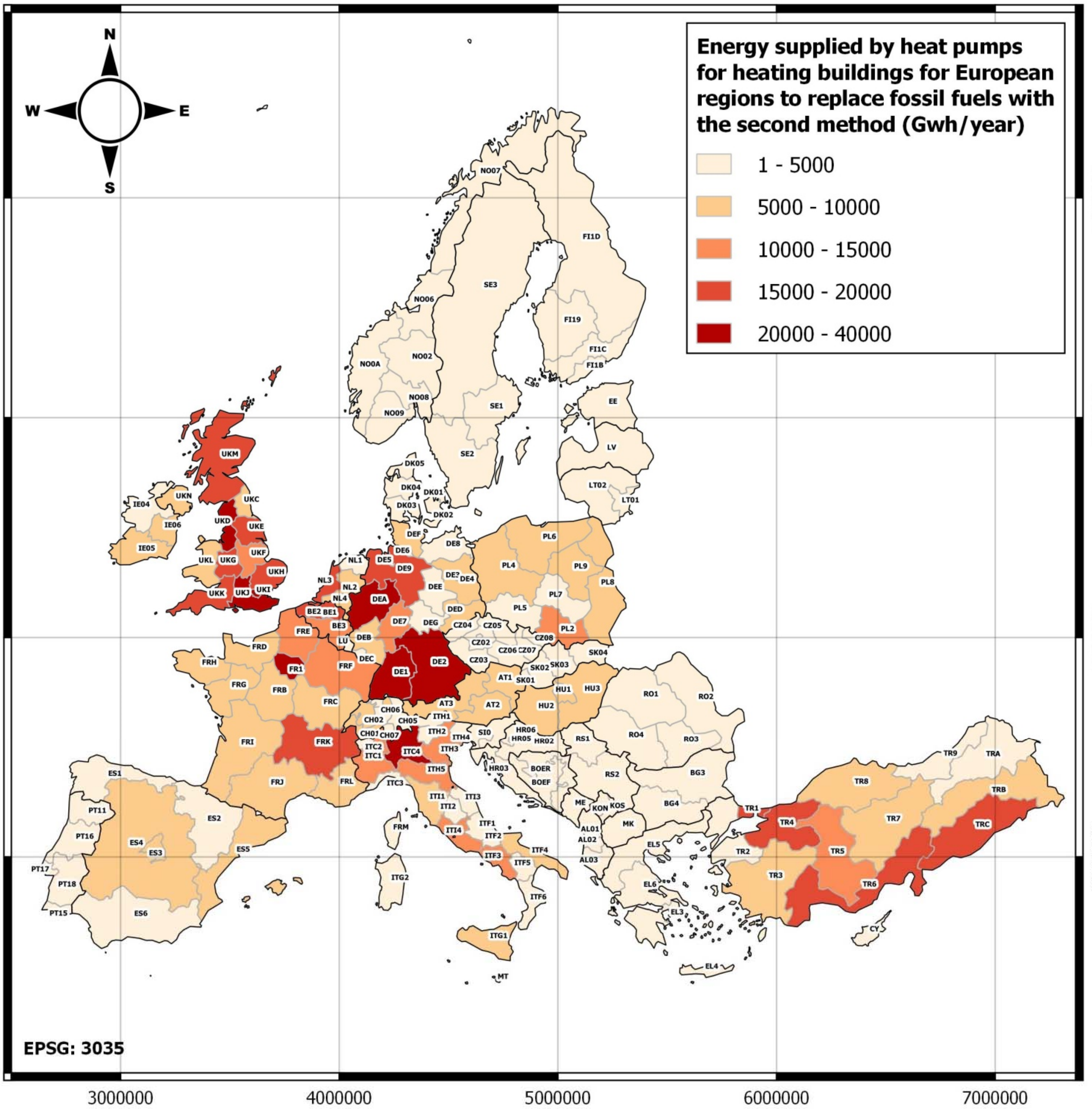


Fig. 10 Energy supplied by heat pumps in European regions

A map of the electricity requirements of the heat pumps in the various European regions is produced (Fig. 11), which represents the total electricity demand for the 38 states of about 195 TWh/year. The greatest demand is for the German regions, the United Kingdom and for Southern Turkey.

The difference between the values of the 2 maps in Figs. 10 and 11, therefore the difference between the thermal energy covered by the heat pumps and the electrical energy required for the heat pumps to operate, provides the map of the total energy that can be saved thanks to heat pumps for the European regions (see Fig. 12), which is 355 TWh/year, or 48% of the total consumption of fossil fuels.

Most European regions show a potential energy savings below 10 TWh/year, while some German, Turkish and United Kingdom regions exceed this threshold, as well as Île-de-France and Lombardy, i.e. the regions of Europe most populated.

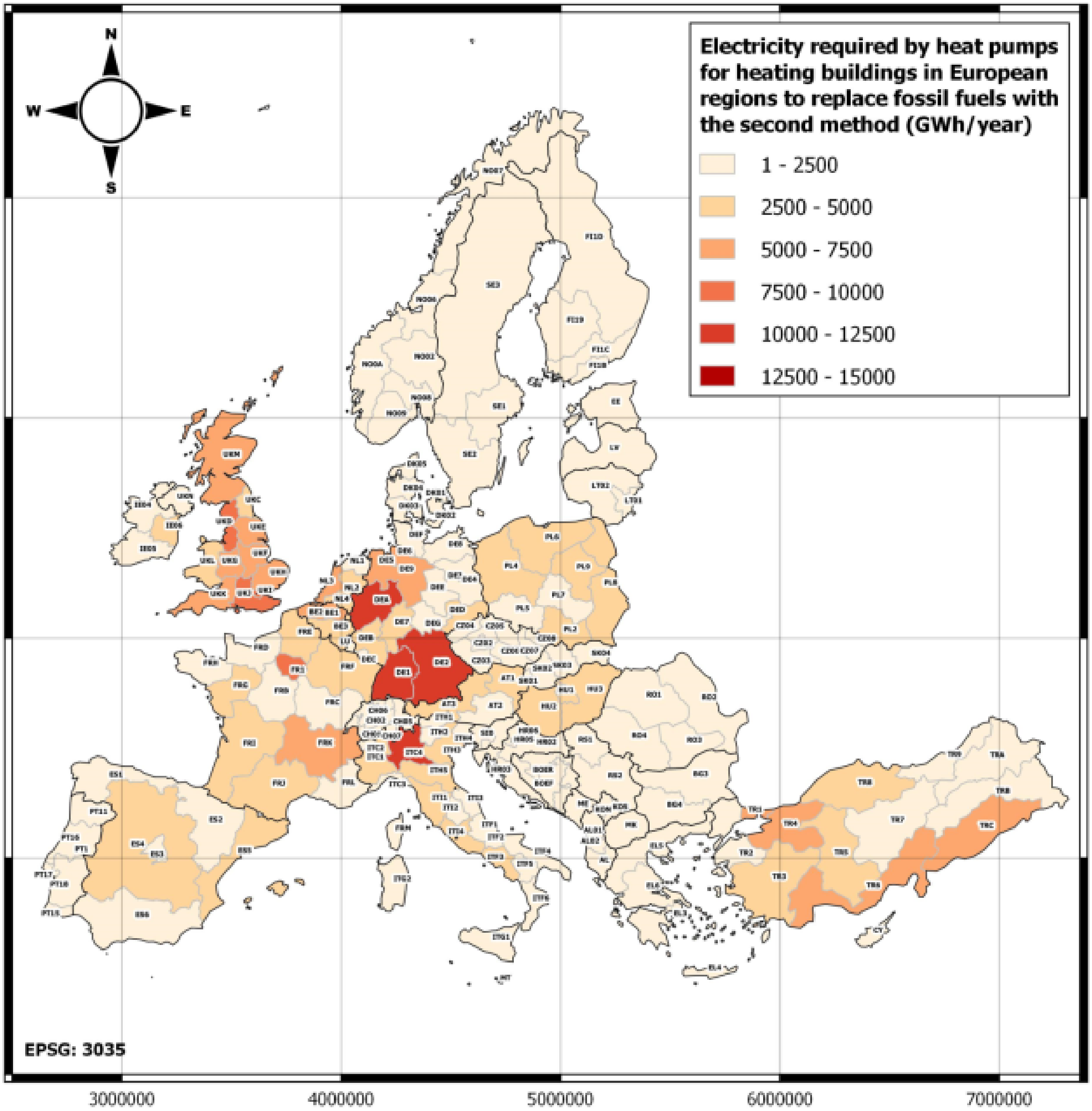


Fig. 11 Electricity required by heat pumps in European regions

The representative map of the percentages (Fig. 13) of net energy saved (final energy) with heat pumps compared to the current fossil primary energy demand for the European regions has been obtained.

By comparing the net energy saved with heat pumps as a percentage of the current requirement of fossil origin, European regions can be divided into 4 large areas: those with high savings (over 70%): Northern Spain, Central-Southern Italy, Cyprus; those with medium-high savings (between 60 and 70%): United Kingdom, Ireland, France, Northern Italy, Croatia and Bosnia-Herzegovina; those with medium-low savings (between 45% and 60%): Central-Southern Spain, Portugal, Turkey, Austria, Switzerland, Greece and Central European countries; those with low savings (below 45%): Germany, Poland, the Baltic and Scandinavian countries, Denmark and the Benelux area.

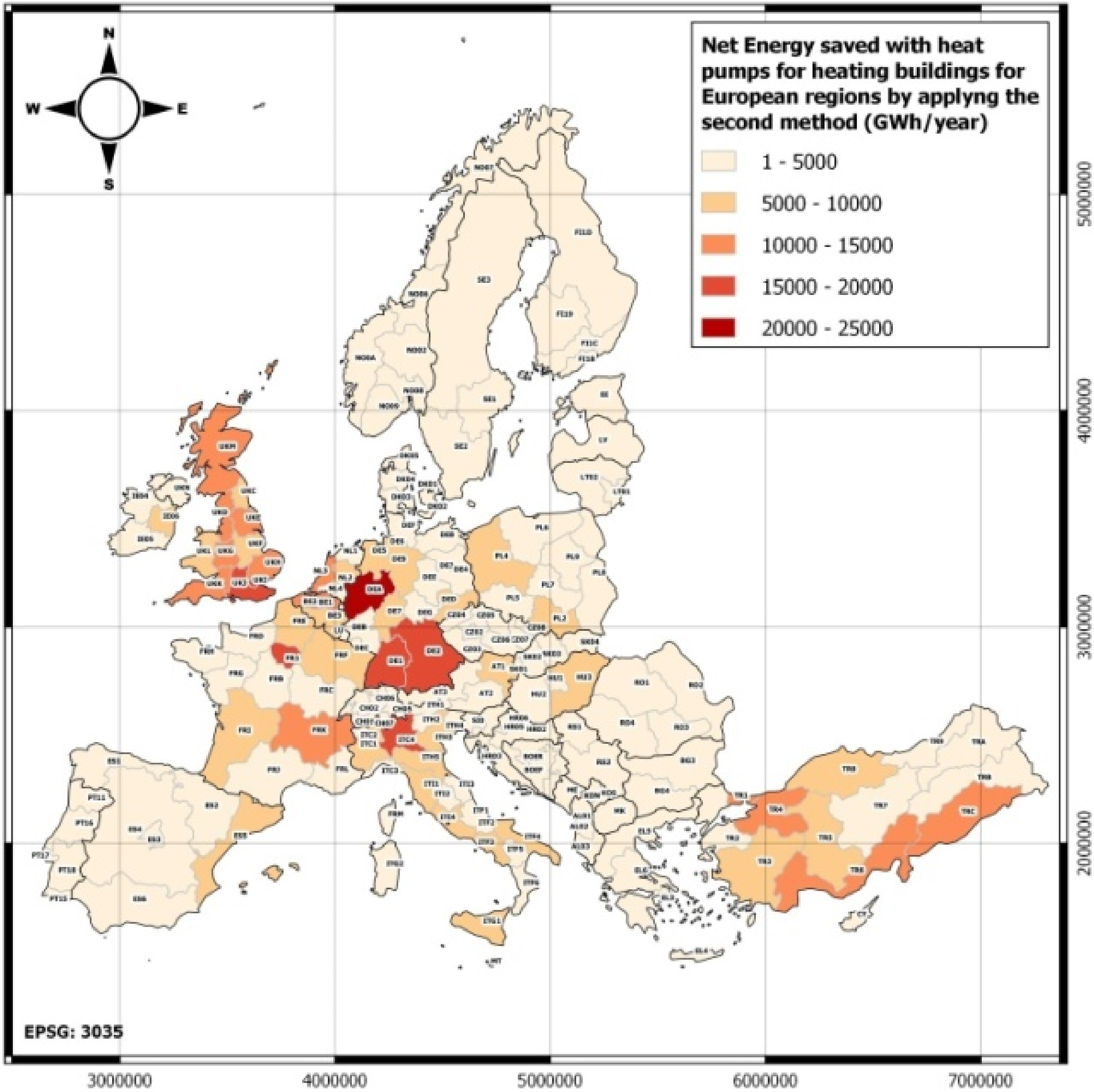


Fig. 12 Net energy saved with heat pumps in European regions

B. Environmental Analysis

The environmental impact obtained by replacing fossil fuel boilers with electric heat pumps to provide space heating in European buildings was addressed.

In particular, for all the 179 European 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 more greenhouse gases (in addition to CO_2, also N_2O, NH_4, PCF, SF_6, NF_3, hydrofluorocarbons).

The environmental impact related to the space heating of residential buildings, contributes for the 17.7% to CO_2 emissions, as well as being responsible for 64% of the quantity of $PM_{2.5}$, 53% of PM_{10} and the 60% of the CO emitted into the atmosphere [12]. To obtain this variation of 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 electricity needed to allow the operation of heat pumps.

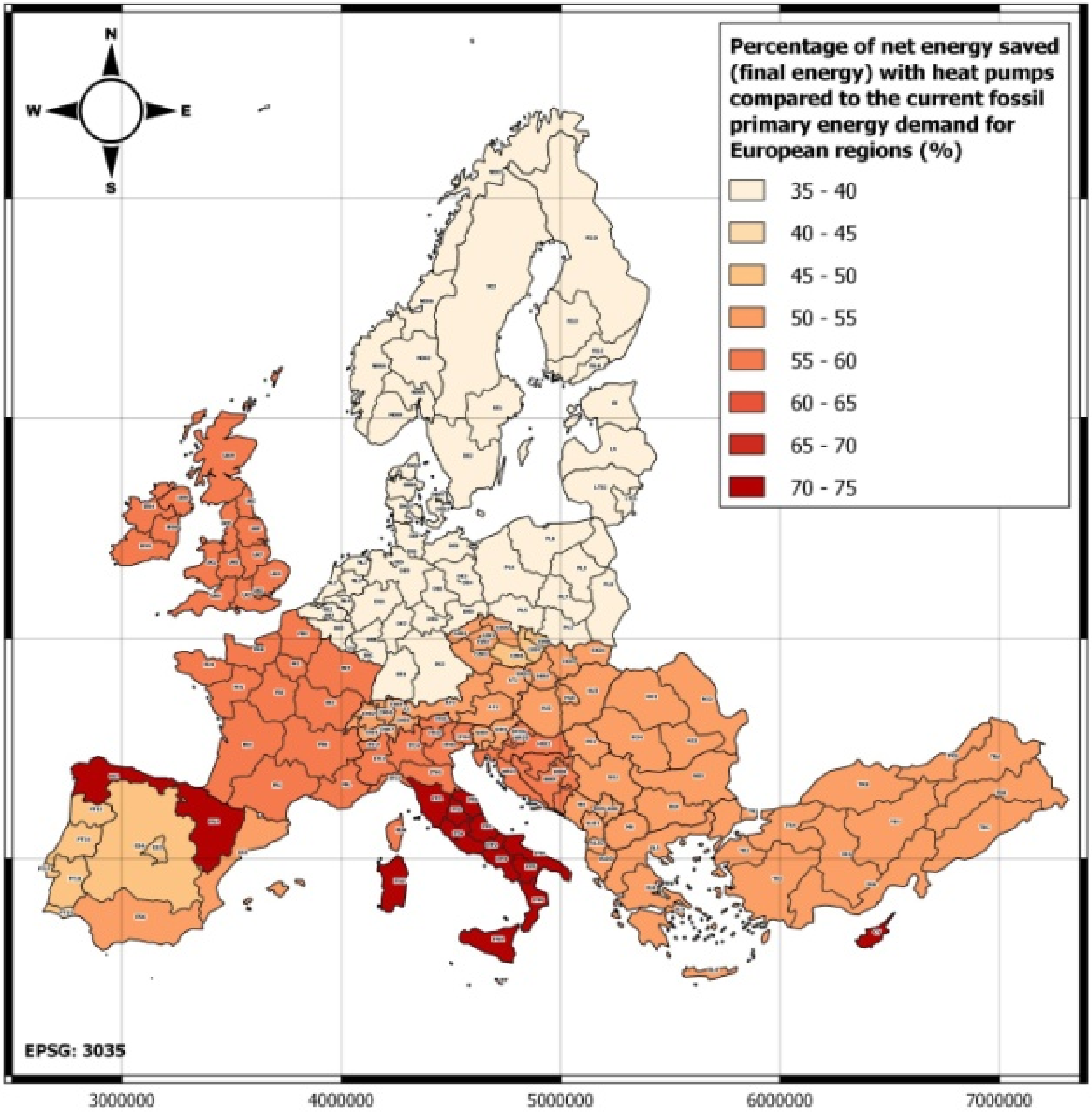


Fig. 13 Percentage of net energy saved compared to the current fossil primary energy demand with heat pumps in European regions

To include other greenhouse gases, the emissions must be considered in terms of CO_{2eq}, therefore the value of 0.237 tCO_{2eq}/MWh was assumed for natural gas, 0.305 tCO_{2eq}/MWh for diesel and 0.375 tCO_{2eq}/MWh for solid fossil fuel [13].

The CO_{2eq} avoided by saving gaseous, liquid and solid fossil fuels was calculated for each region starting from the energy carriers. The amount of CO_{2eq} emitted for each country from the production of electricity for the operation of heat pumps was calculated based on the values provided by a specific website [15], which reports a European average of 279 grams CO_{2eq}/electric kWh.

Fig. 14 shows a significant reduction in absolute terms of CO_{2eq} in southern Germany, the United Kingdom and Turkey. In all 38 countries examined, with the replacement of fossil fuel-fired boilers with electric heat pumps, there is a net reduction of 171.8 million tCO_{2eq}, therefore a 43.7% reduction in CO_{2eq} emissions fossil origin which according to the data collected from the database created are currently 392.7 $MtCO_{2eq}$ for the heating of residential buildings.

Dividing this net reduction of CO_{2eq} by the total number of inhabitants of the 38 European countries covered by this research, equal to 627.5 million, the net annual saving is 0.274 $tCO_{2eq/px}$, which would represent 3.9% of net savings of annual emissions in all activities, overall average value equal to 7 t$_{CO_{2eq}}$/px [14].

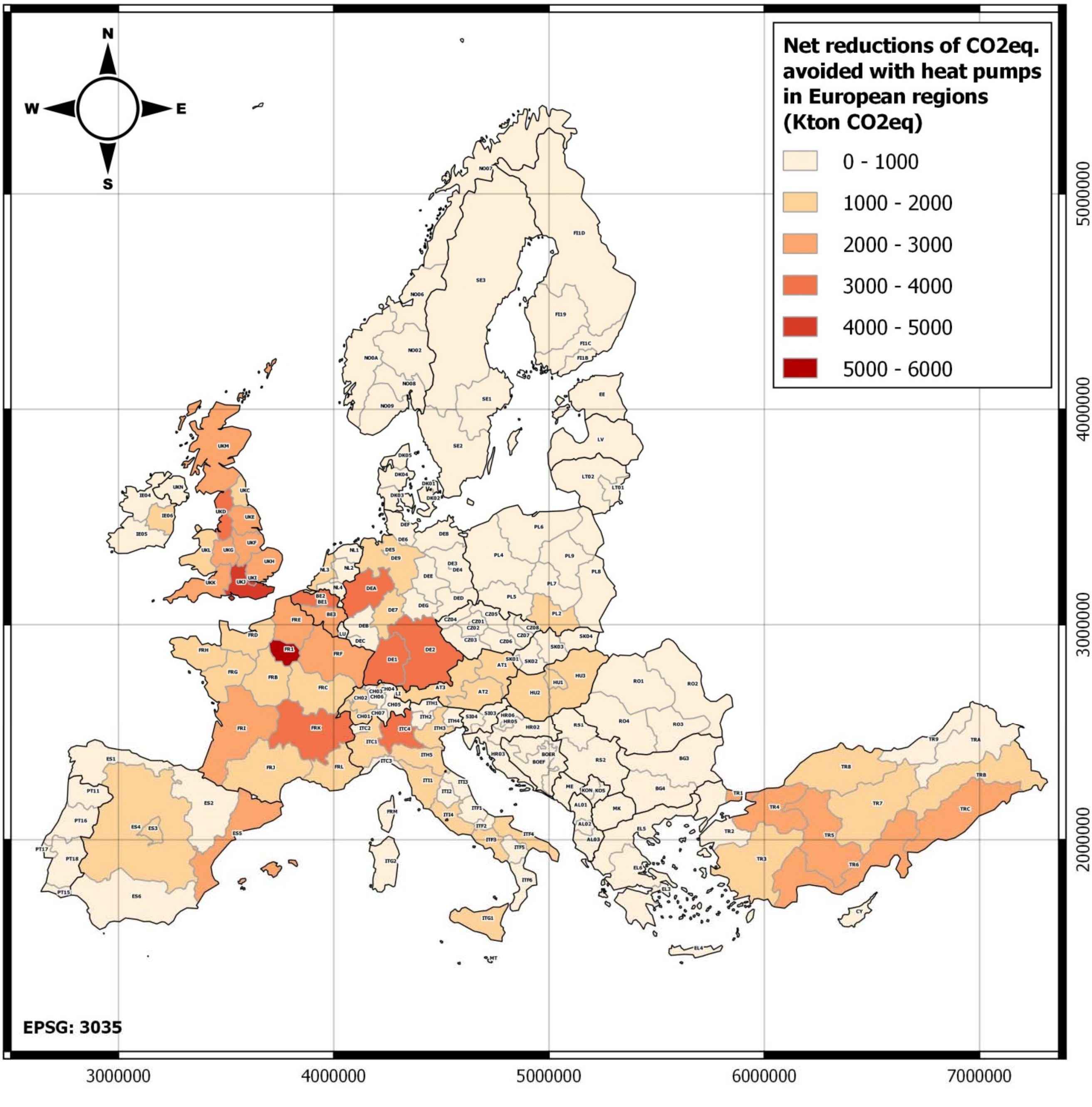


Fig. 14 Net reduction of CO_{2eq}emission avoided with heat pumps in European regions

Once the net value of CO_{2eq} saved was calculated for each region, the percentage value was calculated with respect to the current emissions deriving from the use of fossil fuels (Fig. 15).

Among the 38 countries examined, Albania had the highest percentage and Kosovo the lowest percentage in terms of CO_{2eq} reduction with heat pumps replacing fossil fuel-fired boilers. This result is related to the historic international policy of Albania both in diplomatic and commercial terms; with a lack in primary fossil energy, Albania became energetically autonomous, moving towards available renewable energies, in particular towards hydroelectricity which supplies 95% of the national production of electricity, a figure much higher than that of the other countries examined.

The percentage of CO_{2eq} abatement for the Spanish coastal regions and for the French regions is remarkable.

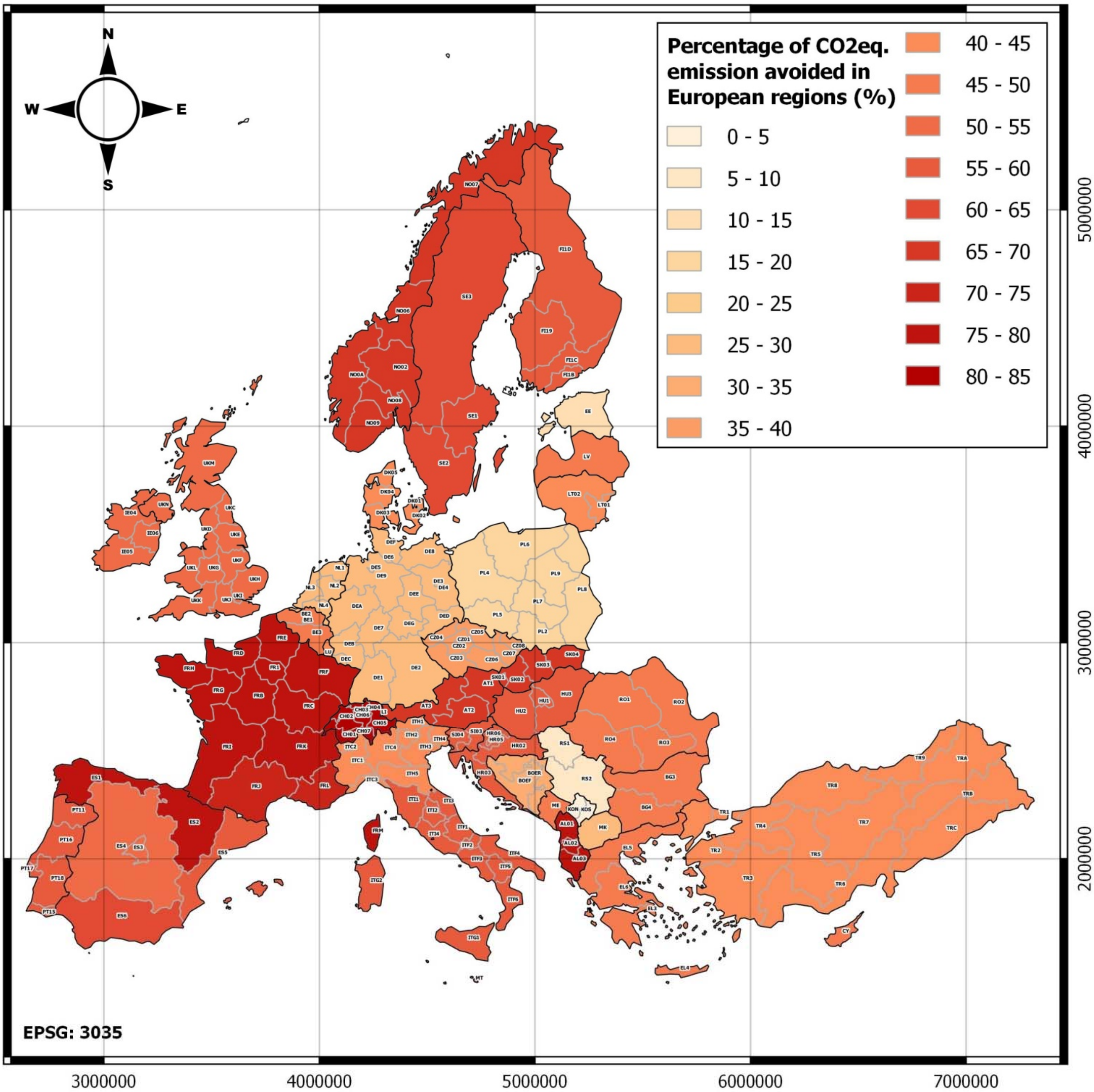


Fig. 15 Percentage of CO_{2eq} emission avoided with heat pumps

V. Discussion and Conclusion

In this work, a preliminary analysis to verify the potential use of high temperature heat pumps for the residential sector in Europe was carried out. The work showed the energy that can potentially be covered by the heat pump in different climatic conditions, in particular for 13 European cities.

The occurrence of the energy demand with respect to the outdoor temperature has been set, using an interpolation to define a linear trend of the energy demand based on the outside temperature. At the same time, the thermal output of a radiator with a climate control strategy was considered in order to find the supply water temperature related to the external temperature. This led to 100% of the thermal energy being covered by heat pumps in La Coruna and 55% in Lodz. On the basis of the technical data of commercial heat pumps on the market, the SPF was calculated.

The energy savings potential of fossil fuels was evaluated regionally according to of the specific climatic conditions and the population. Overall, 550 TWh/year of current energy consumed from fossil fuels could be covered by heat pumps. This would lead to a 195 TWh/year increase in electricity demand for heat pumps.

It should be noted that the majority of European regions, with the simulation of the massive use of heat pumps without modifying the current energy mix object of this research, settle on a percentage close to or greater than 55% of reduction of current emissions of CO_{2eq} deriving from the use of fossil fuels (percentage reduction value to be achieved by 2030 according to the Green New Deal), excepting some regions belonging to Germany, Poland, Holland, Estonia, Serbia and Kosovo, which instead record values lower than this threshold, which in any case could be reached in coordination with other decarbonization actions.

The differences among the European regions, in absolute terms, is mainly given by the number of inhabitants that seems to be the predominant factor. Looking at the percentages comparing the simulations and the current situation, the determining factor for the differences is the different energy mix, both for the production of electricity to supply the heat pumps and for the coverage of the energy demand necessary to provide space heating for buildings.

More work needs to be done, including more detailed analysis to include other climates and also to test potential scenarios with different electricity generation energy mixes.

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