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GLEDAJUĆI U BUDUĆNOST I UTICAJE KLIMATSKIH PROMENA NA ENERGETSKU EFIKASNOST GRČKIH STAMBENIH ZGRADA

Key words:
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LOOKING INTO THE FUTURE AND THE IMPACTS OF CLIMATE CHANGE ON THE ENERGY PERFORMANCE OF HELLENIC RESIDENTIAL BUILDINGS

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Ovaj rad istražuje moguće uticaje klimatskih promena i očekivane promene spoljašnjih vremenskih uslova na energetsku efikasnost tipičnih grčkih stambenih zgrada i scenarije renoviranja. Procena uzima u obzir prosečne klimatske projekcije za dva buduća perioda – jedan za blisku, a drugi za dalju budućnost – prateći dva reprezentativna koncentraciona puta (RCP). Osnovni scenario (RCP8.5) predstavlja najviši nivo emisije gasova sa efektom staklene bašte, dok scenario srednje stabilizacije (RCP4.5) podrazumeva uvođenje konzervativnih politika za ublažavanje emisija. Podaci o budućoj klimi generisani su za 62 grada širom Grčke. Rad se fokusira na arhetipove grčkih stambenih zgrada prema evropskoj tipologiji TABULA za jednoporodične i višeporodične objekte. Dostupni podaci koriste se za procenu potreba za grejanjem i hlađenjem, potrošnje energije i emisija. Ispituju se i procenjuju različiti scenariji renoviranja zgrada – od omotača objekta do sistema za KGH.

This work investigates the possible impacts of climate change and the anticipated changes of the outdoor weather conditions on the energy performance of typical Hellenic residential buildings and renovation scenarios. The assessment considers average climatic projections for two future periods, one for the near and one for the distant future, following two representative concentration pathways (RCPs). The baseline scenario (RCP8.5) represents the highest greenhouse gas emissions, while the intermediate stabilization scenario (RCP4.5) assumes the imposition of conservative emissions mitigation policies. The future climate data are generated for 62 cities throughout Greece. The work focuses on Hellenic residential building archetypes following the European TABULA typology for single- and multi-family buildings. The available data are used to assess the buildings' heating and cooling demand, energy use and emissions. Different scenarios for renovating the building envelope and HVAC systems are investigated and assessed.

1. Introduction

Over the decades, the buildings sector ranks at the top of total energy use, including all of its forms like fossil fuels and electricity. In the European Union Member States (EU-27) final energy consumption for the operation of buildings reached 347.3 Million tonnes of oil equivalent (Mtoe) or 38.5% of the total final energy used in 2023 [1]. Among them, the most important energy end users are residential buildings that amount for 229.3 Mtoe or 25.4% of the total. The percentage breakdown is similar in Greece, with the residential sector reaching 24.5% of the total final energy use or 3.8 Mtoe in 2023 [1].

The EU-27 total greenhouse gas (GHG) emissions were 3105.6 Million tonnes of carbon dioxide equivalent ($MtCO_2$-eq) dropping by 36.3% since 1990 [1] because of improved energy efficiency efforts and the decarbonization of public electricity generation with the integration of more renewables. As illustrated in Figure 1, the European Union is on track towards its commitment to reduce net GHG emissions by at least 55% by 2030 compared to 1990 levels, under the provisions of the European Climate Law and the European Green Deal and finally aims to become climate-neutral by 2050. Buildings are responsible for 27.8% of the total GHG emissions in EU-27, which is split among the direct emissions from the fossil fuels used in buildings (12.2%) and the allocated indirect emissions from the electricity and heat used in buildings (15.6%). Similar contributions are also reported in Greece, where the Hellenic buildings are responsible for 16.5 $MtCO_2$-eq or 20.1% of the total GHG emissions in 2023 [1]. In view of this grim reality, the European Commission and national governments focus on improving the energy performance of new and existing buildings, going beyond current minimum code requirements for nearly zero energy buildings (nZEB) to zero-emission buildings by the end of the decade [2].

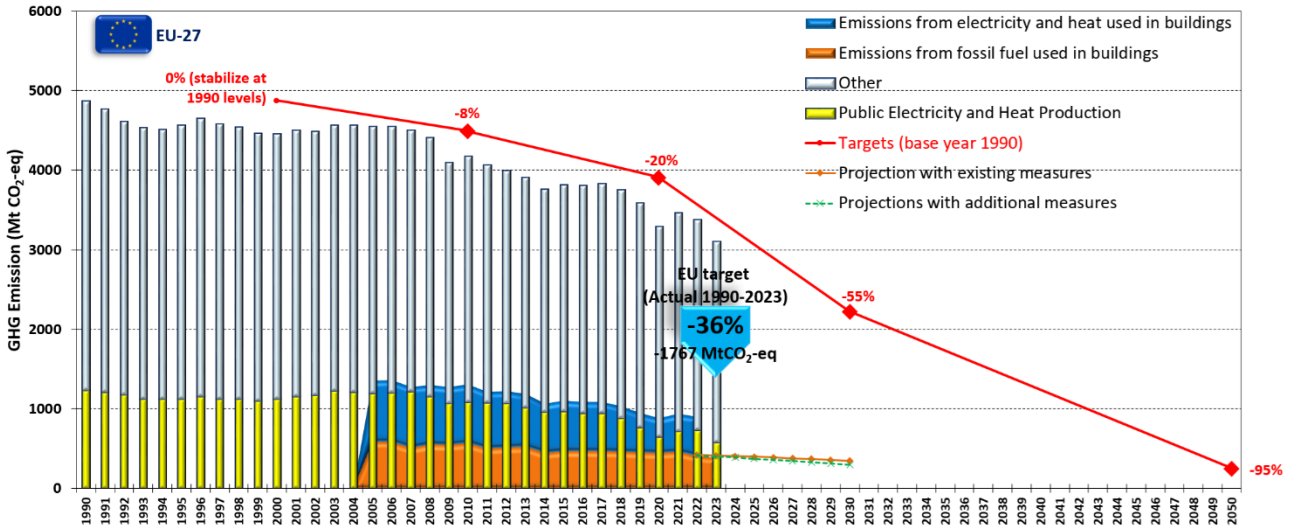

Figure 1 Historic data for greenhouse gas (GHG) emissions ($MtCO_2$-eq) from public electricity and other sources in EU-27 (1990-2023 data from [1]) and from energy use in buildings (2005-2023 data from [3]) along with past and future European emission targets

Figure 1 illustrates the dropping trend of the total GHG emissions over the past decades. In particular, the buildings sector exhibits a notable decrease of emissions over the past couple of decades from the direct use of fossil fuels in buildings and the indirect emissions from the use of electricity in buildings, averaging since 2005 a drop of 35.3% and 36.3%, respectively [3]. These achievements can in part be attributed to the advancing minimum energy codes for new buildings and major renovations that set new improved energy standards for building, the technological advances and the

higher performance of new equipment, the decarbonization of power generation and the electrification of buildings, along with milder climate conditions in winter [3]. National projections of emissions from buildings indicate that with the existing measures in practically all EU-27, it is expected to continue the decreasing trend of emissions towards 2030. Additional measures in some leading countries (i.e. Denmark, Finland, Slovenia and Sweden) may drive additional drop in GHG emissions from buildings, reaching a drop of about 70% by 2030.

Looking into the future, one needs to also take in to account GHG emissions will have a significant impact on climate conditions resulting in rising global temperatures especially in urban environments that may also affect building performance [4]. For example, 2024 is reported to be the warmest year on record at about 1.55°C above pre-industrial level [5-6]. Depending on different future GHG emissions scenarios the global surface temperature is projected to increase by 1.0°C to 1.8°C by the end of this century compared to pre-industrial levels considering a very low emissions scenario and reach up to 5.7°C with a very high emissions scenario[4].

Considering that climate change is a slow process, even if all GHG emissions emitted by human activities were to stop today, the Earth's temperature would continue to rise over the next several decades up to 0.6°C, as ocean currents bring excess heat stored in the deep ocean back to the surface [7]. Temperature increases are expected to be more significant on land, where especially some urban areas will warm-up much more than others. As a result of ambient air temperature and humidity variations, it is anticipated to have changes in average daily peak loads and overall electricity consumption of buildings in different European climate zones. This can lead to a decrease in northern European buildings, for example, a drop by 2% in Norway and by 6% in Sweden, compared to an increase in southern and western Europe, for example, an increase by 3% in Portugal and by 7% in Spain [8].

In this context, it is important and relevant to understand how the climate is changing in order to prepare for the future, adapt if necessary, but most important take proper precautionary measures to alleviate major negative impacts. The amount of future GHG emissions is a key parameter for predicting how future global warming will contribute to climate change. The projections of GHG emissions vary widely depending on several assumptions, for example, population growth, economic development, technological innovation and climate policies. Based on different possible future pathways of GHG emissions expressed by the Representative Concentration Pathways (RCP), the scientific community has defined different scenarios (e.g. RCP4.5, RCP8.5) for calculating future climate conditions [9]. An optimistic scenario of future emissions is based on different pathways for which the GHG concentration stabilizes after 2100 (RCP4.5) with the surface air temperature increasing by 1.9–2.9°C [10]. On the other extreme, assuming no climate policies are considered (RCP8.5) representing a business-as-usual scenario that continuous an increase of GHG concentration until 2100, is projected to cause the most significant surface air temperature increase by 3.5–4.5°C.

1.1. Climate change impacts on buildings

The increase of global temperature due to climate change is expected to affect the built environment and the outdoor conditions under which buildings will operate. Several EU policies and directives on the energy performance of buildings, renewables and energy efficiency help us advance to an era of high-performance new buildings and nZEBs, and slowly for major building renovations [11]. Progressively energy use in buildings is shifting towards electricity that is ideally generated from renewables. Progressively, the new buildings will become net-zero or even net-positive energy buildings that produce as much or more energy from on-site renewables than they import over a year. All these efforts reduce energy use and GHG emissions.

Considering that buildings have a long lifetime of about 50 to 100 years and their annual replacement rate remains very low at about 0.3–0.7% [12], the existing and future building stock will be affected by long-term (30-70 years) changes in climate. Therefore, there is interest to analyze how buildings will respond to climate change and to assess possible changes in energy use and operational GHG emissions.

Studies have assessed and quantified the impacts of climate change on the operational energy use and the overall performance of buildings. In the United States, by 2070 the total energy consumption for residential buildings is predicted to decrease by 2% in cold zones (e.g., Chicago, Philadelphia) and to increase by 14% in warm zones (e.g., Phoenix, Miami), while in office buildings the final energy use is expected to reduce by 3.3% and by 0.1%, respectively [13]. For European residential buildings, the heating demand is expected to decrease over time, for example, 5% in Nordic countries, 16% in central regions, up to 19% in southern counties [14]. On the other hand, cooling demand will increase progressively, for example, 10% in southern countries, 28% in central regions and up to 44% in northern regions, which is expected to outweigh the decrease in the heating demand [14].

In Greece, a study estimated that the space heating energy consumption of a typical building would decrease by up to 10% in 2030, while the cooling consumption may increase by 28% [15]. Long-term projections for 2100 estimate that the building heating demand will decrease by up to 50%, while cooling demand will skyrocket by as much as 248% in the southern parts of the country [16]. A recent theoretical study of existing non-residential Hellenic buildings in all climate zones of Greece that will remain in their original condition, estimated that the average heating energy use will decrease by 22–26% in 2050 and by 23–52% in 2090, while the average cooling energy use is expected to increase by 24–30% in 2050 and by 28–66% in 2090 [17]. Short and long-term renovation scenarios were also used to assess energy conservation and energy efficiency measures for various types of the Hellenic non-residential buildings stock [18].

2. Methodology

The current work focuses on the Hellenic residential buildings typology and adapting an overall methodological approach that is elaborated in [17-18]. The first stage of the work is the generation of future climate data that are then used to assess building energy performance for present and future climate conditions, namely for the near future (2050) and for the distant future (2090). Each time the work considers two climate scenarios, specifically a business-as-usual scenario that represents the highest GHG emissions (RCP8.5) and an intermediate stabilization scenario that is more likely to occur (RCP4.5), assuming the imposition of conservative emissions mitigation policies with moderate policies.

The model climate raw data were derived from Regional Climate Models (RCMs), producing time series up to 2100 for the various meteorological parameters. The model projections up to 2005 correspond to the model climate data for the present, while the future emission scenarios are implanted in the simulations afterwards. Finally, future climate data were generated for 62 Hellenic cities that spread around the country, covering the four national climate zones (A-D). Zone A in the south includes most of the Hellenic islands and is characterized by mild climate conditions, with an average value of heating degree days of 859 HDD and average cooling degree hours of 2502 CDH. Zone B includes the greater metropolitan area of Athens, averaging 1164 HDD and 3481 CDH. The most adverse winter conditions include Zone C in the central and northern parts of the country that averages 1825 HDD and 2576 CDH, and Zone D in the north with the coldest conditions with 2260 HDD and 929 CDH.

The format and the time step of the climate data depends on the calculation tool that is used for the assessment. In this work, the calculations are performed using as input the outdoor air temperature, specific humidity and total horizontal solar irradiation. As a reference, the standard code compliance calculations are performed using measured weather data from the official records from the Hellenic National Meteorological Service that are available for 62 Hellenic cities. They were derived from 30-year meteorological measurements during the period of 1970 to 2000 and used as default input in the national calculation engine for performing energy performance assessment calculations and labeling of buildings. The hourly data used from the regional climate model of the Swedish Meteorological and Hydrological Institute [12] were adapted using the RCMs at the different grid cells. The spatial and other needed corrections to match the exact locations of the specific cities are elaborated in [17].

The second stage of the work is the building energy performance assessment. In this work, a set of building types defined in line with the TABULA methodology are used to represent the Hellenic residential building stock in terms of the building's use (i.e. residential), size (i.e. single-family houses (SFH) and multi-family houses (MFH) for apartment buildings) and vintage that is related to the building age (i.e. with different construction practices and thermal insulation building regulations in place at the time of construction) [19-20]. For example, pre-1980 buildings are not thermally insulated (e.g. walls with a U-value of 1.8 W/m2.K) since they were constructed before the introduction of the first national thermal insulation regulation (NTIR). The 1981-2010 buildings were constructed according to NTIR (e.g. walls with 0.6 W/m2.K). The post-2011 buildings were constructed in line with the strict Hellenic building energy performance regulation (e.g. walls with 0.55 W/m2.K in the warm climate zone A down to 0.35 W/m2.K in the coldest climate zone D), with additional improvements for the nZEB buildings (e.g. walls with 0.5 W/m2.K in climate zone A and 0.3 W/m2.K in climate zone D).

The type and performance of the building's technical installations (e.g. heat generation, cooling equipment) and the form of energy used (e.g. heating oil or natural gas for fuel-fired boilers, electricity for heat pumps) are also related to the different building typologies and have a determinant role on the energy consumption of the different building types. Table 1 summarizes the assumed system performance characteristics, for example, old buildings (pre-1980) are most likely equipped with oil- or natural gas-fired boilers depending on the building location in one of the 62 cities and the availability of natural gas (e.g. not available in climate zone A or west regions of the country).

Table 1. Technical system characteristics for the different building types and scenarios

System	*pre-1980*	*1981-2010*	*post-2011*	*Deep retrofit*	*nZEB*
Boiler (oil/nat. gas) efficiency	0.80	0.86	0.98		
Heat pump (COP)	2.00	2.20	2.50-2.70	3.60	3.60
Solar collectors (m^2)			SFH: 2.5-6.0 MFH: 10.0-27.0	SFH: 2.0-14.0 MFH: 15.0-35.0	SFH: 10.0-16.0 MFH: 30.0-55.0
Photovoltaics (m^2)			SFH: --- MFH: 5.0-10.0	SFH: 2.0 MFH: 5.0	SFH: 1.0-2.0 MFH: 8.0-10.0

Two scenarios consider deep renovations of existing buildings and nZEB according to the minimum national energy performance code, including the installation of solar collectors and photovoltaics in new buildings and deep renovations. For 2050, it is assumed that any remaining boilers will be condensing natural gas fired boilers with a thermal efficiency of 98% and heat pumps with a COP of 3.5. Deeply renovated buildings and nZEBs are not candidates for system renovations by 2050.

Finally, all buildings are considered to be decarbonized and use heat pumps with a conservative COP of 4.5 for the end of the study period by 2090.

The calculation tool used in this work was the official national calculation engine that is used for building energy performance assessments and issue energy performance certificates in Greece. The tool uses a quasi-steady state monthly method for assessing the building's energy demand, according to the European standards like EN 13790. The end uses considered in the calculations are heating, cooling, domestic hot water, while mechanical ventilation is included in heating and cooling. For residential buildings, lighting and other electric appliances, plug loads, and process loads are not used in the calculations according to the national code for building energy performance assessment. Alternatively, one can use other building simulation software, for example, TRNSYS or Energy Plus. This is actually part of the ongoing work since building simulation models can be more sensitive and capture the dynamic building behavior and the impacts of climate change on the ambient conditions like the outdoor temperature.

The setup of the overall methodology, the building models and weather files used for the baseline calculations were validated considering different criteria in order to gain confidence on the results. The calculated climate data corresponding to each location were compared with the measured data that are available in the national guideline for the 62 cities. The process and the outcome of the comparisons are elaborated in [18]. The complete process, using the building typologies with the calculated present weather data as inputs to the national calculation engine was validated by comparing the energy demand, energy use and corresponding emissions with the available national baselines and benchmarks for residential buildings [21-24].

3. Results

The climate data for the present (baseline year), the near (2050) and distant (2090) future and the 62 Hellenic cities, were derived using the two average climatic projections, i.e. RCP8.5 for a business-as-usual scenario that projects the highest GHG emissions and RCP4.5 for the implementation of conservative emissions mitigation policies that estimate realistic reductions of GHG emissions. The data include monthly values for outdoor air temperature (°C), specific humidity (g/kg) and total horizontal solar irradiation (MJ/m^2). These data are then used in the calculations for the energy performance of the SFH and MFH in their existing condition, following a deep renovation and for the nZEB typology. The building's energy demand, which does not account for heating or cooling system performance, the final energy use intensity (EUI energy use per unit floor area in kWh/m^2), and the related operational carbon emissions ($kgCO_2/m^2$) for the different forms of energy used by the building typologies for heating and cooling were assessed using the different climate data, in order to analyze the buildings' response to climate change.

A comparative analysis of the present, near and distant future climate data revealed that the temperature increase is higher in the colder parts of the country, i.e. the northern climate zones C and D. Using RCP8.5, the annual air temperature increase ranges from 10% in zone A up to 17% in zone D for 2050 and from 21% to 37% for 2090, respectively. Using RCP4.5, the corresponding values range with an increase of 8-14% for 2050 and 9-16% for 2090. For the specific humidity there are no clear deviation trends since the values also depend on temperature variations in the various climate zones. Cloud cover is the dominant parameter that influences solar irradiance, which presents variating behavior in global and regional climate models, resulting in different trends for the different locations and then normalized for average conditions over the country. Consequently, there are small variations for the different time periods. For example, using RCP8.5, the average values range from

323.0 MJ/m^2 for 2050 and 323.4 MJ/m^2, while with RCP4.5 the corresponding values are 483.1 MJ/m^2 and 482.3 MJ/m^2.

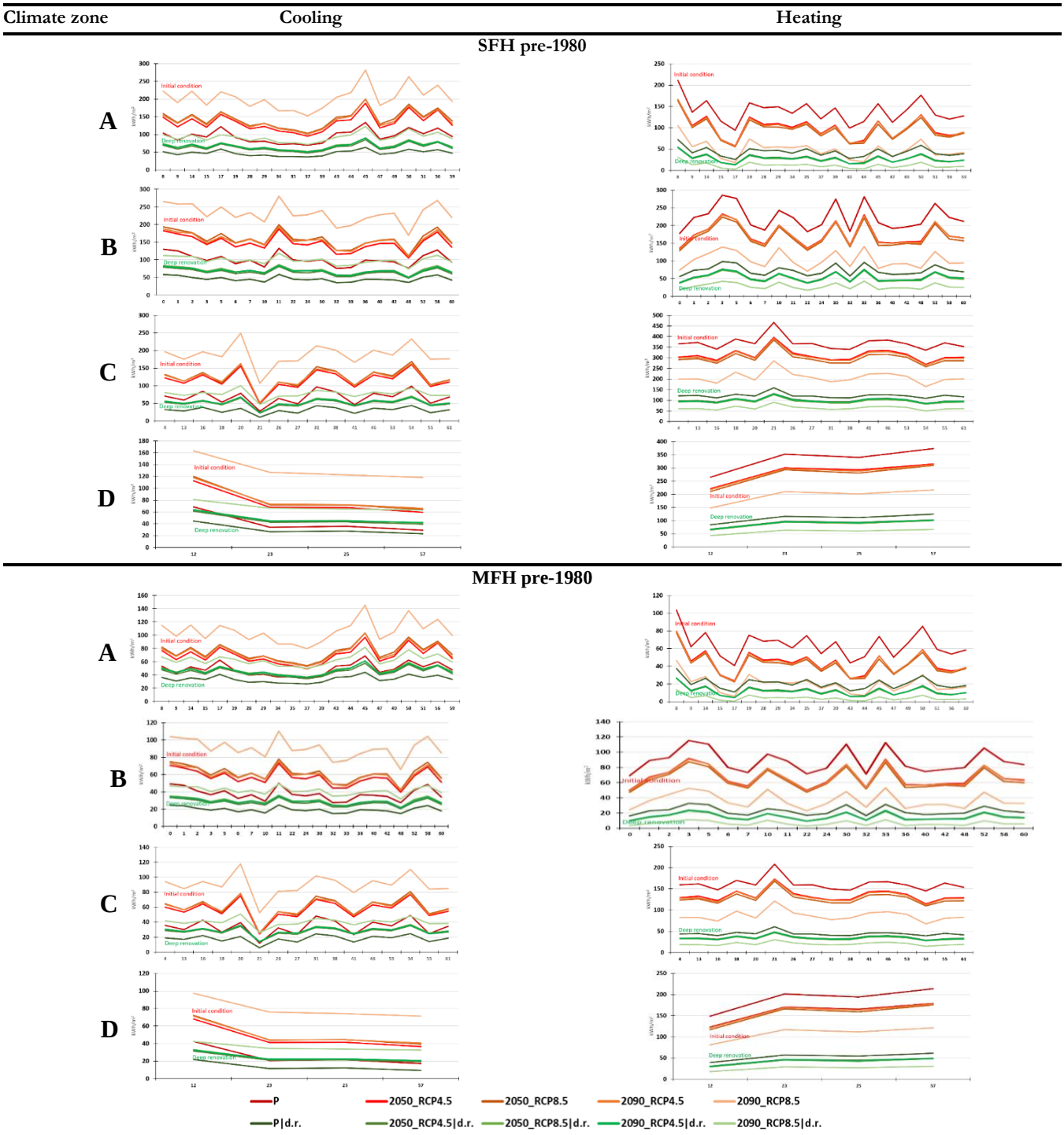

Figure 3 Variations of cooling and heating energy demand per unit floor area (kWh/m^2) for the pre-1980 building typologies (SFH and MFH) for each location in the four climate zones (A-D), in the initial condition and after deep renovation (d.r.) for the present baseline (P) and different climate change scenarios (RCP8.5 and RCP4.5)

Given the variations of the future climate with increasing ambient temperature and humidity it is expected that there will be an increase of the cooling demand and a decrease for heating. Representative results for different typologies are captured in Figure 2a for SFH and Figure 2b for MFH. The variations illustrated by the whiskers correspond to the different values from 21 locations in the

four climate zones. The whisker plots illustrate the variations for the corresponding locations considered in each climate zone. The median value of the EUIs is included inside the box, while the mean value is identified with an "X". The width of the box shows the interquartile range between the lower 25th and the upper 75th quartile, which in most cases illustrates a small data spread out.

The total energy demand variations on an annual basis are small, balancing out the increase for cooling and the decrease for heating of the building's energy demand. Figure 4 presents representative results for SFH and MFH typologies for the average conditions of climate zone B, accounting for both changes of cooling and heating (C&H). This underlines the importance of addressing these issues on a seasonal basis that can reveal different priorities. Apparently, it is important to account for the time that the different loads will occur during the day and the season (summer vs winter) in view of the different energy mixture for power generation and the emissions depending on the type of fuel used for heating and cooling. For example, an increase of energy demand during summer can be easier to handle with higher performing PV generated green electricity. On the other hand, a lower energy demand in winter can ease the efforts to decarbonize buildings and replace fuel-fired boilers with heat pumps, adding up on the benefits from higher heat pump performance.

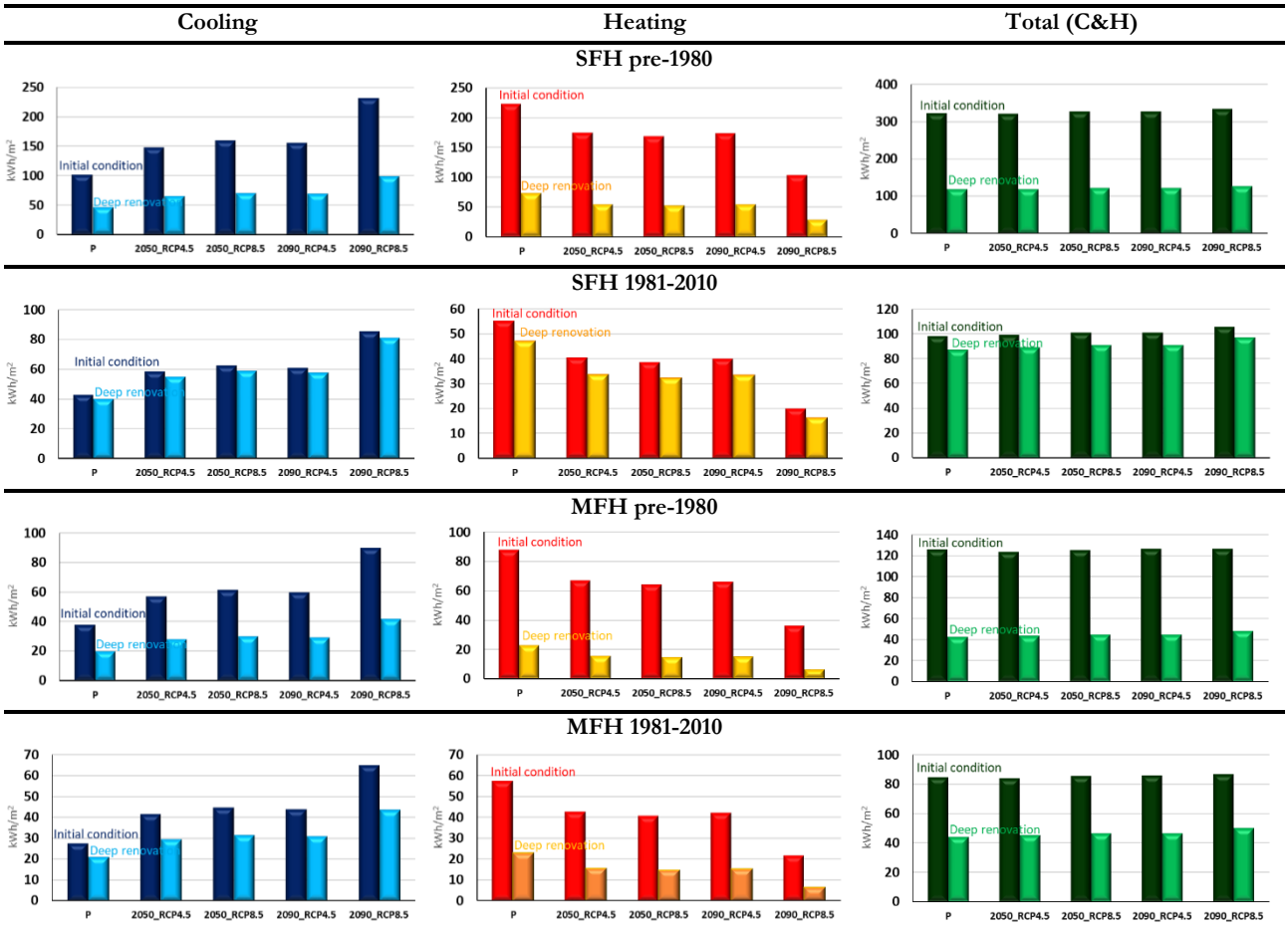

Figure 4 Variations of cooling, heating and total annual energy demand per unit floor area (kWh/m^2) for the building typologies (SFH and MFH) in climate zone B, in the initial condition and after deep renovation for the present baseline (P) and different climate change scenarios (RCP8.5 and RCP4.5)

Analyzing the results for the final energy use intensities reveals a somewhat different behavior. The analysis complies with the European policies for building decarbonization, switching away from fossil fuels towards green electricity. In addition, the improved equipment performance of using heat

pumps for C&H can outweigh some of the climate change impacts, lowering energy consumption for both cooling and heating and the associated emissions. The results depend on several assumptions, for example, the technological advances that will lead to higher performance C&H equipment, resulting in less energy use, the building renovation rates, along with the other assumptions used in this work. Figure 5 presents representative results for SFH and MFH typologies for the average conditions of climate zone B. The actual energy use will benefit from the improved equipment performance, improved building construction and renovation practices according to future and more demanding energy performance regulations, which will balance the implications from the more adverse outdoor conditions in summer.

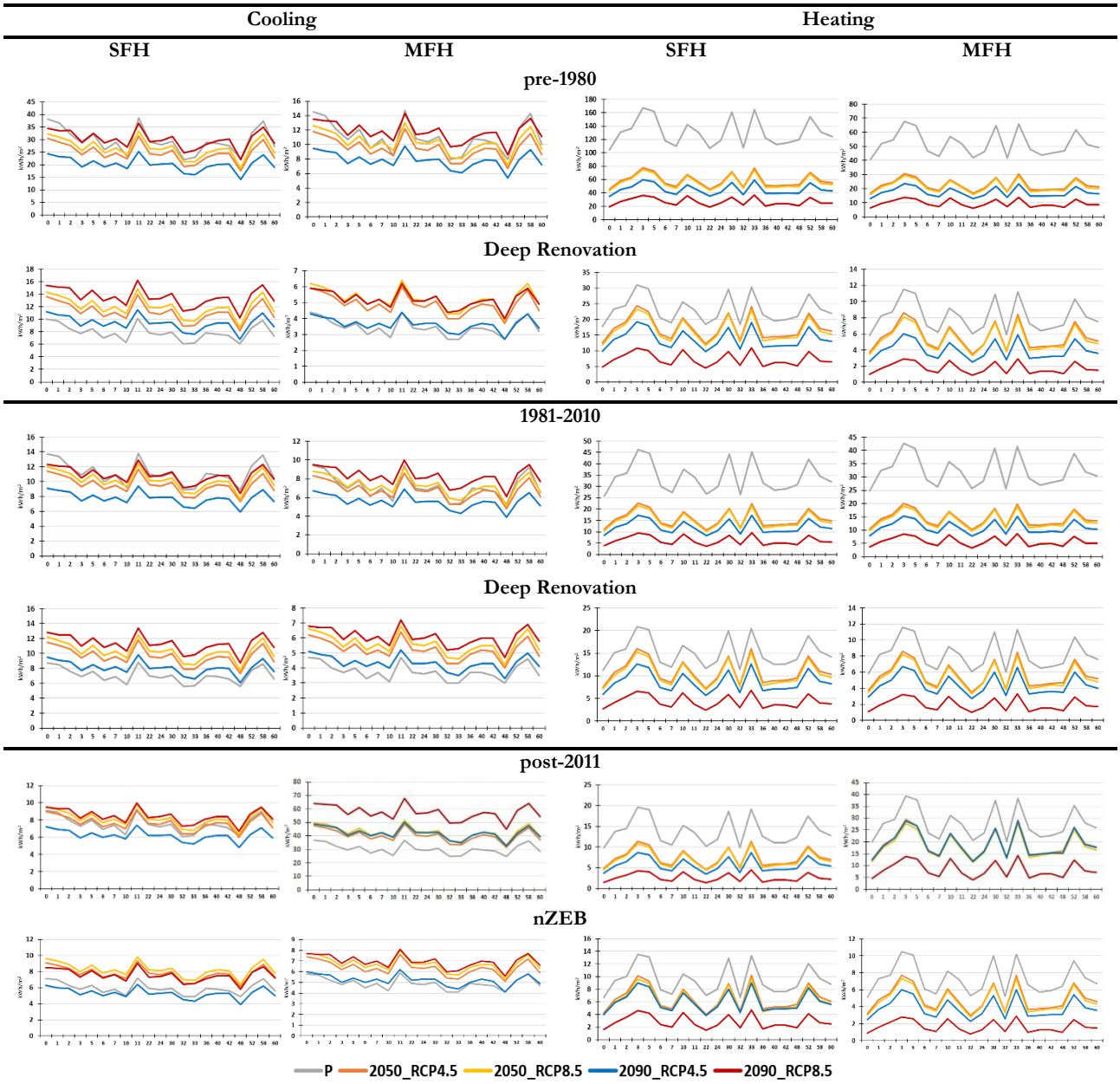

Figure 5 Variations of cooling and heating final energy use per unit floor area (kWh/m^2) for the building typologies (SFH and MFH) in climate zone B, for the present baseline (P) and different climate change scenarios (RCP8.5 and RCP4.5)

The operational emissions for the different fuels are calculated in this work using the predefined default values that are locked in the calculation engine according to the national regulation. For

example, the default emission factor for electricity is 0.989 $kgCO_2/kWh_{el}$ and the primary energy conversion factor is 2.9, which were derived from energy balances that date 15 years ago. As a result, the quantified emissions for the use of electricity from the main grid are overestimated, since there have been notable national efforts to phase out the use of lignite and oil for power generation, use better filter technologies and higher efficiency combustion technologies, and integrate renewables in the energy mix. For information, the current estimates are 0.225 to 0.363 $kgCO_2/kWh_{el}$ for the carbon emissions and 0.4142 to 0.3192 $kgCO_2$-eq/kWh_{el} for the GHG emissions [25] and 1.94 to 2.34 for the primary energy factors [26]. The results are summarized in Figure 6a for SFH and 6b for MFH for the building typologies that use only electric C&H services for all the investigated scenarios in the four climate zones. This is the only building typology that uses the same energy source throughout the near- and long-term periods. The other building typologies shift from oil-fired boilers to natural gas as a transition fuel and eventually to all electric buildings, in line with the EU target for a decarbonized buildings sector. The values average 179.7 $kgCO_2/m^2$.a for pre-1980 SFH buildings and 74.9 $kgCO_2/m^2$.a for MFH, 62.4 $kgCO_2/m^2$.a for 1981-2010 SFH buildings and 51.7 $kgCO_2/m^2$.a for MFH, 31.6 $kgCO_2/m^2$.a for post-2011 buildings, and after deep renovations drop down to 35.0 $kgCO_2/m^2$.a for SFH and 16.1 $kgCO_2/m^2$.a for MFH, 22.7 $kgCO_2/m^2$.a and 12.7 $kgCO_2/m^2$.a, and 13.4 $kgCO_2/m^2$.a and 9.4 $kgCO_2/m^2$.a, respectively.

4. Conclusions

There is strong scientific evidence from the IPCC and other international entities that human-induced GHG emissions have triggered short- and long-term climate change impacts that are expected to influence building energy performance, energy demand, use and emissions, among others. This work addresses these issues by quantifying the current and future energy performance of Hellenic residential buildings under two climate scenarios namely RCP8.5 that reflects a business-as-usual scenario by continuing high GHG emissions, and RCP4.5 that results from the implementation of conservative emissions mitigation policies, at two time periods of interest, i.e. near future (2050) and distant future (2090). The work follows a coherent method for developing the future climate data in 62 locations in Greece that cover all climate zones that is used as input to the national calculation tool to performs the calculations for 24 Hellenic residential building typologies, including single-family houses (SFH) and multi-family houses (MFH).

The short- and long-term calculations were carried out under the assumption that no envelope refurbishment will take place. However, taking into account that the lifespan of C&H systems does not exceed 15 years, an upgrade of the C&H systems was necessary to consider. Specifically, heat pumps with a conservative COP 3.6 and 4.5 replace existing systems providing space heating and cooling by the years 2050 and 2090, respectively.

According to the findings of this work, the cooling energy demand decreases from the warmer climate zones (A, B) to the colder zones (C, D) for major building typologies (Figure 7). The impact of climate change on the existing building stock is first considered with no envelope renovations but replacing equipment at the end of their life. The calculations are first performed using the two scenarios (RCP4.5 and RCP8.5) until the year 2050. The results reflect an increase of the cooling energy demand ranging from 35% to 64% for SFH (55%-82% for MFH) in the warmer zones, and from 52% to 84% for SFH (33%-54% for MFH) in the colder zones. However, the two climate scenarios lead in different long-term (2090) projections. Scenario RCP8.5 leads to a twice as high energy demand for cooling compared to the baseline demand, on average 65% and 81% higher than the energy demand calculated using scenario RCP4.5 for the warmer zones and colder zones, respectively.

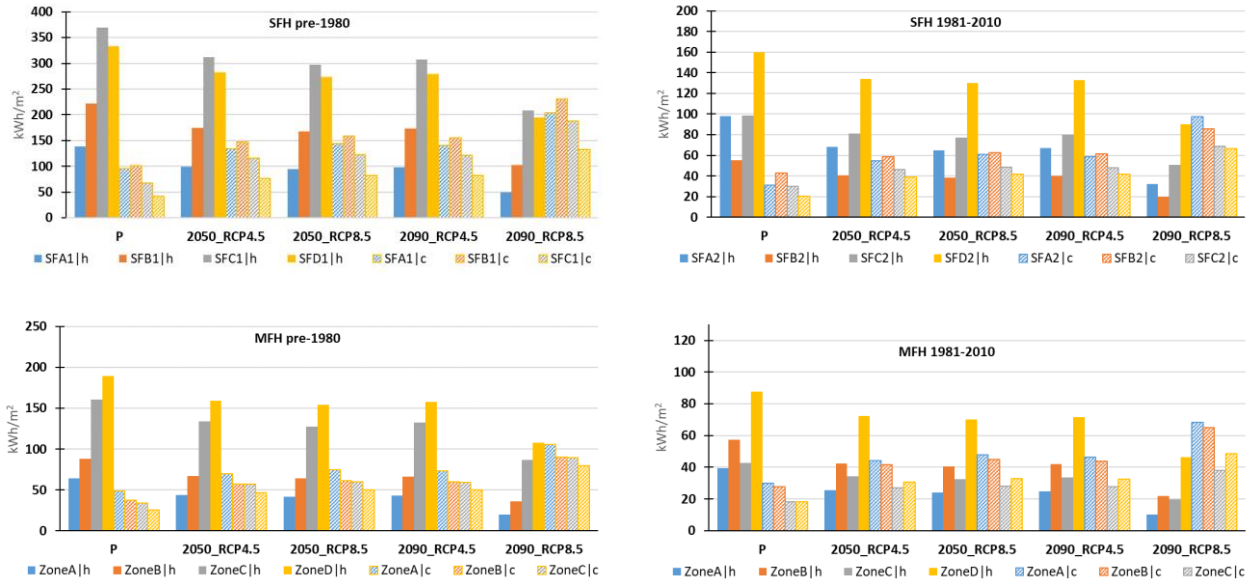

Figure 7 Variations of energy demand per unit floor area (kWh/m^2) for the building typologies (SFH and MFH) in the four climate zones (ZoneA-ZoneD) for cooling (|c) and heating (|h), for the present baseline (P) and different climate change scenarios (RCP8.5 and RCP4.5)

On the other hand, the heating energy demand increases from the warmer climate zones (A, B) to the colder zones (C, D). The near future (2050) impacts are reflected in a decrease ranging from 26% to 38% for SFH (30%-41% for MFH) in the warmer climate zones and from 17% to 22% for SFH (17%-24% for MFH) in the colder zones. However, the two climate scenarios lead in different long-term (2090) projections. Scenario RCP8.5 results in a significantly higher decrease in heating demand than scenario RCP4.5, ranging from 59% to 74% for SFH (64%-79% for MFH) for the warmer zones and from 43% to 52% for SFH (43%-56% for MFH) for the colder zones. The average difference in the calculated demand using the two scenarios is 34%.

Technological advances, higher performance cooling, and heating equipment will outweigh some of the impacts from more adverse operating conditions during summer, resulting from higher outdoor ambient conditions, and the need for more cooling and longer operating conditions. In any event, the renovation of the existing building stock remains a top priority for controlling the escalation of energy use from millions of high-energy consuming buildings.

The energy consumption for space cooling decreases from the warmer (A, B) to the colder (C, D) climate zones for major building typologies (Figure 8). Until the year 2050, the increased energy demand for cooling in the older, poorly performing buildings (built before 1980) is outweighed by replacing the existing cooling systems with higher efficiency ones (COP=3.5 for heat pumps) leading to an average decrease of 15% in the cooling energy consumption for both climate scenarios. SFH with a better envelope quality (built after 1980) exhibit an increase of 5% in the warmer climate zones (A&B) and up to 20% in the colder zones (C&D). For MFH the respective increase ranges from 18-33% and from 34-57%. The two scenarios (RCP4.5 and RCP8.5) lead to different long-term results. In the year 2090, higher efficiency C&H systems (COP=4.5 for heat pumps) combined with the moderate temperature increase foreseen by climate scenario RCP4.5 mostly leads to a decrease of cooling energy consumption ranging from 15-33% for SFH (3-31% for MFH) in the warmer zones (A&B) and from 3-16% for SFH (16-17% for MFH) in the colder zones (C&D). The much higher energy demand foreseen by the climate scenario RCP8.5 cannot be covered by the high performing C&H

systems considered in this study. As a result, an increase of the cooling energy consumption is observed, ranging from 2-28% for SFH (1-34% for MFH) in the warmer zones (A&B) and from 32-58% for SFH (19-55% for MFH) in the colder zones (C&D). The average difference in the calculated energy consumption using the two scenarios is 37%.

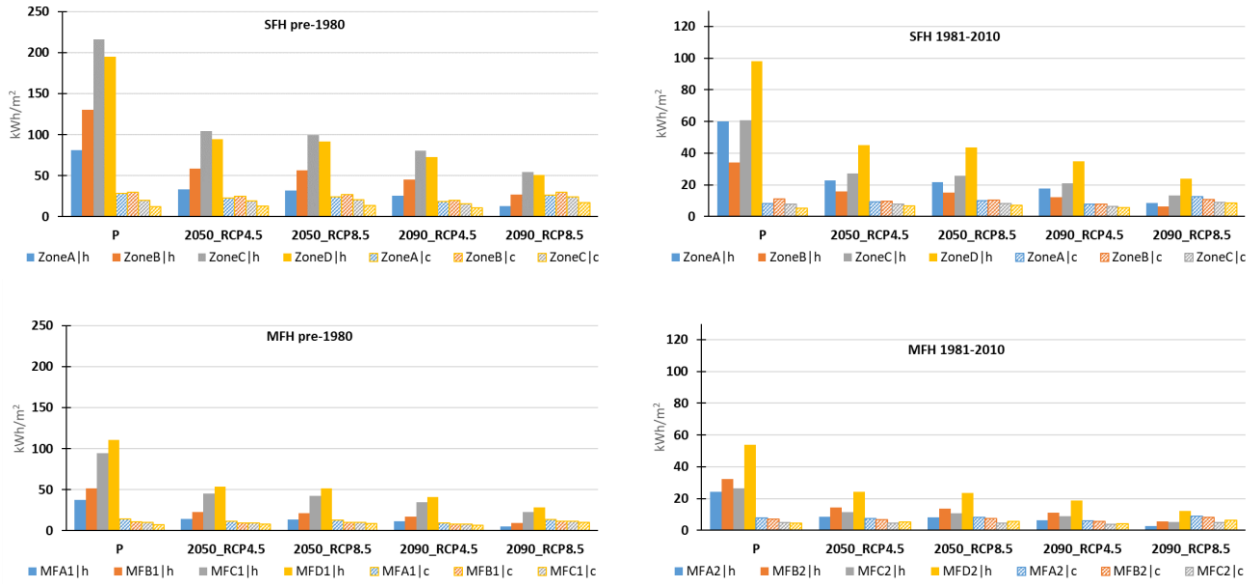

Figure 8 Variations of energy consumption per unit floor area (kWh/m^2) for the building typologies (SFH and MFH) in the four climate zones (ZoneA-ZoneD) for cooling (|c) and heating (|h), for the present baseline (P) and different climate change scenarios (RCP8.5 and RCP4.5)

The energy consumption for space heating increases from the warmer (A, B) to the colder (C, D) climate zones. In line with the heating energy demand, the impact of climate change calculated using the two scenarios (RCP4.5 and RCP8.5) until the year 2050, is reflected in a decrease ranging from 37% to 59% for SFH (40%-61%, for MFH) in the warmer zones and from 21% to 56% for SFH (22%-57% for MFH) in the colder zones. In the year 2090, scenario RCP8.5 results in a significantly higher decrease than scenario RCP4.5, ranging from 74% to 84% for SFH (81%-86% for MFH) for the warmer zones and from 56% to 77% for SFH (67%-79% for MFH) for the colder zones. The average difference in the calculated energy consumption using the two scenarios is 20%.

Considering deep retrofit of existing buildings seems to have a significant impact towards responding to the increased cooling energy demand foreseen for both the near and distant future. Calculations have shown that a decrease in the cooling energy consumption can be achieved for both single and multi-family houses under the climate conditions foreseen by the two scenarios examined in this study. The decrease is larger in the older buildings; specifically using scenario RCP4.5, a decrease of 54% and 68% is calculated for SFH in the colder and warmer zones respectively (53% to 72% for MFH). A 20% lower decrease is calculated using scenario RCP8.5.

Given the fact that climate change will result in ever-increasing ambient temperatures it is evident that taking the minimum required actions to mitigate the GHG emissions, represented by scenario RCP4.5, works better than adopting a business as usual scenario (RCP8.5) keeping the differences in energy demand for both heating and cooling at a lower level in the long run.

The work presented herein has some limitations that are currently being addressed. First, the use of the quasi-steady state monthly method of the national calculation engine for the energy performance analysis may not be suitable for capturing the dynamic impacts of projected future climate conditions. The choice to use this tool was made since this is the calculation approach that is currently

used as the most popular decision making tool for renovations and the selection of different scenarios and the technoeconomic assessments in the framework of state supported energy savings programmes and similar financing tools. In any event, the work is currently being enhanced by following the same methodology, but this time use a building simulation tool (TRNSYS) to perform dynamic energy calculations. Advancing towards a decarbonized electricity grid in the coming decades, current work is also considering adapting the results from this work and future work to use future projections of emission factors for near- and distant future periods to make more realistic projections of emissions. Finally, the work is also being enhanced by considering non-residential buildings in order to complete the typologies of the Hellenic building stock.

5. Acknowledgments

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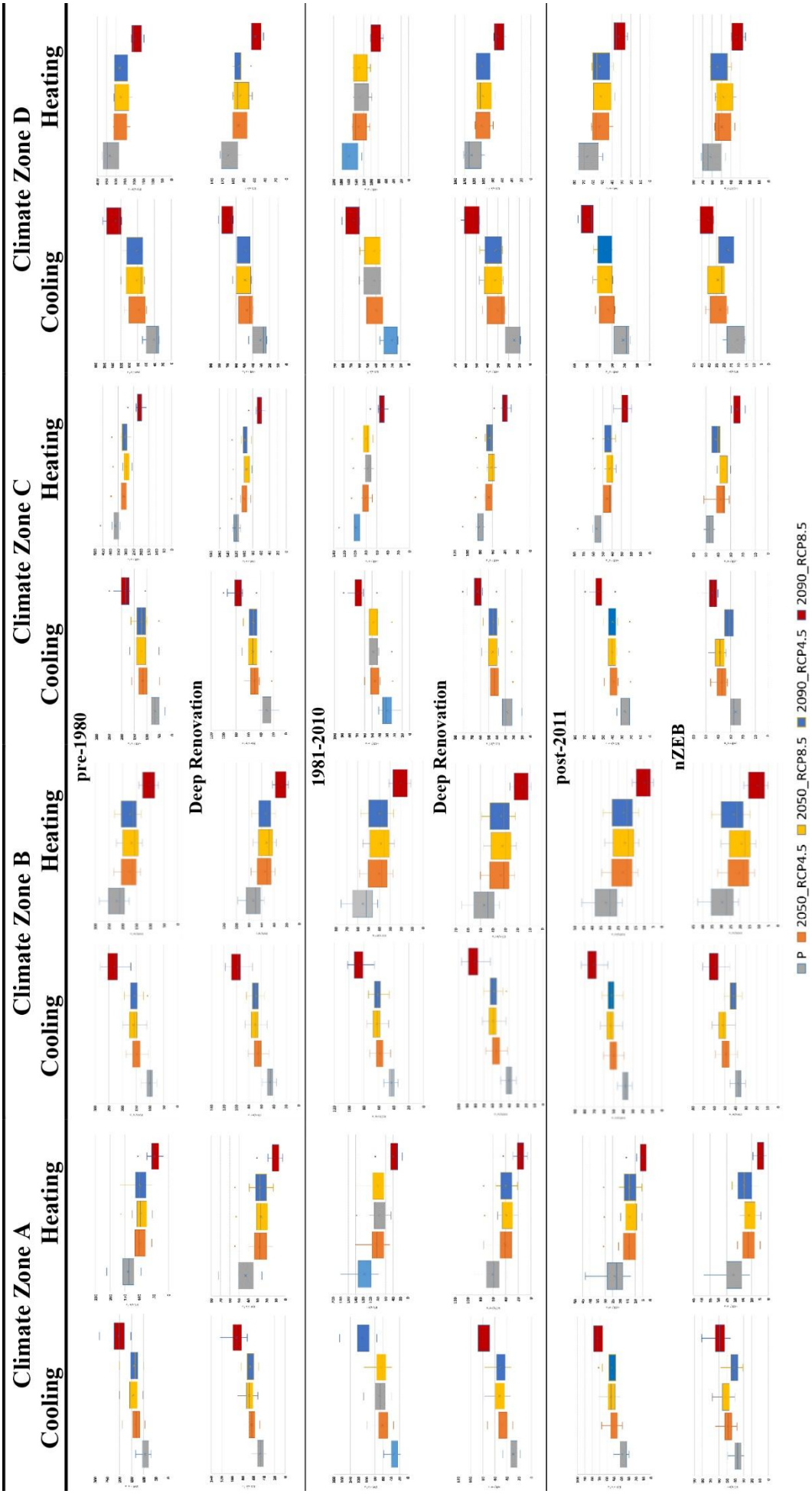

Figure 2a Range and distribution of cooling and heating energy demand per unit floor area (kWh/m²) for SFH typologies in the four climate zones, in the initial condition and after deep renovation for the present baseline (P) and different climate change scenarios (RCP8.5 and RCP4.5)

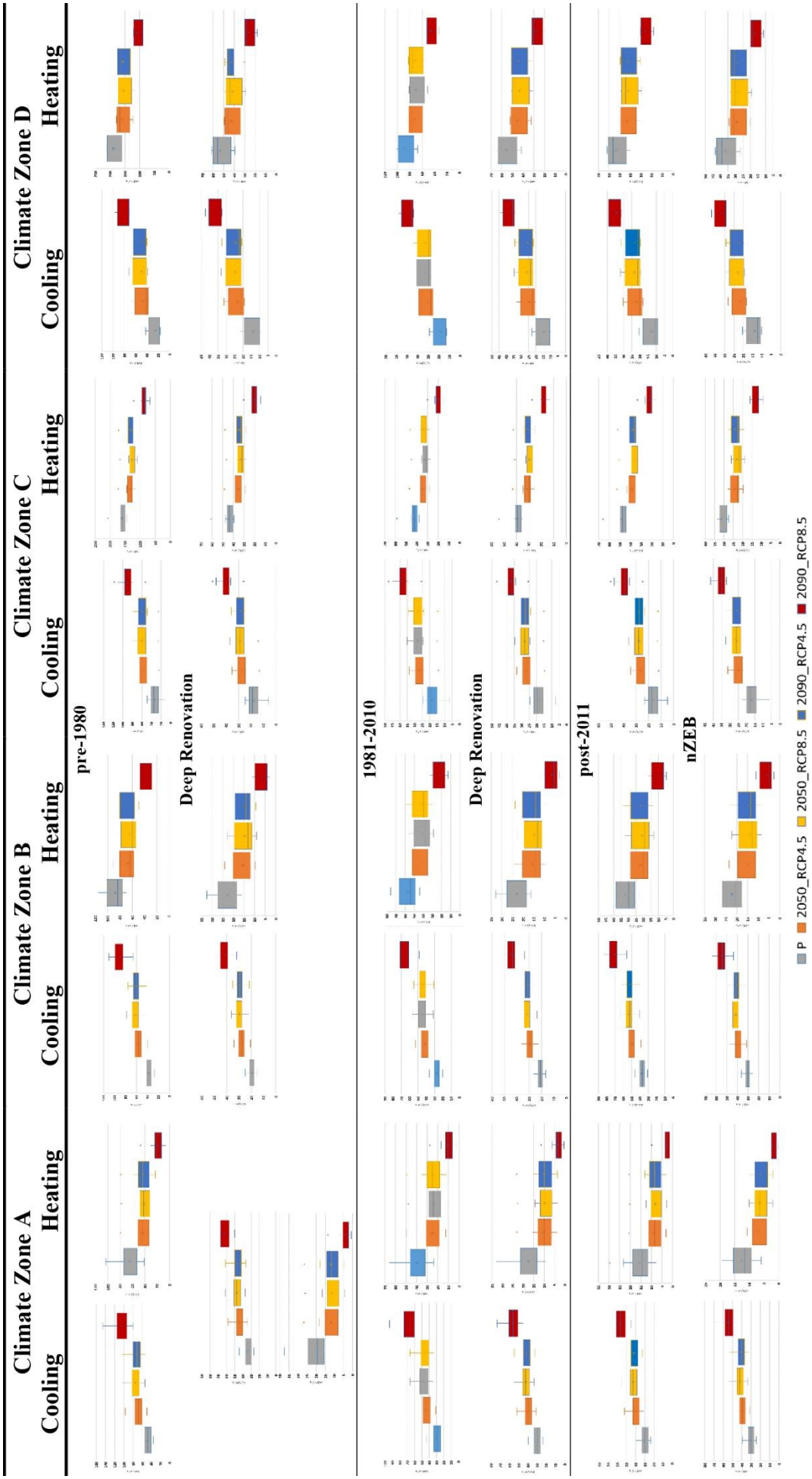

Figure 2b Range and distribution of cooling and heating energy demand per unit floor area (kWh/m²) for MFH typologies in the four climate zones, in the initial condition and after deep renovation for the present baseline (P) and different climate change scenarios (RCP8.5 and RCP4.5)

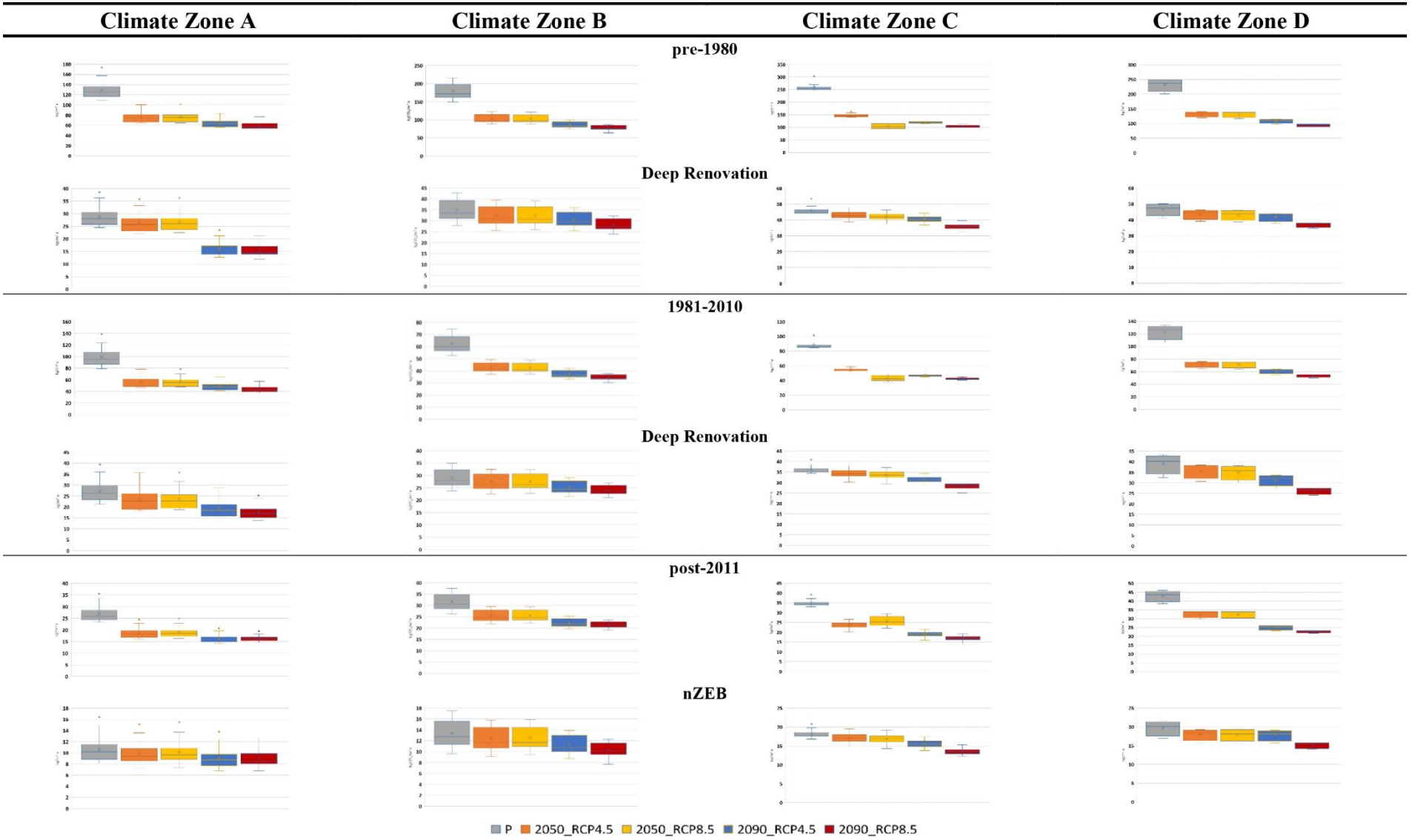

Figure 6a Range and distribution of annual carbon emissions per unit floor area ($kgCO_2/m^2$) for SFH typologies with all electric services for cooling and heating in the four climate zones, in the initial condition and after deep renovation for the present baseline (P) and different climate change scenarios (RCP8.5 and RCP4.5)

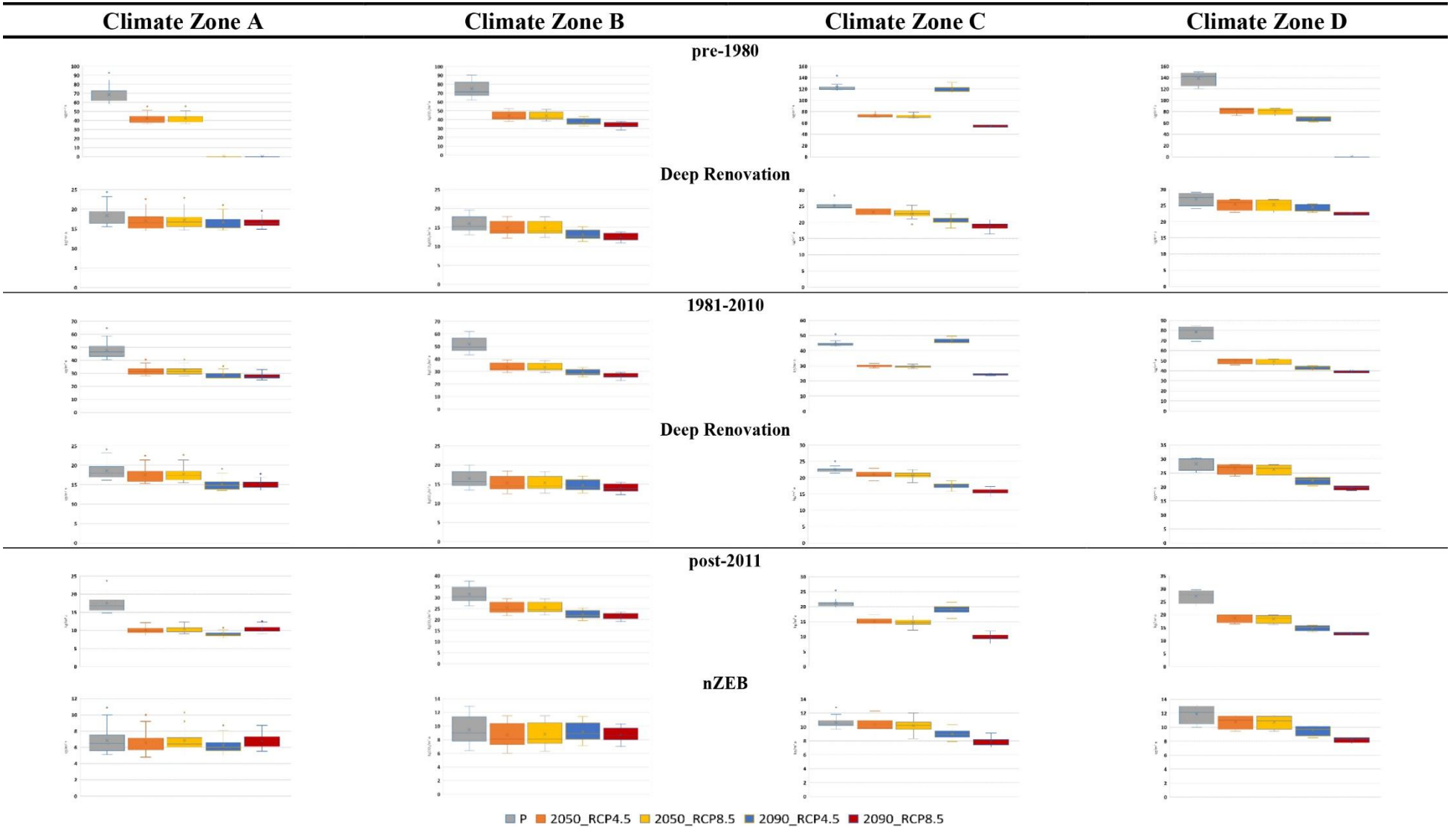

Figure 6b Range and distribution of annual carbon emissions per unit floor area ($kgCO_2/m^2$) for MFH typologies with all electric services for cooling and heating in the four climate zones, in the initial condition and after deep renovation for the present baseline (P) and different climate change scenarios (RCP8.5 and RCP4.5)