Future energy demands of European buildings in the framework of climate change: a scoping study

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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 paper 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.

1. Introduction

The Earth is experiencing a rapid climate change whose effects are occurring with an average warming of the atmosphere happening in a relatively short period of time (“AR5 Climate Change 2013: The Physical Science Basis — IPCC,”; U.S. Global Change Research Program, 2018).

Currently, around 30% of global energy production is earmarked for end-use in the civil sector ("Energy Statistics," 2017, United Nations Statistics Division, 2018). Specifically, almost 60% of world electricity is consumed in residential and commercial buildings (Ürge-Vorsatz, n.d.). In the most industrialized countries the energy needs in buildings concern winter heating, summer cooling, domestic hot water production, lighting and household appliances (Salata et al., 2018).

Energy needs are strongly linked to local weather conditions (Ciancio, Falasca, Golasi, Curci, & Coppi, 2018), 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 (Andrić et al., 2017). Buildings will be subjected to new weather conditions that will change the needs of the civil sector in terms of primary energy required (Huang & Gurney, 2016; Lo Basso, Nastasi, Salata, & Golasi, 2017; Zhai & Helman, 2019).

The international scientific community dealing with energy demand of buildings is analysing the close relationship between climate change, energy demand and greenhouse gas emissions

(Guan, 2009) and the resulting cause-effect loop worsening this situation (Kershaw, Eames, & Coley, 2011; de Wilde & Coley, 2013). 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 situation for each location; ii) the energy analysis of the buildings needs corresponding to future climate conditions; iii) the calculation of the modification of climate-altering gases emissions associated with increasing energy requirements (Salata et al., 2017).

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 analyzed area and to different scenarios of global warming (Moazami, Nik, Carlucci, & Geving, 2019). 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 (Kershaw et al., 2011). 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 (Chan, 2011). 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 (Shen, 2017). Zhai and Helman analyzed 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 (Zhai & Helman, 2019).

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 (Invidiata & Ghisi, 2016). 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 (Xu, Huang, Miller, Schlegel, & Shen, 2012). 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 (Dirks et al., 2015). 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 (Huang & Gurney, 2016). 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 (Matsuura, 1995). Li et al. analysed similar problems for the city of Tianjin in northern China, underlining a decrease in heating needs (Li et al., 2014).

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 (Wan, Li, Pan, & Lam, 2012). Andric et al. analyzed 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 (Andrić et al., 2017).

2. 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. 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. 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. In order to create weather files representative of future climate scenarios, suitable climate models must be implemented. 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. This is possible thanks to the computerization of knowledge provided by climatology and energy engineering.

This work aims at assessing the impact of climate change of annual energy consumption for heating and cooling across Europe of a model building, located in 19 European cities characterized by different Köppen-Geiger classification. To this end, dynamic hourly simulations were performed for each location with the EnergyPlus software, using alternatively the weather files provided with EnergyPlus for the current climate, and those relative to two future years (2050 and 2080) under a predetermined emission scenario, created for each location. 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 one and the same building allows to highlight the impact of the climate change on the energy needs across different Köppen-Geiger climate zones. A future development of this work could take into account the variation of construction types across the continent.

3. Materials and methods

In this work, the dynamic predictive software EnergyPlus was used to evaluate the energy consumption of a building alternatively located in 19 European cities, selected according to the (different) latitude and the climatic Köppen-Geiger classification (Peel, Finlayson, & Mcmahon, 2007a). Simulations were carried out on the current climate conditions and on the climate conditions of 2050 and 2080 for the 19 locations considered using weather files described in Section 3.2.

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.

3.1. Computation of energy needs through EnergyPlus

The EnergyPlus software was developed by the US Department of Energy (Crawley, Hand, Kummert, & Griffith, 2008) 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 (Foucquier, Robert, Suard, Stéphan, & Jay, 2013). 3D geometries can be created using SketchUp (Inc., 2018) modeling software and imported into EnergyPlus after defining with OpenStudio (Energy, 2018) the characteristics of the thermal zones on which to set up calculations for exchanges of heat with the external environment.

3.2. 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 (NREL, 2018).

In this work the weather files available in the EnergyPlus database were used for the “current climate” simulations, while the “future climate” simulations are based on climate change weather files produced using the Climate Change tool World Weather file Generator (CCWorldWeatherGen). The generation of this future file weather required computational techniques based on climate models able to provide detailed meteorological information decades apart, specific to the geographic location, for the 8,760 hours of the typical year. The National Renewable Energy Laboratory (NREL) of the US Department of Energy (DOE) provides online ("Weather Data | EnergyPlus") EnergyPlus users with a comprehensive climate database that includes more than 2,100 geographic locations on all continents. The EnergyPlus database weather files were also used to create climate change weather files for 2050 and 2080 and all the 19 selected locations through the CCWorldWeatherGen tool. This tool creates a weather file starting from the current climate weather file by means of a "morphing" procedure and using the HadCM3 model output corresponding 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 (Sedac, 2019). For further details on the tool and the morphing procedure see (Jentsch, James, Bourikas, & Bahaj, 2013).

3.3. Geographic area

This study took into consideration 19 different cities of Europe. The geographical sites have been chosen according to: i) the latitude, on which the solar radiation depends; ii) the climatic classification according to Köppen-Geiger (Peel, Finlayson, & Mcmahon, 2007b). The sites selected are summarized in Table 1.

Tab. 1 – Selected cities: latitude, climatic classification e carbon intensity for electricity production.

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

United Kingdom	Aberdeen	56.4	Cfb	0.3888
United Kingdom	Belfast	54.5	Cfb	0.3888

It is hypothesized that the amount of carbon dioxide produced for the generation of electricity is constant over time and refers to current values (Ecometrica, 2011). The emission of carbon dioxide due to the combustion of natural gas is equal to $0.1842\ kg(CO_2) \cdot kWh_{termico}^{-1}$.

3.4. 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. 1 shows the plan of a plane, a 3D and the geographic orientation of the building.

Properties of materials of building envelope surfaces are summarized in Tab. 2.

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. The ventilation of the rooms is natural, with a turnover equal to 0.5 hourly volumes. Internal thermal loads are assumed to be equal to $38\ W\ m^{-2}$.

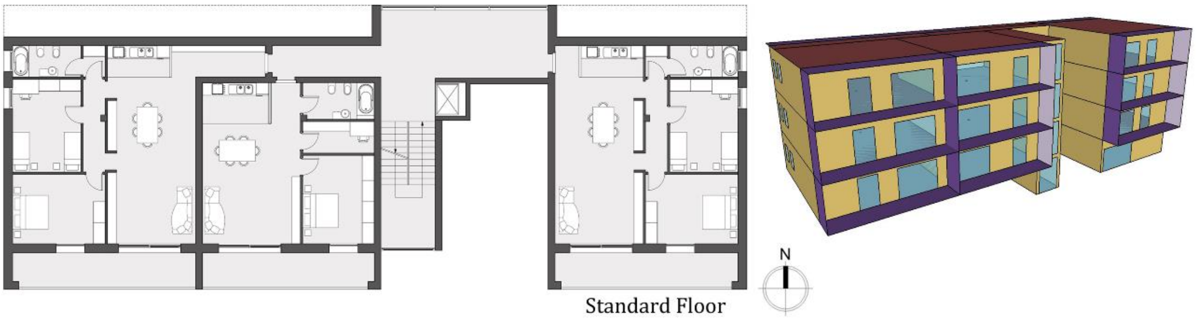


Figure 1: Analysed building: standard floor and three-dimensional representation.

Tab. 2 – Properties of building envelope surfaces.

Orientation	Type	Surface area [m^2]	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

4. Results and discussion

Figure 2 shows that the progressive increase in average monthly temperatures in all 19 locations considered in 2050 and 2080.

The few geographical locations that in 2020 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.

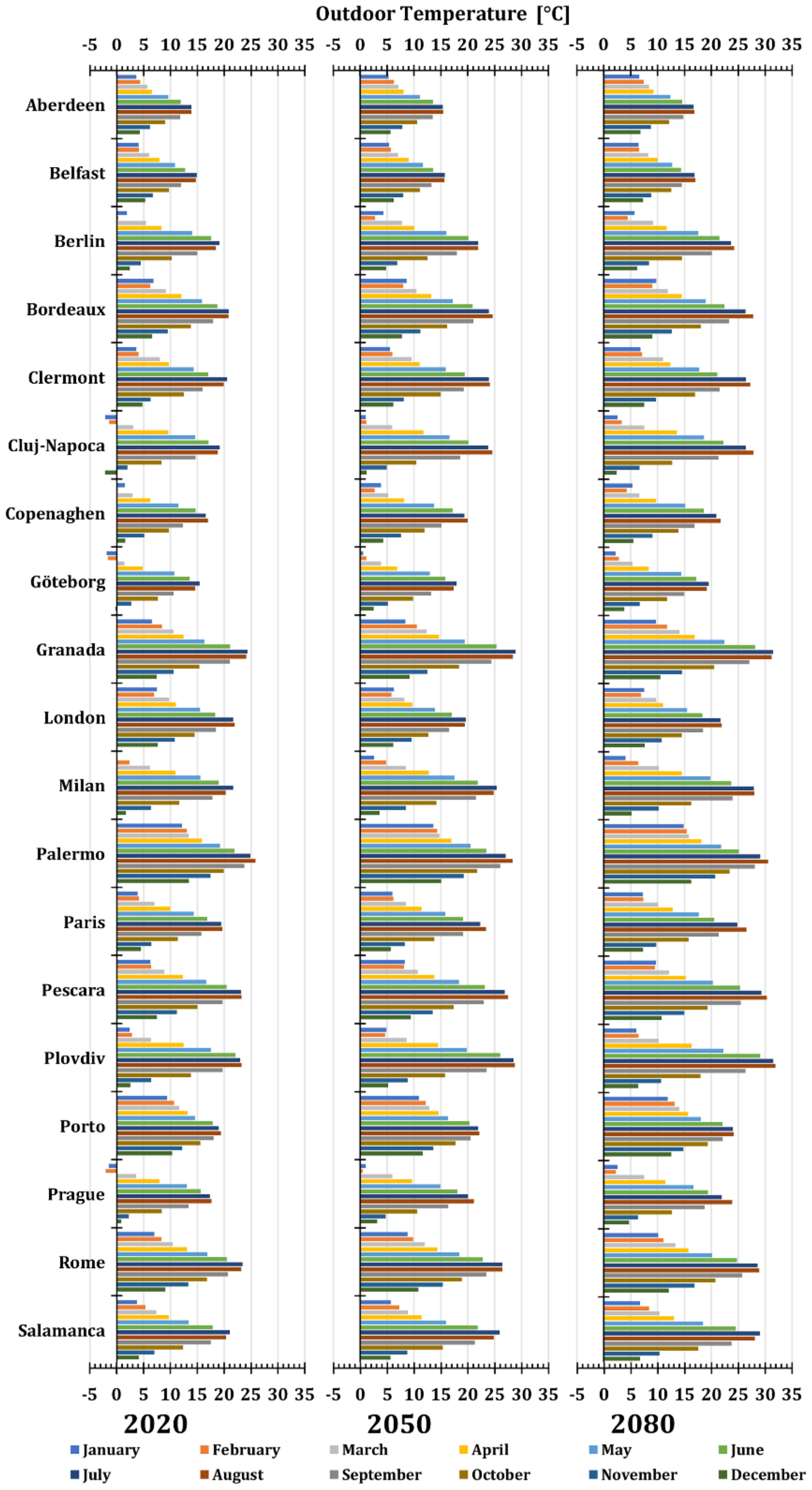
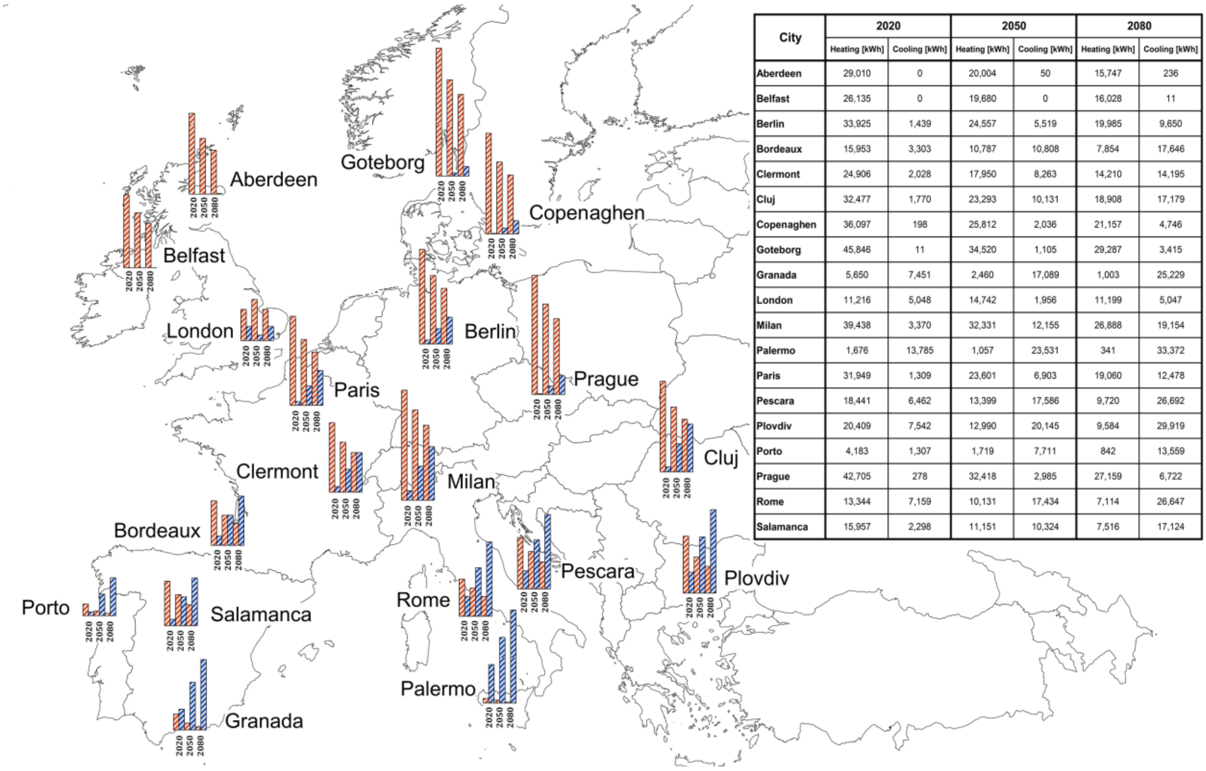


Figure 2: Mean monthly temperatures for the considered cities in years 2020, 2050, 2080.

Fig. 3 shows the energy consumption (in kWh per year) for 2020, 2050 and 2080 for both the heating and cooling of the building for each of the 19 cities.



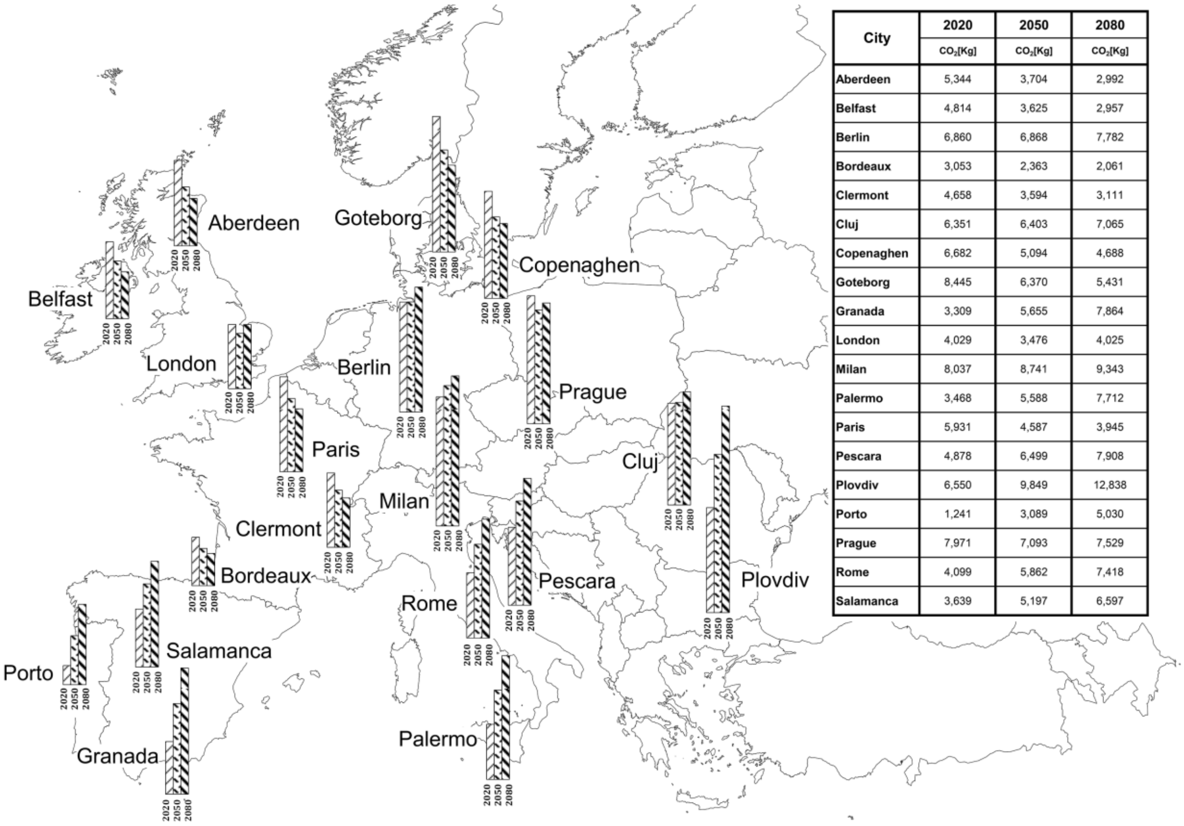
City	2020		2050		2080	
	Heating [kWh]	Cooling [kWh]	Heating [kWh]	Cooling [kWh]	Heating [kWh]	Cooling [kWh]
Aberdeen	29,010	0	20,004	50	15,747	236
Belfast	26,135	0	19,680	0	16,028	11
Berlin	33,925	1,439	24,557	5,519	19,985	9,650
Bordeaux	15,953	3,303	10,787	10,808	7,854	17,646
Clermont	24,906	2,028	17,950	8,263	14,210	14,195
Cluj	32,477	1,770	23,293	10,131	18,908	17,179
Copenaghen	36,097	198	25,812	2,036	21,157	4,746
Goteborg	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	11,216	5,048	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

Figure 3: Annual energy consumption (kWh per year) for heating and cooling in the locations analyzed for 2020, 2050, 2080.

Annual CO_2 emissions respectively for cooling and heating the studied building are computed multiplying the annual energy consumption (in Fig. 3) for the carbon dioxide emission coefficients due to the production of electricity (fifth column of Table 1, corresponding to the national energy mix of each State) or to the stoichiometric combustion of natural gas (Fig. 4).

Figure 4 shows 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. 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 2020 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.



City	2020	2050	2080
	CO_2[Kg]	CO_2[Kg]	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	6,351	6,403	7,065
Copenaghen	6,682	5,094	4,688
Goteborg	8,445	6,370	5,431
Granada	3,309	5,655	7,864
London	4,029	3,476	4,025
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

Figure 4: Annual carbon dioxide produced for energy needs: scenario 2020, 2050, 2080.

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.

5. 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. Specifically, 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.

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 (Andreani & Gasparotto, 2002; Shikama et al., 2008).

These results are the first step in a research work aiming at using optimization computational techniques such as genetic algorithms. The goals of the next steps will be the identification of 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. 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, 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 can be reorganized.

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