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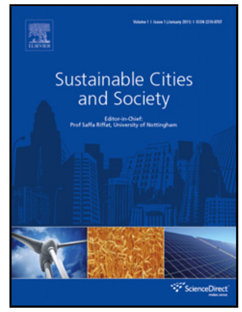

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Energy demands of buildings in the framework of climate change: an investigation across Europe

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Highlights:

- The impact of global warming across the different climates of Europe is explored;
- The energy needs of a residential house located in 19 cities are evaluated;
- Present and future building performance simulations are performed with EnergyPlus;
- Southern Europe will be the most exposed and vulnerable to the global warming;
- The necessity to increase the energy efficiency of buildings is emphasized

Abstract:

Climate change is considered an important global threat, with a significant impact on the energy performance, since buildings will be subjected to higher average outdoor temperatures. This article explores the relative impact of global warming across the different regional climates of Europe comparing present and estimated future energy needs of a hypothetical residential house located in 19 cities characterized by different latitude and Köppen-Geiger class. Building performance simulations with EnergyPlus are performed in order to simulate the heating and cooling needs of the building and the associated CO_2 emissions in the present and in the future. The progressive increase in average temperatures in 2050 and 2080 leads to a general decrease of thermal energy request for heating and to an increase in the demand for electricity for cooling especially in the southern Europe, where high carbon intensity coefficients cause large CO_2 emissions. The resulting vicious circle can be interrupted by increasing the energy efficiency of buildings and properly converting thermoelectric power plants. Results also show that in the future the Mediterranean basin will suffer more than other European areas for phenomena linked to global warming.

Keywords:

energy demands; buildings; climate change; future weather data; EnergyPlus.

○ .

1 Introduction

The Earth is experiencing a rapid climate change whose effects are appearing with an average warming of the atmosphere happening in a relatively short period of time [1,2].

Currently, around 30% of global energy production is earmarked for end-use in the civil sector [3,4]. Specifically, almost 60% of world electricity is consumed in residential and commercial buildings [5]. In the most industrialized countries the energy needs in buildings concern winter heating, summer cooling, domestic hot water production, lighting and household appliances [6].

Energy needs are strongly linked to local weather conditions [7], therefore it can be expected that changes in global and local weather conditions will lead in the future to an evolution of the annual energy requirement for the existing building stock [8]. Buildings will be subjected to new weather conditions that will change the needs of the civil sector in terms of primary energy required [9–11].

The international scientific community dealing with energy demand of buildings is analysing the close relationship between climate change, energy demand and greenhouse gas emissions [12] and the resulting cause-effect loop worsening this situation [13,14]. Many researchers have studied these aspects for different geographical areas. Basically, issues in this type of research can be divided into the following three points: i) the need to create weather files describing the future climate conditions for each location [15,16]; ii) the energy analysis of the buildings needs corresponding to future climate conditions [17,18]; iii) the calculation of the modification of climate-altering gases emissions associated with increasing energy requirements [19].

On the first point, Moazami et al. worked to create a robust dataset of climatic information representing the future climatic conditions, in particular for the city of Geneve (Switzerland), according to the peculiarities of the analysed area and to different scenarios of global warming [20]. The UK Climate Projections 2009 are an example of the probabilistic approach that Kershaw et al. used to create, and then validate, a climate file representative of future conditions for the city of Plymouth in England [13]. Chan has developed future hourly weather files for the city of Hong Kong and calculated an increase of up to 24% of the electricity consumption for cooling a typical building [21]. Shen analysed future energy consumption for residential buildings in 4 US cities representing 4 different weather conditions on the North American continent, through morphing techniques and he estimated increases or decreases in the total annual energy needs according to the location [22]. Zhai and Helman analysed 56 combinations of climate models and emission scenarios to obtain 4 different reference climate scenarios, validated with historical data for 7 climate zones, and they were able to describe the effects of future variations on a typical building [11].

Regarding the second point, Invidiata and Ghisi showed significant percentage increases (even 180%) of the annual energy needs of the buildings considered in three Brazilian cities [23]. Xu et al. conducted similar studies in California, determining a 50% increase in the use of electricity for cooling buildings with respect to the current values [24]. Similarly, Dirks et al. considered more than 100 USA cities, counting new peaks for energy demand and claiming an increasing energy consumption for cooling up to 130%, compared to a much less marked decrease in energy needs for heating [25]. Also, in the USA, Huang and Gurney analysed 925 different locations, identifying discrepancies in energy requirements by up to 20% depending on the different use of buildings of type [9]. Matsuura carried out a study on energy consumption based on projections of future average temperature in 9 USA cities, determined energy increases for cooling and energy decreases for heating and suggested constructing buildings with geometries that can mitigate the negative effects of climatic variations [26]. Li et al. analysed similar problems for the city of Tianjin in northern China, underlining a decrease in heating needs [27].

With reference to the third point, Wan et al. studied 5 Chinese climatic areas in order to identify technological solutions able to counter balance the increase in the buildings energy needs and the consequent emission of CO_2 [28]. Andric et al. analysed the energy needs of 5 locations in Europe and northern Canada, determining the change in energy requirements for future climate scenarios and possible solutions to improve the insulation of the building envelope [8].

The interest towards the topic of the effect of climate change on energy consumption for the heating and cooling of buildings concerns the whole terrestrial globe and this is proved by the high number of scientific studies on different geographical areas (Fig. 1): Europe (Cellura et al. 2018 on the Southern Europe [29], Liua and Coley [30] and Pathan et al. [31] on England, Sabunas and Kanapickas [32] on Lituania, Jylha et al. [33] on Finland, Kočí et al. [34] on the Czech Republic, Cox et al. [35] on Denmark, Hamdy et al. [36] on The Netherland, Dodoo e Gustavsson [37] on Sweden), far East (Shibuya and Croxford [38] on Japan, Li et al. [27] on the northern China [39], Wan and Lam [40] on Honk-Kong), middle East ([41] et al. on Iran), United States (Petri and Caldeira [42], Shen et al [22] Wang and Chen [43]), South America (Flores-Larsen et al. [44] on Argentina, Rubio-Bellido et al. [45] on Chile), Australia (Farah et al. [18]).

While varying in the methodology used and in the geographical area of interest, most of these studies agree in establishing the forecast of a decrease in the heating energy demand and an increase in cooling energy demand [46]. Therefore, studies on building interventions aimed at lightening the summer heat load are essential. For example, Kuo-Tsang and Hwang analysed passive measures to adapt in buildings to counteract climate change in Taiwan [47], while Wan and Lam investigated potential mitigation measures for Honk-Kong.

Also the economic impacts of these changes in energy consumption have been analyzed by Clark et al. [48] which proved that net expenses will decrease in regions where heating demands currently prevail, and conversely, they will increase in regions where cooling demands currently prevail.

1.1 Purpose of the work

Among the potentialities of computing techniques, the predictive simulation of the heat exchange phenomena between the environment and buildings allows engineers to predict future energy needs in the building sector in ever greater detail and precision [49]. In the last few years, software simulating the energy performance of more and more detailed and complex buildings in a dynamic regime, have allowed to face the technological challenge to design increasingly more efficient buildings [50]. Now the attention of the scientific community is shifting towards the prediction of the buildings energy resilience to changes in local climatic conditions due to global warming [51,52]. The scientific community also aims to identify the best energy efficiency upgrading of buildings in order to mitigate the effects of global warming and reduce energy demand and emissions of greenhouse gases to the atmosphere [19,53,54]. This implies also the need of making design choices characterized by greater awareness of future climatic scenarios, in order to modernize the building park in a more efficient way avoiding fuel poverty problems for people with limited economic resources [55]. With the definition of future scenarios on a large scale (and not only at European scale as in this study), taking into account the new energy needs of the building sector [56,57], the costs of energy sources and the modification of the energy mix for the electricity production in each nation due to climate change, the energy production sector and therefore the energy market [55] can be reorganized.

In order to create weather files representative of future climate scenarios, suitable climate models must be implemented [58]. Then, starting from historical meteorological data, annual database files can be created that can be used with dynamic simulation software for the analysis of energy performances of buildings [59,60]. This is possible thanks to the computerization of knowledge provided by climatology and energy engineering [61].

This work aims at assessing the impact of climate change on annual energy consumption for heating and cooling the same building, if located in 19 European cities characterized by different Köppen-Geiger classification [62]. To this end, dynamic hourly simulations were performed for each location with the EnergyPlus software. In particular, the following steps were carried out: i) production of EnergyPlus weather input files representative of the future climate under a predetermined emission scenario in the 19 selected cities, for the years 2050 and 2080; ii) EnergyPlus simulations of the same building sited in the 19 cities using the weather files provided with EnergyPlus for the current climate; and iii) EnergyPlus simulations of the same building sited in the 19 cities using weather files relative to years 2050 and 2080.

In this way, it is possible to study the relative change attributable to climate change on the future energy needs of a building and on the relative carbon dioxide emissions of a building for residential use in Europe. In particular, the choice of using the same building for the 19 cities allows to highlight the impact of the climate change on the energy needs across different Köppen-Geiger climate zones.

2 Methodology

In this work, the dynamic predictive software EnergyPlus was used to evaluate the energy consumption of the same building alternatively located in 19 European cities, selected according to the (different) latitude and the climatic Köppen-Geiger classification [63]. Simulations were carried out on the current climate conditions and on the climate conditions of the years 2050 and 2080 for the 19 locations considered using weather files described in Section 2.4.

The analyzed type building was specifically designed to provide useful information during the energy analysis phase. The 3D geometry was created in SketchUp and through the OpenStudio tool it was provided as input to Energyplus.

2.1 Computation of energy needs through EnergyPlus

The EnergyPlus software was developed by the US Department of Energy [64] for the simulation of the entire building envelope/plant in an annual dynamic regime. EnergyPlus is an open source software that allows an in-depth analysis of all the phenomena of heat exchange affecting a building of particular architectural and plant complexity and has become a point of reference for the international scientific community studying the energy performances of the buildings [65]. 3D geometries can be created using SketchUp [66] modeling software and imported into EnergyPlus after defining with OpenStudio [67] the characteristics of the thermal zones on which to set up calculations for exchanges of heat with the external environment.

2.2 Study building

A residential building consisting of three floors and three apartments for each floor was taken as a case study. The first floor is raised on pillars with respect to the ground; the intermediate level exchanges heat towards the outside only through its vertical infill panels; the upper floor is characterized by a flat roof. The air-conditioned interior floor area is 765.6 m^2. The height of each floor is 3 m. Two apartments have a common border area, while the third apartment totally adjoins the exterior or the landing and the stairwell that are unheated. Fig. 2 shows the plan of a plane, a 3D and the geographic orientation of the building.

The building is heated by radiators connected to a condensation boiler powered by natural gas and characterized by efficiency of 104.8% and 107.2% when the nominal power is equal to 100% and 30% respectively. Cooling takes place through split-type steam compression refrigeration systems characterized by C.O.P. equal to 3.1. To simulate the activation of the plants and calculate their energy requirements, an internal temperature has been assumed: i) greater than 18 °C, in heating; ii) less than 26 °C, in cooling [68]. The ventilation of the rooms is natural [69], with a turnover equal to 0.5 hourly volumes. Internal thermal loads are assumed to be equal to 38 W m^{-2} [70,71].

Properties of materials of building envelope surfaces are summarized in Tab. 1.

2.3 Geographic area

This study takes into consideration 19 different European cities. The geographical sites have been chosen according to: i) the latitude, on which the solar radiation depends; ii) the climatic Köppen-Geiger class [63]. According to the Köppen-Geiger classification, the European regions investigated are characterized by: 4 main climates (B - arid; C – temperate; D - continental; E - polar); 3 subgroups (S - steppe; f – fully humid; s – dry summer); 4 tertiary groups (a - hot summer; b - warm summer; c - cool summer; k – cold arid).

The selected cities, together with their State, latitude, climatic class and carbon intensity are listed in Tab. 2. The last column of Tab.2 shows the values of the "carbon intensity" for the 19 cities. It is hypothesized that the amount of carbon dioxide produced for the generation of electricity is constant over time and refers to current values, in order to highlight the effect of the variations in the climatic conditions [72]. The emission of carbon dioxide due to the combustion of natural gas is equal to 0.1842 $kg(CO_2) \cdot kWh_{thermal}^{-1}$.

Fig. 3 shows the geographical location of the 19 cities analyzed in this article, along with the latitude and the Köppen-Geiger classes.

2.4 Weather data

The EnergyPlus software needs to load a weather file (.epw format) containing hourly weather information of a typical year for the selected location. Such format is text-based with comma-separated data [73]. The data include parameters identifying a specific location (e.g. name, data source, latitude, longitude, time zone, elevation, peak design conditions, holidays, daylight saving period) and meteorological variables, that is dry bulb and dew point temperature, relative humidity, station pressure, solar radiation (global, extraterrestrial, horizontal infrared, direct, and diffuse), illuminance, wind direction and speed, sky cover. All the data are in SI units.

In this work two kinds of weather files are used for simulations with the EnergyPlus software: i) the weather files available in the EnergyPlus database for the “current climate” simulations and ii) the “climate change” weather files for the “future climate” simulations produced with the Climate Change tool World Weather file Generator[74].

2.4.1 “Current climate” weather data

The “current climate” weather file includes data “typical” of a specific location, resulting from hourly observations acquired by the designated meteorological service, typically in airport areas adjacent to the location.

According to the definition provided by the National Renewable Energy Laboratory (NREL), “a typical meteorological year (TMY) is a data set of hourly values of solar radiation and meteorological elements for a 1-year period. It consists of months selected from individual years and concatenated to form a complete year. The intended use is for computer simulations of solar energy conversion systems and building systems”. It is derived from the 1961-1990 National Solar Radiation Data Base, using a methodology similar to that developed by Sandia National Laboratories (Hall et al. 1978).

The National Renewable Energy Laboratory (NREL) of the US Department of Energy (DOE) provides online a comprehensive ("Weather Data | EnergyPlus") climate database that includes more than 2,100 geographic locations all over the world, of which almost 200 in Europe. It is available at the EP website [75].

As specified above, EP weather files include data acquired at airports and this makes them typical of a rural area. This aspect is crucial when the files are used in big cities, where the difference between the weather conditions in the urban area and in the non-urban surrounding areas are significant due to the urban heat island phenomenon. Ciancio et al. 2018 [7,76] showed that the use of EP files determines an underestimation of the cooling energy needs close to 50% for a building located in the center of Rome. However, in this context the contribution of the urban context to energy contributions has not been assessed as it is beyond the objectives of the work.

2.4.2 "Future climate" weather data

Similarly to standard input weather files for EnergyPlus, climate change weather files include 8,760 hourly values of the weather variables for each location. Climate change weather files were produced through the CCWorldWeatherGen tool for 2050 and 2080 and all the 19 selected locations.

The "CCWorldWeatherGen" is a Microsoft® Excel based tool, available free of charge, developed in the frame of a joint project between the Sustainable Energy Research Group at the University of Southampton and the Department of Mechanical Engineering at the University of Malaya in Kuala Lumpur [17]. It transforms original EnergyPlus weather files to "climate change" weather files by means of a so-called "morphing" procedure [77], using outputs from UK Hadley Centre Coupled Model (version 3, HadCM3), a General Circulation Model (GCM) assessing the climate change. Together with the original EnergyPlus weather files for the selected location, therefore the CCWorldWeatherGen tool has to be provided with the output of the HadCM3, that is the weather data representative of the future. Weather parameters included in HadCM3 files data are: temperature (°C), maximum and minimum temperature (°C), total incident solar radiation (W/m^2), total downward surface shortwave flux (W/m^2), total cloud in long-wave radiation (fraction), total precipitation change (%), relative humidity (fraction), mean sea level pressure (hPa), wind speed change (%).

Since HadCM3 data (as in general GCM data) are provided at spatial and temporal resolution coarser than resolution used for simulating energy needs of buildings, a downscaling is needed and in this work the "morphing" procedure is applied. It is essentially an adjustment of the "present-day" EP weather file based on the climate characteristics of future decades (2050 and 2080) according to the HadCM3 model, in the four grid points closest to the chosen location in accordance with the IPCC recommendations [78]. It includes two main steps: the computation of monthly means of the weather variables, acting as the climate baseline, and the application of three "morphing" operators to these monthly means. More Details on the procedure are provided in [79]. The "morphing" method used in the "CCWorldWeatherGen" slightly differs from the original one, developed in the early 2000s for the United Kingdom and the UKCIP02 model, that quickly spread becoming in those years the most used approach for building performance simulation there [80]. According to the developers of the "morphing" procedure, it has the limitation that morphed files keep the character and variability of the present-day climate, while the future climate may have a different character. On the other side, this method is simple and adaptable to different climate change scenarios, as well as reliable [79]. For what concerns the HadCM3, it was developed in 1999 and was one of the major models used in the IPCC Third and Fourth Assessments, and also contributes to the Fifth Assessment. It has a horizontal resolution of 2.5° x 3.75° (latitude x longitude), that is a global grid of 96 x 73 cells. This corresponds to a surface resolution of about 417 km x 278 km at the Equator, and of 295 km x 278 km at 45° of latitude [81]. HadCM3 data are provided with as monthly values for the present climate baseline (1961-1990, as recommended by the World Meteorological Organization) and for two future time segments (2050s, 2080s). It is available for free download on the web, and corresponds to the A2 emissions scenario (more properly, the A2 scenario family) of the IPCC Third Assessment Report. According to the IPCC definitions, such scenario family is characterized by "a very heterogeneous world with continuously increasing global population and regionally oriented economic growth" more fragmented and slower than in other scenarios [82]. For further details on the tool and the CCWorldWeatherGen tool see [83].

3 Results and discussion

In this section results of the simulations with EnergyPlys are illustrated and discussed. Results are discussed in terms of: i) monthly average air temperature, ii) peak power required by the heating and cooling systems, iii) annual number of operation hours, iv) total amount of energy consumptions, v) hourly average energy consumption with relative standard deviation. Note that the "current climate" label refers to the simulations based on the weather files available on the official EnergyPlus website, while the "2050" and "2080" labels are assigned to the simulations based on "future climate" weather files for the year 2050 and 2080 respectively.

Figure 4 shows the current monthly average air temperatures (labeled “current climate”) for the 19 cities considered in this study and the temperature increase in 2050 and in 2080 compared to the current climate simulation. Current temperature data have been extracted from the “current climate” weather files driving EnergyPlus simulations, while 2050 and 2080 temperatures data have been extracted from the “future climate” weather files. As far as the values of temperature differences, in 2050 they are in the range between 1°C and 5°C, while in 2080 they are in the range between 2°C and 9°C. It can be observed that both in 2050 and 2080 the temperature delta for some cities (e.g. Aberden, Belfast, Copenhagen, Palermo) is almost uniform during the year, while for other cities (e.g. Clemont-Ferrand, Plovdiv, Granada, Salamnca) this delta is higher during the central months of the year, especially July and August. This behavior is more evident in 2080 and cannot be connected with belonging to a climatic class rather than another, nor to latitude. The cases of Cluj-Napoca and Plovdiv require special attention because they have the highest delta temperature values in 2080; in particular, Plovdiv has high temperature delta values both in July and August. Belfast instead is the city with the lowest delta temperature values.

The temperature trend strongly influences the peak powers required by the plants during the heating and cooling periods. Fig. 5 shows the maximum powers (or peak powers) required both for heating (in red) and cooling (in blue) for each year and for each city, on which the size of the power of the plants depends. It is possible to observe the decreasing trend of peak power for heating and the increasing trend of peak power for cooling and that these trends are not equal for the time slice current climate - 2050 and the subsequent slice 2050 – 2080, with values generally slightly higher for the first slice. Moreover, it can be observed that the temporal variations of peak power are more accentuated for cities characterized by more extreme climatic conditions, such as Clermont-Ferrand, Göteborg and Paris (in Northern Europe) for heating and Pescara, Rome or Salamanca (in the Mediterranean area) for cooling.

The comparison between Milan and Aberdeen is interesting: in the present Milan has a peak power for heating slightly greater than that of Aberdeen (24.3 kW versus 23.1 kW), but it has a peak power for cooling much higher than that of Aberdeen (20.6 versus 0.1). In 2080 the peak cooling power in Milan will double compared to the present, while in Aberdeen it will increase about 100 times. The interpretation of these results is that the two cities currently have a similar winter, while summers in Milan are much warmer than in Aberdeen. From now until 2080 summer weather conditions will change more significantly in Aberdeen than in Milan, while summers in Aberdeen remain cooler than in Milan.

Power requests are associated with the number of operating hours of the plant for heating or cooling the simulated building. Fig. 6 shows the number of operation hours for heating and cooling in the current climate simulation and in years 2050 and 2080, as computed through the EnergyPlus simulations. The trend already observed for the peak powers is confirmed: i) the amount of operation hours of the boiler for heating decrease for all 19 cities studied; in particular in Granada, Palermo and Porto this value in 2080 becomes so low as not to justify the investment for the installation and maintenance of heating systems in buildings; ii) the operating hours of the cooling system increase; as expected, this increase in hours is considerable in cities like Palermo, Granada or Rome (southern Europe), but it is also significant in geographical areas characterized by a continental climate (such as Plovdiv). In cities such as Aberdeen, Copenhagen, Gothenburg, London and Prague this amount becomes so important that it is necessary to install of cooling systems (if not present) necessary to ensure comfort conditions in buildings.

The requested power and the number of operating hours of the plants are linked to the annual energy consumption, shown in Fig. 7 and in Tab. 4. In particular, in Fig. 7 the energy consumption (in kWh per year) for the air conditioning of the same building in the 19 cities is represented by bars (red bars for heating, blue bars for cooling) for the current climate simulation and the years 2050 and 2080.

The few geographical locations that in the current climate simulation present the coldest winters (such as Cluj-Napoca and Gothenburg, with average temperatures below 0°C) have milder seasons in 2050 and 2080. Some Mediterranean locations, such as Granada and Palermo, have extremely high average temperatures in the summer months (which in 2050 go well beyond 30 °C). Some cities in northern Europe (e.g. Aberdeen or Belfast) do not have large needs for summer cooling of the building as they have relatively cool summers. And since heating needs are there cut due to climate change, the annual energy needs are reduced. All this leads, in general, to a lower consumption of thermal energy for winter heating and to an increase in the demand for electricity for summer cooling through the steam compression refrigeration machines.
From the annual energy consumption values in Table 3 it can be seen how the energy needs of the countries in Northern Europe will approach those of the countries at lower latitude: for example, in 2080 the energy consumption for the heating a building in Aberdeen will be approximately equal to that of Salamanca in the current climate simulation and that of Copenhagen in 2080 approximately equal to that of London in the current climate simulation. Still, the energy consumption for heating the analyzed building in the city of Berlin in 2080 (19,985 kWh) will be close to that computed for the same building if located in Pescara with the current climate conditions (18,441 kWh). As regards cooling, the city of Cluji-Napoca will reach energy consumption values of around 17,000 kWh in 2080, very close to that of Salamanca, although starting from a lower value (1,770 kWh versus 2,298 kWh).

Furthermore, in several cities (Berlin, Bordeaux, Clermont-Ferrand, Cluji-Napoca, Milan, Paris, Porto, Salamanca) in Central Europe, more energy will be consumed in 2080 for cooling than in Rome currently. The city of Belfast is the only one that has a value of energy consumption equal to zero for cooling in the current climate simulation and in 2050. On the other side, the total energy consumption (sum of heating and cooling energy needs) in 2080 is higher than in other cities located further south, such as Berlin and Prague. This is due to the contribution of the energy needs for heating.

Using energy consumption, it is possible to calculate the average hourly value during the hours when the plants are switched on, for each of the 19 cities in the current climate simulation and in years 2050 and 2080 (Fig. 8).

This data provides information on the trend of average hourly consumption (in kWh), indicative of the average energy intensity of the plant during its operation. In fact, a plant could have a short and intense use (therefore a high average annual energy consumption), or a long and low consumption (therefore a low average annual energy consumption) despite having the same annual energy consumption.

Together with the average value of the hourly energy consumption, it is advisable to take into account the standard deviation (in kWh) with respect to the average value requested. This parameter represents the dispersion of energy needs during the entire period of operation of the plant, in other words the discontinuity of consumption which is linked to the variability of external climatic conditions and therefore to the temperature range.

The first thing that can be deduced from Fig. 8 is that the variation (decrease) of average annual consumption for heating is much lower than the variation (increase) of average annual consumption for cooling. For example, in Goteborg and Palermo (characterized by extreme values of average annual consumption in the current climate simulation, for both heating and cooling), the average annual consumption increase for cooling between the current climate simulation and 2080 is very different (around 700% and 16%, respectively) while the decrease for heating is of the same order of magnitude (about -20% and -30% respectively). The variation in the value of the standard deviation between the current climate and 2080 is also very different, in fact it is about 20% for both cities for heating, while for cooling it is about 250% for Gothenburg and about 90% for Palermo. The city of Plovdiv has the highest standard deviation in the current climate simulation and in 2080 it retains one of the highest values (after Palermo and Pescara). These values are significant for the evolution of the climate and consequently of the energy needs and the use of air conditioning systems. In particular, the fact that the standard deviation during the winter varies little between the present and 2050 means that the characteristics of the season with respect to extreme cold events will not vary significantly; on the contrary, the fact that during the summer season the standard deviation increases significantly means that of 2050 and 2080 the frequency and intensity of heat waves will increase. So not only will the required peak power increase, but the distribution of the use of cooling systems will also vary.

Consistently with what has been observed above regarding the hours of operation of the plants and energy consumption, it is not possible to identify a common behavior of the cities depending on the climate class to which they belong or the latitude. For example, the cities of Bordeaux and Pescara (respectively in Cfb and Cfa K-G classes) have similar values of energy consumption for heating, number of hours of operation, same average hourly consumption and similar standard deviation. The same can be said of other couples in cities like Milan and Prague (respectively in Cfa and Dfb K-G classes) and Berlin and Paris (respectively in Dfb and Cfb K-G classes).

Annual CO_2 emissions respectively for cooling and heating the studied building are computed multiplying the annual energy consumption (in Fig. 7) for the carbon dioxide emission coefficients due to the production of electricity (fifth column of Tab. 2, corresponding to the national energy mix of each State) or to the stoichiometric combustion of natural gas. 10 and Tab. 4 show that there are three opposite trends in terms of annual carbon dioxide production in the future and the 19 cities can be divided into three groups according to their trend.

To compare the results of the three climatic scenarios considered, the hypothesis of a constant carbon intensity [kgCO2 $year^{-1}$] is assumed. That is, the current value of the carbon intensity for each country is applied also for the future decades.

The first large group consists of cities with a cold climate (Aberdeen, Belfast, Bordeaux, Clermont, Copenhagen, Gothenburg and Paris), where emissions tend to decrease globally; the second large group is made up of cities (Berlin, Granada, Milan, Palermo, Pescara, Plovdiv, Porto, Rome and Salamanca) where CO_2 emissions tend to increase. The behavior of these two groups can be explained as follows: i) the decrease in energy demand for heating favors the reduction of CO_2 emissions; ii) reduced cooling needs for the northern Europe locations, associated with their low carbon intensity coefficients, correspond to little carbon dioxide emissions for cooling; ii) large quantities of electricity for cooling in the cities of southern Europe, associated with their high coefficients of carbon intensity, give rise to the production of CO_2. The third, small, group of cities is formed by Cluj-Napoca, London and Prague and shows a decrease in annual CO_2 production from the present to 2050 and a trend reversal from 2050 to 2080. This is because in the medium temporal term there is an important decrease in energy needs for heating in the winter months, but these savings are counterbalanced by a large increase in electricity for summer cooling. It can be deduced that the decrease of natural gas demand for winter heating at many sites is neutralized by the increased demand for electricity (for summer cooling). Since to date only France, Sweden and Denmark have a value of the carbon intensity related to electricity generation lower than CO_2 emissions related to natural gas combustion, the trend observed above involves the increase in the emission of greenhouse gases into the atmosphere. Therefore, it is necessary, for the purpose of climate change mitigation, to find more environmentally friendly solutions such as the conversion of large thermal power plants for electricity generation.

4 Conclusions

In the last 20 years major efforts haves been made to reduce energy consumption in the building sector, especially for private homes for residential use. The owners energetically redevelop the apartments little and very slowly and the old buildings are not replaced by more modern and efficient buildings. Long awareness campaigns have been conducted, but it is not enough. In the meantime, in fact, the global climate is undergoing major changes and the expected future warming of the Earth surface will lead to new scenarios.

Focusing on the European scene, in the next 60 years the homes will change their energy demands according to climate changes and the geographical position will play an important role in this evolution of energy needs. In fact, the energy needs linked to winter heating tend to decrease, while consumption related to summer cooling are expected to increase, especially in southern Europe. This will result in a reduction in the quantity of fossil fuels (such as natural gas) combusted for heating and, at the same time, in the increase in electricity demand used to power compression refrigeration machines.

In this study, 19 European cities belonging to different Koppen-Geiger climatic class and located at different latitude were examined. Thanks to the CCWorldWeatherGen tool it was possible to create the EnergyPlus input weather files for the 19 selected cities and the future years 2050 and 2080. The EnergyPlus simulations of the same building using alternatively the "current climate" and the "future climate" weather files and the subsequent analysis produced significant results for achieving the aim of this work.

This study is based on a quantitative analysis of the energy needs of a specific building, taken as a case study. Its energy needs for heating and cooling are compared for different climatic scenarios and geographical locations thanks to the assumption of a building with the same technological characteristics. It was therefore possible to analyze the energetic behavior of the building in question as the weather conditions vary, depending on the geographical area and on the future climatic scenario due to global warming.

A preliminary analysis of the results shows that the response of cities to climate change is not linked either to the climate class to which they belong or to latitude. Clearly this response is linked to a combination of the two factors. Therefore, a comparative analysis was carried out between the 19 cities, without groupings based on the climatic class or latitude.

This study highlighted how the future climate change, compared to current conditions, could lead to a decrease in the winter heating requirement of northern European cities such as Aberdeen (-31% in 2050 and -45% in 2080), Gothenburg (-24% in 2050 and -36% in 2080) and Copenhagen (-28% in

2050 and -41% in 2080) and an increase in the summer cooling requirement of southern European cities such as Rome (+143% in 2050 and +272% in 2080), Palermo (+70% in 2050 and +142% in 2080) or Granada (+129% in 2050 and +238% in 2080). Comparing the energy demands of 2080 with the present one and taking into account all the examined European cities at the same time, the increase in energy needs for cooling will be higher than the decrease in energy needs for heating. Therefore, this would increase global energy consumption.

For each city and scenario, the following quantities were analyzed: i) the peak power required to meet the most heavy operating conditions for the plants during the year; ii) the annual total and average energy consumption; iii) the annual operation duration (in hours) of the heating and cooling systems. For all these quantities, the same trend is observed for the three scenarios (since current climate to future climate), i.e. a decrease in energy needs for heating the analyzed building and an increase in energy requests for cooling it.

The analysis of peak power and energy consumption values shows that the energy needs of northern European and central European cities will approach those of Mediterranean cities in the coming decades (e.g. Aberdeen or Berlin). The decrease of the peak power is generally higher for the time slice present-2050 than for the time slice present-2080 and the differences in time are higher for cities characterized by coolest winters and warmest summers.

With the change in the number of operation hours, the opportunity to install or not the heating and cooling systems may vary. In fact, for some cities in southern European (Palermo, Granada or Rome) the small number of operation hours makes the installation of heating systems unnecessary, while for other cities (Aberdeen, Copenhagen, Gothenburg, London and Prague) the increase in the number of operation hours of cooling systems makes it advisable to install the cooling systems.

The significant increase in the standard deviation of average hourly consumption reflects the prediction of the increase in frequency and intensity of heat waves due to climate change. In this sense, studies investigating advantages and disadvantages of using mitigation strategies as high albedo materials become crucial [84].

Assuming that the current carbon intensity coefficients are conserved in the future, European countries producing electricity mainly from fossil fuels will contribute to increasing the levels of greenhouse gases in the atmosphere, responsible for the increase in the average temperature of the earth. This vicious circle can be interrupted mainly thanks to two different strategies to be implemented on a large scale and thanks to appropriate investments: i) increasing as much as possible the energy efficiency of the existing building stock; ii) converting large thermal power plants to supply sources with reduced emissions of climate-altering species into the atmosphere.

The results presented here made it possible to quantify the exposure of different European areas to global warming and southern Europe turned out to be the most vulnerable. The issue will be especially heavy for buildings used as residences for the elderly (the European population is gradually aging and the public expense of many countries will grow consequently) and for care homes for people with health problems. Using the same building for the whole of Europe has made it possible to focus on the effect of the climatic variable and at the same time makes this work a first step in the study of the risks to which the European territory is exposed in the framework of climate change. The specificity of the constructions of each individual country must be included in such a line of research, therefore a future development of this work should take into account the variation of construction types across the continent.

Global warming represents a major challenge for each country for the future energy supply of the existing building park. Taking into account the climatic evolution of the next decades implies complex choices. From this point of view, the optimization computational techniques, such as genetic algorithms, seems to be a decisive tool in designing new buildings or redeveloping existing ones with the aim of obtaining better and truly optimized energy performances for future scenarios [85].

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Conflict of Interest

None

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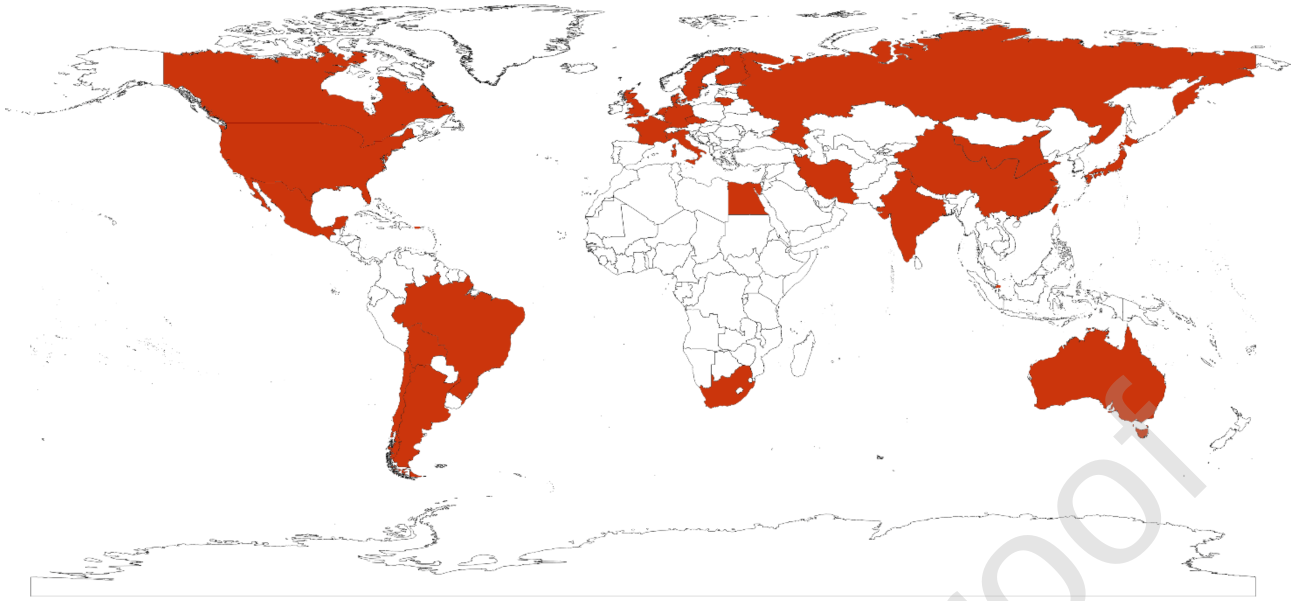

Fig. 1 – Geographical areas subject to scientific research on the effects of climate change on the energy needs of buildings.

Figure 2: Analysed building: standard floor and three-dimensional representation.

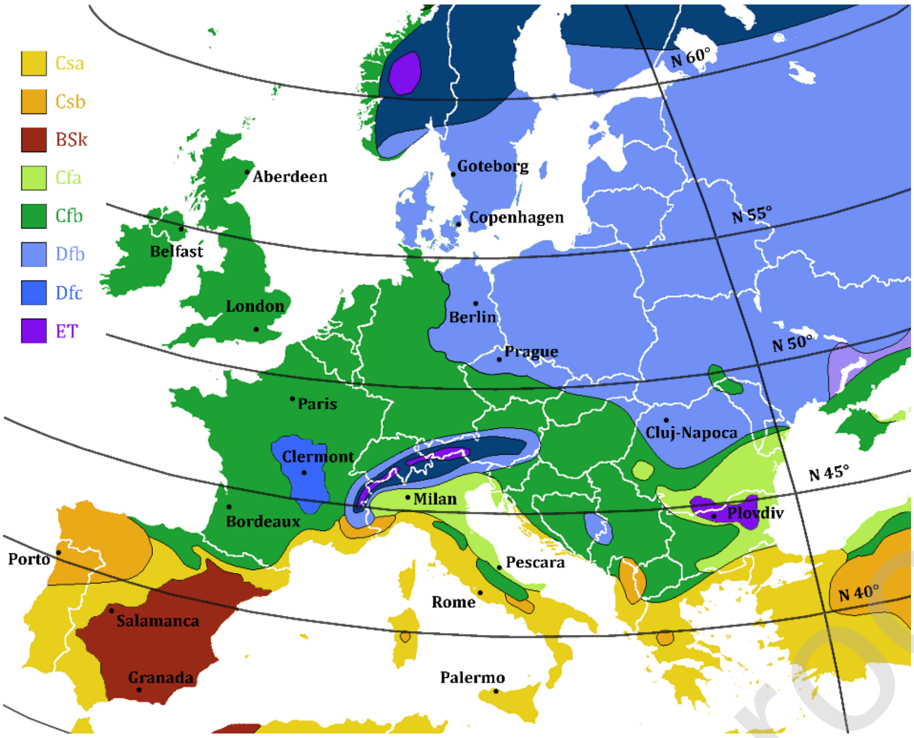

Fig. 3 – Geographical location of the 19 cities. Different colors indicate different Köppen-Geiger classes.

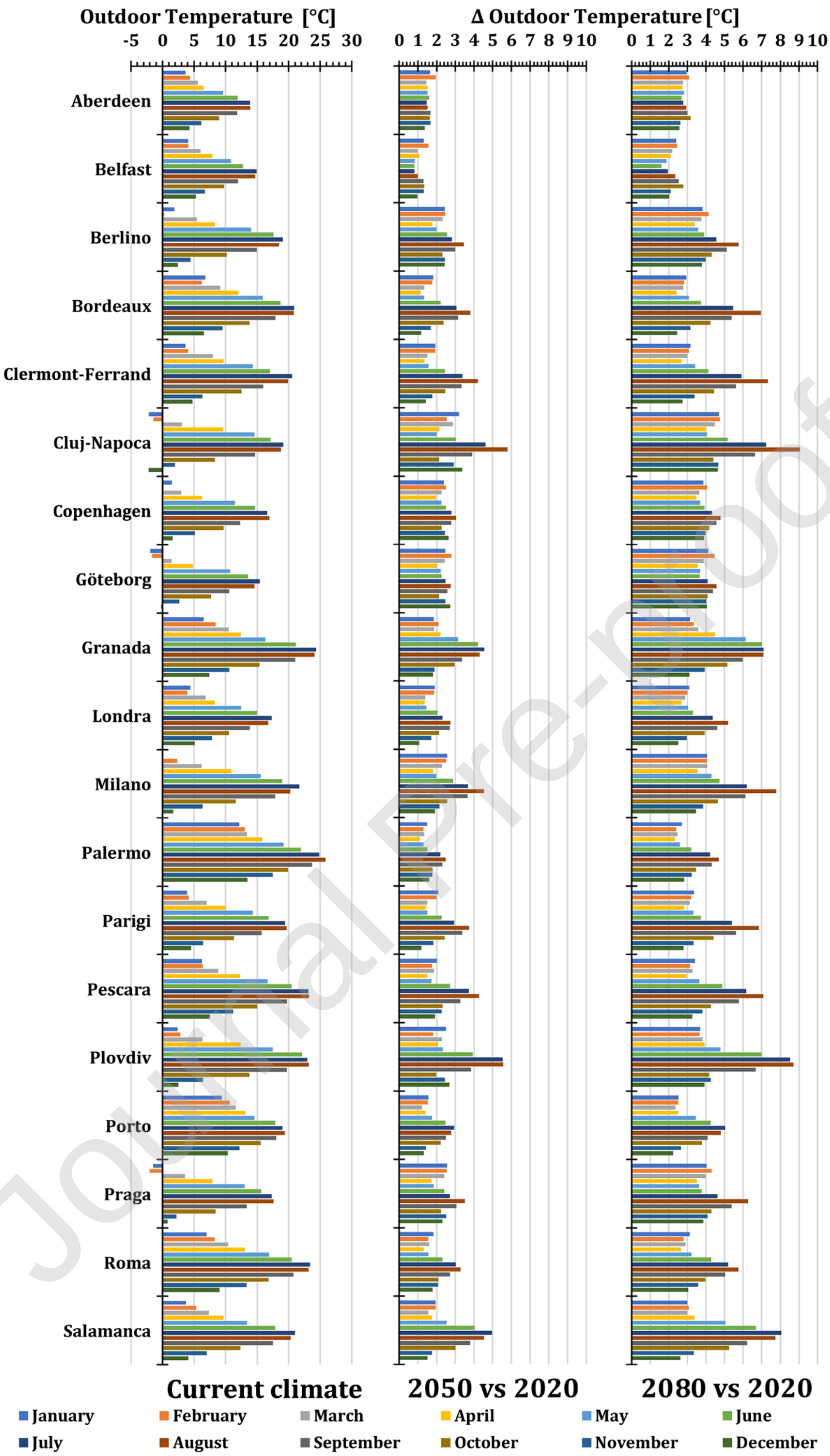

Fig. 4 - Mean monthly temperatures for the considered cities in the current climate simulation and in years 2050, 2080.

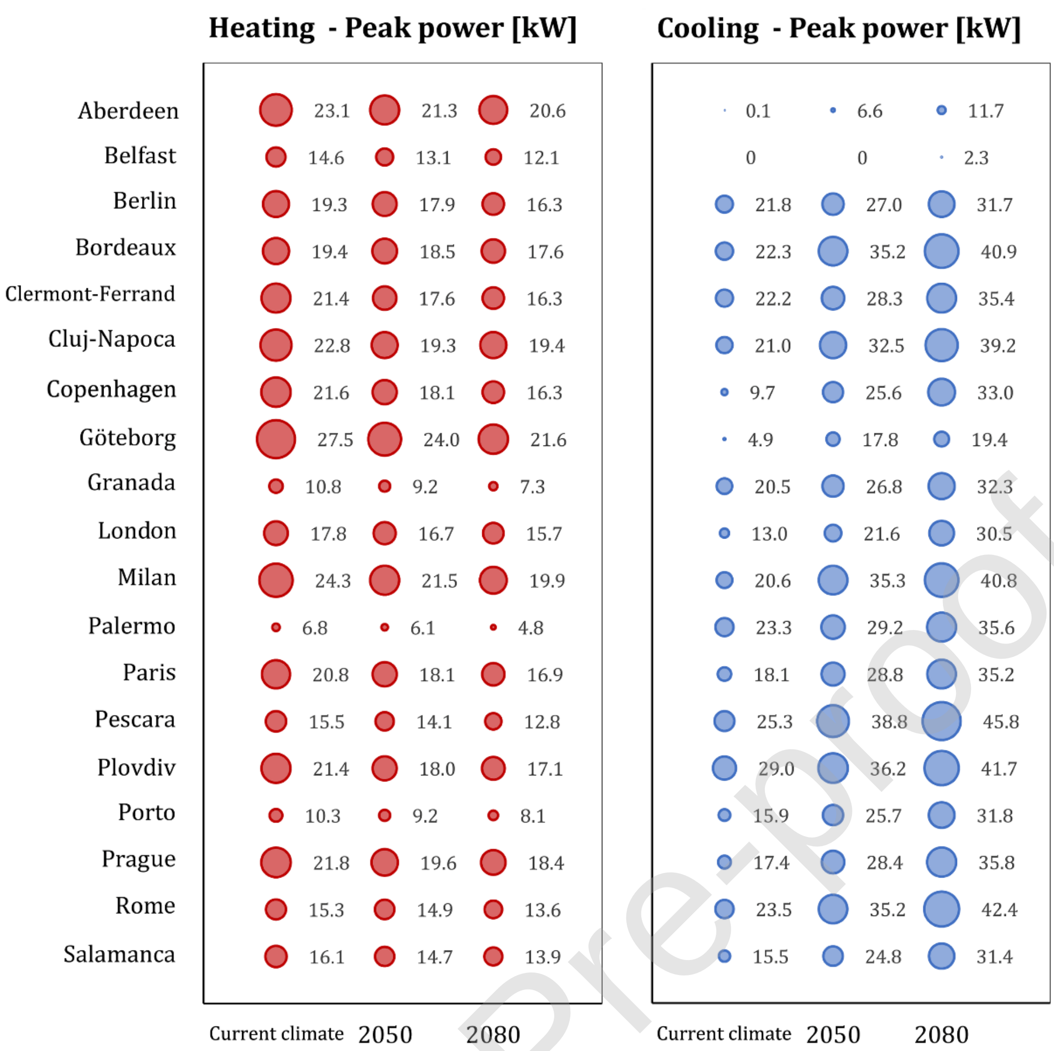

Fig. 5 – Peak power [kW] for heating (on the left) and cooling (on the right) in the current climate simulation and in years 2050 and 2080.

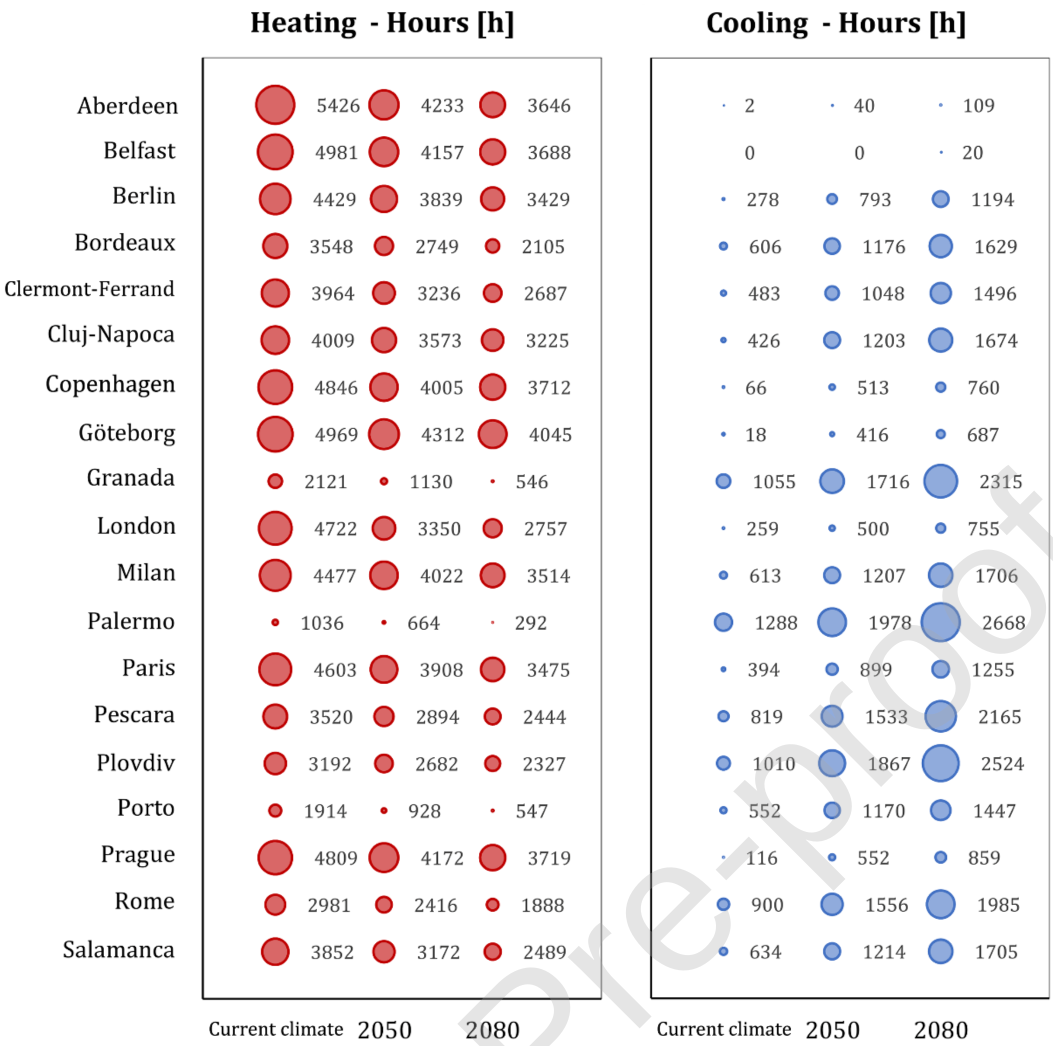

Fig. 6 – Duration of operation [h] for heating (on the left) and cooling (on the right) in the current climate simulation and in years 2050 and 2080.

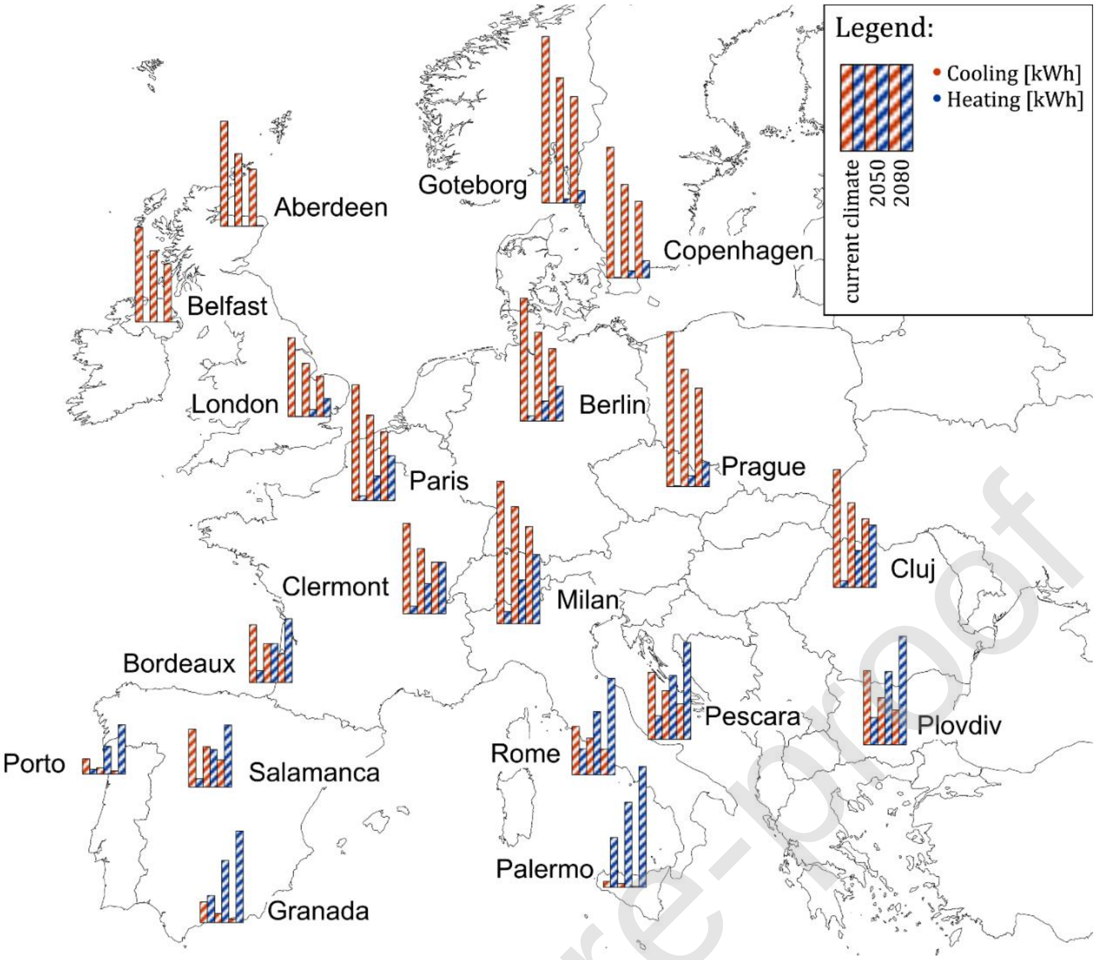

Fig. 7: Annual energy consumption (kWh per year) for heating (red bars) and cooling (blue bars) the same building in the 19 cities studied for the current climate simulation and the years 2050 and 2080. Values are displayed in Tab. 4.

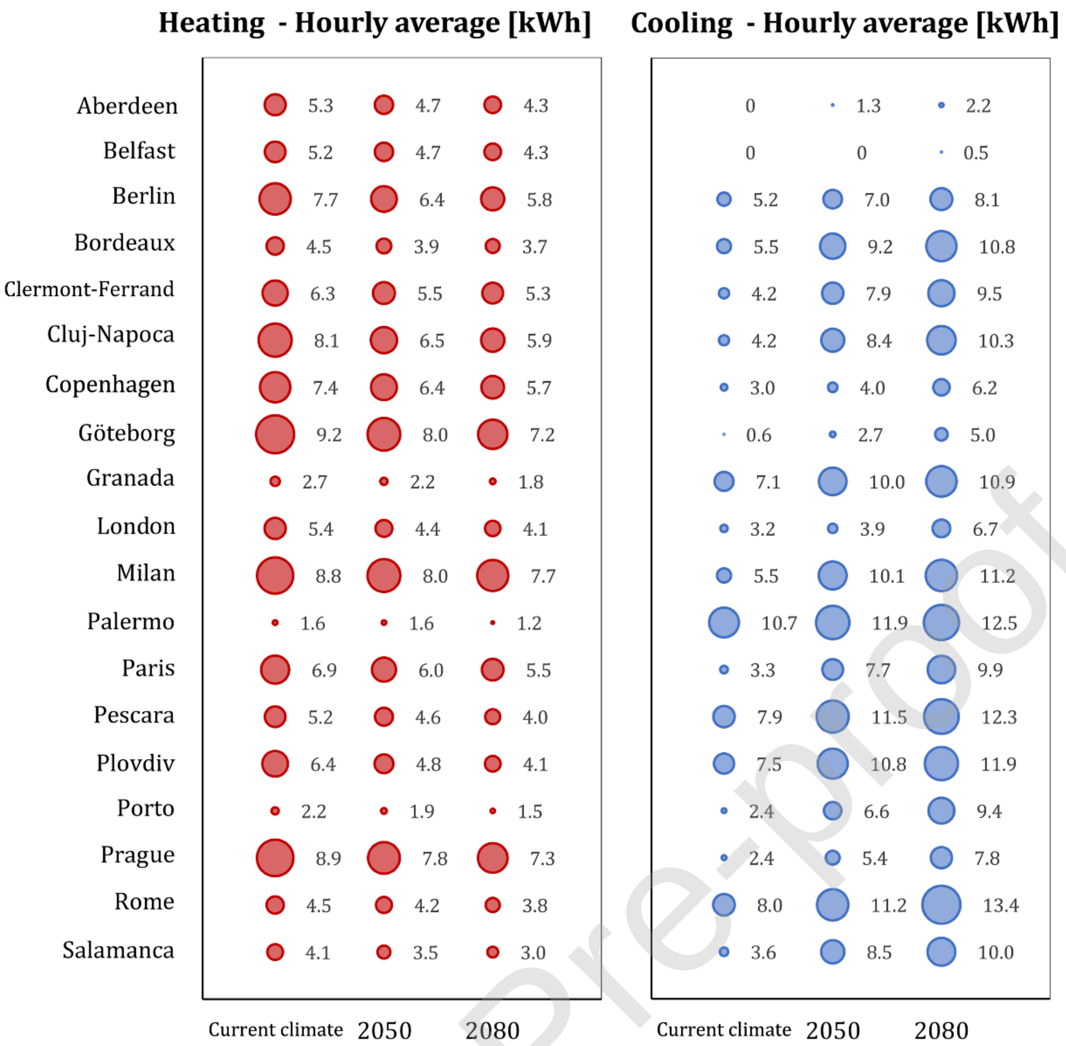

Fig. 8: Hourly average energy consumption (kWh) for heating (in red on the left) and cooling (in blue on the right) the same building in the 19 cities analyzed for the current climate simulation and the years 2050 and 2080.

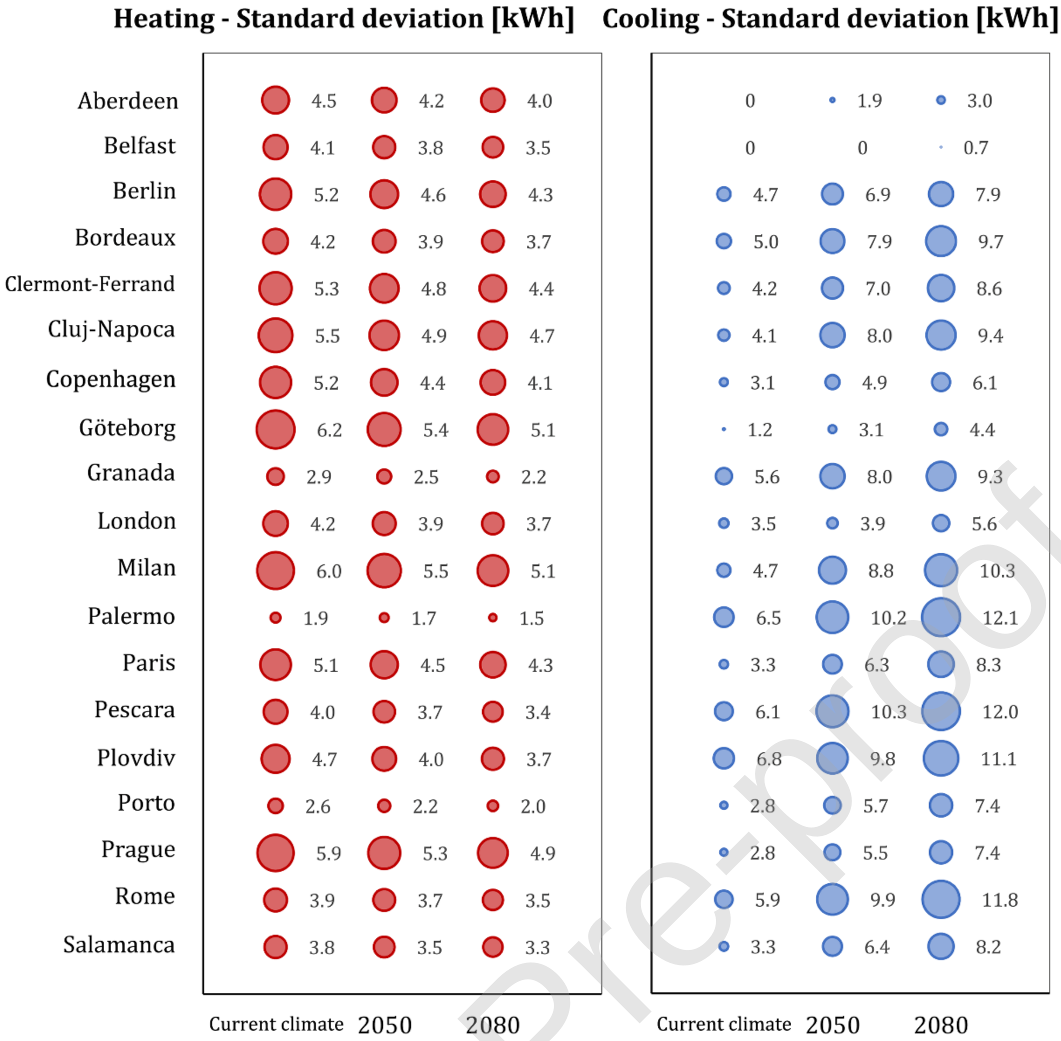

Fig. 9: Standard deviation of energy consumption (kWh) for heating (in red on the left) and cooling (in blue on the right) the same building in the 19 cities analyzed for the current climate simulation and the years 2050 and 2080.

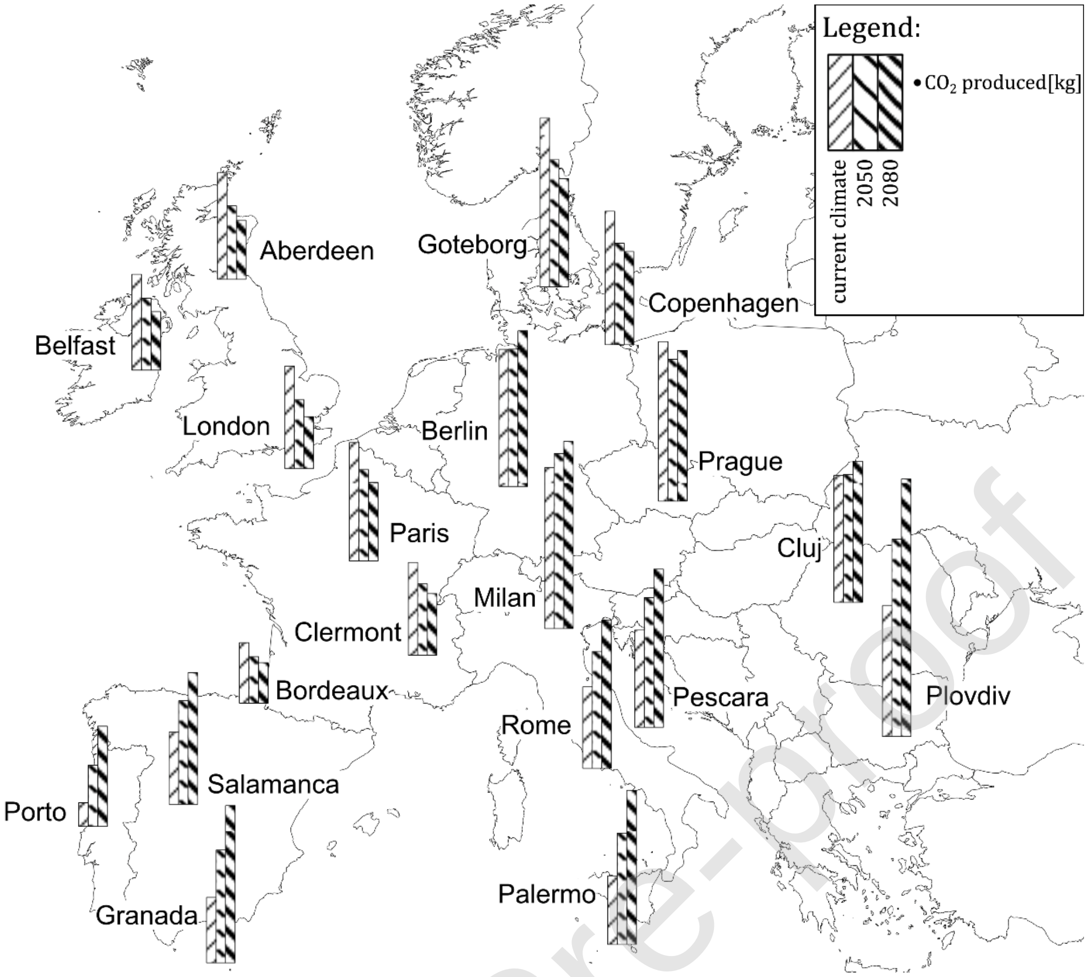

Fig. 10: Annual carbon dioxide produced for energy needs: scenarios “current climate”, “future climate” 2050 and “future climate” 2080. Values are displayed in Tab. 4.

Orientation	Type	Surface area [m²]	Transmittance [W · m⁻² · K⁻¹]
North	Opaque	258.6	0.273
	Glass	59.7	1.60
East	Opaque	111.6	0.273
	Glass	7.6	1.60
South	Opaque	184.5	0.273
	Glass	112.3	1.60
West	Opaque	81.0	0.273
	Glass	6.4	1.60
Horizontal	Roof	181.15	0.263
	Floor	181.15	0.343

Tab. 1 – Properties of building envelope surfaces.

City	State	Latitude [°]	Climatic Classification	Carbon intensity [kg(CO_2) kWh^{-1}]
Aberdeen	United Kingdom	56.4	Cfb	0.3888
Belfast	United Kingdom	54.5	Cfb	0.3888
Berlin	Germany	52.5	Dfb	0.4249
Bordeaux	France	45.0	Cfb	0.0348
Clermont-Ferrand	France	45.8	Dfc	0.0348
Cluj-Napoca	Romania	46.0	Dfb	0.2085
Copenhagen	Denmark	55.5	Dfb	0.1666
Göteborg	Sweden	56.8	Dfb	0.0105
Granada	Spain	37.2	BSk	0.3044
London	United Kingdom	51.5	Cfb	0.3888
Milan	Italy	45.5	Cfa	0.2292
Palermo	Italy	38.0	Csa	0.2292
Paris	France	49.0	Cfb	0.0348
Pescara	Italy	42.0	Cfa	0.2292
Plovdiv	Bulgaria	42.0	ET	0.3701
Porto	Portugal	41.2	Csb	0.3595
Prague	Czech Republic	50.0	Dfb	0.3758
Rome	Italy	41.8	Csa	0.2292
Salamanca	Spain	41.0	Bsk	0.3044

Tab. 2 – Selected cities: State, latitude, climatic classification e carbon intensity for electricity production [72].

City	Current Climate		2050		2080	
	Heating [kWh]	Cooling [kWh]	Heating [kWh]	Cooling [kWh]	Heating [kWh]	Cooling [kWh]
Aberdeen	29,010	0	20,004	50	15,747	236
Belfast	26,135	0	19,680	0	16,028	11
Berlin	33,925	1,439	24,557	5,519	19,985	9,650
Bordeaux	15,953	3,303	10,787	10,808	7,854	17,646
Clermont	24,906	2,028	17,950	8,263	14,210	14,195
Cluj-Napoca	32,477	1,770	23,293	10,131	18,908	17,179

Copenhagen	36,097	198	25,812	2,036	21,157	4,746
Göteborg	45,846	11	34,520	1,105	29,287	3,415
Granada	5,650	7,451	2,460	17,089	1,003	25,229
London	21,841	133	14,742	1,956	11,199	5,047
Milan	39,438	3,370	32,331	12,155	26,888	19,154
Palermo	1,676	13,785	1,057	23,531	341	33,372
Paris	31,949	1,309	23,601	6,903	19,060	12,478
Pescara	18,441	6,462	13,399	17,586	9,720	26,692
Plovdiv	20,409	7,542	12,990	20,145	9,584	29,919
Porto	4,183	1,307	1,719	7,711	842	13,559
Prague	42,705	278	32,418	2,985	27,159	6,722
Rome	13,344	7,159	10,131	17,434	7,114	26,647
Salamanca	15,957	2,298	11,151	10,324	7,516	17,124

Tab. 3 – Annual energy consumption (kWh per year) for heating and cooling in the cities analyzed for the current climate simulation and the years 2050 and 2080.

City	Current climate CO_2 [kg]	2050 CO_2 [kg]	2080 CO_2 [kg]
Aberdeen	5,344	3,704	2,992
Belfast	4,814	3,625	2,957
Berlin	6,860	6,868	7,782
Bordeaux	3,053	2,363	2,061
Clermont	4,658	3,594	3,111
Cluj-Napoca	6,351	6,403	7,065
Copenhagen	6,682	5,094	4,688
Goteborg	8,445	6,370	5,431
Granada	3,309	5,655	7,864
London	5,151	3,476	2,641
Milan	8,037	8,741	9,343
Palermo	3,468	5,588	7,712
Paris	5,931	4,587	3,945
Pescara	4,878	6,499	7,908
Plovdiv	6,550	9,849	12,838
Porto	1,241	3,089	5,030
Prague	7,971	7,093	7,529
Rome	4,099	5,862	7,418
Salamanca	3,639	5,197	6,597

Tab. 4 – Annual carbon dioxide produced for energy needs in the current climate simulation and in years 2050 and 2080.