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Framework to assess climate change impact on heating and cooling energy demands in building stock: A case study of Belgium in 2050 and 2100

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ABSTRACT

Climate change has a broad impact on different aspects of energy use in buildings. This study explores potential changes in future heating and cooling energy demands. Increasing comfort expectations resulting from events like the extraordinary summer heatwaves in Europe are accelerating this trend to develop future scenarios for a better understanding of the relationship between future climate changes and the cooling need. This study used future weather data to estimate the heating and cooling energy demands in the Belgian building stock by 2050 and 2100 under base and business-as-usual scenarios using a dynamic building simulation model. The study showed that heating energy demand in the base scenario is expected to decrease by 8% to 13% in the 2050s and 13% to 22% in the 2090s compared to the 2010s. Additionally, the cooling energy demand is expected to increase by 39% to 65% in the 2050s and by 61% to 123% in the 2090s compared to the 2010s. Retrofit strategies applied to different building types contribute to lower the increase in cooling energy demand in the business-as-usual scenario compared to the base scenario. The cooling energy demand for an average building in the business-as-usual scenario is expected to increase with a range of 25% to 71% in the 2050s compared to 45% to 92% in the base scenario and 77% to 154% in the 2090s compared to 72% to 198% in the base scenario compared to the 2010s. The findings of the study provide insights to mitigate the impacts of climate change on heating and cooling energy demands.

1. Introduction

In recent years, there has been a growing emphasis on the issue of global warming and climate change. The sixth assessment report by the Intergovernmental Panel on Climate Change (IPCC) highlights that the 21st century will witness a surpassing of the 1.5 °C and 2 °C global warming thresholds. According to the report, the average global surface air temperature is projected to rise by 1 to 5.7 °C between 2081 and 2100 compared to the period between 1850 and 1900, depending on the various CO_2 emission scenarios [1,2]. The energy demand for HVAC systems increases significantly as a result of this temperature rise. Warmer temperatures increase the demand for air conditioning [3], while more frequent heat waves increase the demand for cooling. On the other hand, declining temperature levels, particularly in winter, reduce the demand for heating. Over the coming years, changes in CO2 emissions are anticipated to have an impact on humidity, wind patterns, and solar radiation [4–6].

Various emissions scenarios have been defined to evaluate potential future climate changes and assess their possible impacts [7,8]. The calculation of these emissions scenarios involves the utilization of diverse models that encompass societal development, taking into account economic factors and technological advancements. Five narrative scenarios, along with a set of radiative forcing levels, have been established. Each scenario encompasses distinct groups that represent alternative energy technology advancements, thereby influencing carbon emissions [8]. Each of these scenarios is fed into Earth System Models (ESMs) to provide climate projections [9]. The set of these ESMs is listed in the CMIP6 (Sixth Coupled Model Intercomparison Project) database [2].

The disadvantage of the models proposed by the CMIP6 is that global models have a coarse spatiotemporal resolution (∼100 km and ∼ 6 h).

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Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ACH	Air Change Per Hour
BAU	Business-as-usual
CO_2	Carbon dioxide
CMIP6	Sixth Coupled Model Intercomparison Project
DHW	Domestic Hot Water
ESM	Earth System Models
EPB	Energy Performance of Buildings
EU	European Union
ERA5	Fifth-Generation European Reanalysis
GWh	Gigawatt-hour
GHG	Greenhouse Gas
HVAC	Heating, Ventilation, and Air Conditioning
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
km	Kilometre
kW	Kilowatt
kWh	Kilowatt-hour
MWh	Megawatt-hour
MAR	Modèle Atmosphérique Régional
NG	Natural Gas
RCP	Representative Concentration Pathways
SLPs	Synthetic Load Profiles
SSP	Shared Socioeconomic Pathways
SuFiQuaD	Sustainability, Financial and Quality evaluation of Dwelling types
TABULA	Typology Approach for Building Stock Energy Assessment
TMY	Typical Meteorological Year
US	United States

Nomenclature

1/H	Thermal resistance [1/(W/K)]
A	Effective surface area of occupants [m^2]
C_m	Thermal capacity [J/K]
$H_{tr,em}$	External part of the heat transfer coefficient for non-window opaque elements [W/K]
$H_{tr,is}$	Heat transfer coefficient by thermal transmission due to thermal conductance [W/K]
$H_{tr,ms}$	Internal part of the heat transfer coefficient for non-window opaque elements [W/K]
$H_{tr,op}$	Heat transfer coefficient by transmission through opaque components [W/K]
$H_{tr,w}$	Heat transfer coefficient by thermal transmission through windows [W/K]
H_{ve}	Heat transfer due to ventilation [W/K]
Φ	Heat flux [W]
$\Phi_{HC,nd}$	Heating or cooling need [W]
$\Phi_{H,max}$	Maximum available heating power [W]
Φ_{int}	Heat flow rate due to internal heat source [W]
Φ_{sol}	Heat flow rate due to solar heat source [W]
$\Phi_{C,max}$	Maximum available cooling power [W]
θ_{air}	Air temperature node [°C]
$\theta_{int,set,H}$	Heating setpoint temperature [°C]
$\theta_{int,set,C}$	Cooling setpoint temperature [°C]
θ_s	Surface temperature node [°C]
θ_m	Mass temperature node [°C]
θ_{sup}	Supply air temperature [°C]
θ	Temperature node [°C]
m_{occ}	Number of occupants per household [-]
met_{occ}	Metabolic rate coefficient [-]

The use of regional models fed from these global models has the advantage of refining their spatial and temporal resolutions over a specified region.

The impact of climate change on energy demand has become a major concern in recent years, particularly for the building sector. Within the European Union (EU), buildings contribute to 40% of our overall energy consumption and 36% of greenhouse gas emissions. Interestingly, in the majority of European countries, the energy demand for heating purposes significantly surpasses the energy consumed for space cooling [10]. Several studies have been conducted around the world to study the impact of climate change on various building types. However, this impact will vary in the different climate regions, as indicated in Table 1 [11–16]. Wang and Chen [11] focused on their study on assessing how climate change would affect the heating and cooling consumption in residential and commercial buildings across all seven climate zones in the US. The results revealed that by the year 2080, there would be a notable decrease in heating energy demand, ranging from 30% to 65%. On the other hand, cooling energy demand would experience a significant increase of 50% to 150%. Furthermore, the study identified that in certain cities, natural ventilation would no longer be a feasible option by the 2080s, indicating a need for alternative cooling strategies. In a study conducted by Frank [12] in Switzerland, the focus was on studying climate change's influence on heating and cooling energy demands in both residential and office buildings. The study used four different climate scenarios. The results showed residential buildings would experience a decrease in heating energy demand ranging from 33% to 44%. In contrast, office buildings would see a larger decrease in heating energy demand, ranging from 36% to 58%. However, it was observed that the cooling energy demand in both residential and office buildings would increase significantly, with a range of 223% to 1050%. In the Mediterranean climate, Pérez-Andreu et al. [13] assessed the impact of climate change on heating and cooling energy demands in a residential building. The study analysed eight different models for a house by applying different active and passive measures. The models of the study showed different results in each scenario with the proposed measures to meet or reduce the total cooling energy demand based on the proposed cooling measures.

Berardi and Jafarpur [14] assessed the potential effects of climate change on a set of 16 ASHRAE prototype buildings located in Toronto. The results indicate that by 2070, the heating energy demand for buildings will experience a reduction ranging from 18% to 33%. Conversely, the cooling energy demand is expected to witness an increase ranging from 15% to 126%. Another study conducted by Invidiata and Ghisi [15] assessed the future energy consumption for different buildings in three cities in Brazil for the years 2020, 2050, and 2080. The findings revealed that there will be an increase in the annual energy demand by 112–185% in 2080 across all three cities. However, in the coldest city, the study indicated a significant decrease in the annual heating energy demand by 94%. Additionally, the study explored various passive strategies aimed at mitigating the future annual cooling energy demand, potentially leading to a reduction of up to 50% in both the future cooling energy demands.

While there have been numerous studies examining the impact of climate change on energy demand at the building scale, only a limited number of studies have focused on the building stock scale, particularly with regard to a multi-zone approach at the stock level. Another study by Nik and Kalagasidis [16] assessed the energy performance of the building stock in Sweden by a sample of 153 existing and statistically selected buildings where each building is represented as one thermal zone in the period 1961–2100. The aforementioned study takes into account four factors of uncertainty in climate: global climate models, regional climate models, emissions scenarios, and initial conditions. The

Table 1
Summary of previous literature on climate change impacts on building heating and cooling energy demands. This table is based on a review of published studies, but it is not comprehensive.

Study	Country	Methodology	Simulation tool	Building type	Building approach	Conclusion
Wang & Chen [11]	US	Assuming a 2.7–7 °C temperature increase for the different simulated scenarios with weather projections from 1964 to 2080.	EnergyPlus	Residential and commercial	Typical	Heating energy demand is projected to decrease by 30–65%, and cooling energy demand is projected to increase by 50–150%. The effect of natural ventilation is dramatically reduced, and the average peak energy demand for cooling increases by up to 120%, expecting more significant peaks for punctual heat waves not modelled in the study.
Frank [12]	Switzerland	Assuming a 0.7–4.4 °C temperature increase for the different simulated scenarios for the period 2050–2100.	HELIOS	Residential and commercial	Typical	Heating energy demand is expected to decrease by 33–58%, and the cooling energy demand is expected to increase by up to 1050%
Pérez-Andreu et al. [13]	Mediterranean climate	Assuming a 1–5.6 °C temperature increase for the different simulated scenarios for temperature projections for 2050 and 2100	TRNSYS	Residential	Typical	Heating energy demand can decrease by up to 90% with the combined effect of climate change, passive measures such as insulation and ventilation with heat recovery. Cooling energy demand increased in future scenarios. To reduce the cooling energy demand in one model, the effectiveness of passive measures such as natural ventilation and the use of shading can deteriorate with climate change but can yet help reduce the cooling energy demand by up to 50%.
Berardi & Jafarpur [14]	Canada	Assuming a 3.7–4.5 °C temperature increase for the different simulated weather scenarios for 2041–2070	OpenStudio	Residential, offices and commercial	Representative	Heating energy demand is expected to decrease by 18%–33%, and cooling energy demand is expected to increase by 15–126%.
Invidiata & Ghisi [15]	Brazil	Assuming a mean temperature increase of 3.6–5.1 °C for the 2020–2080 period.	EnergyPlus	Residential	Typical	Heating energy demand is expected to decrease by 94%. Cooling energy demand is expected to increase, and buildings, therefore, have to be designed to reduce the associated energy consumption. Using passive strategies helps to reduce the increase by up to 50%.
Nik & Kalagasidis [16]	Sweden	Assuming a mean temperature increase of 2.5–4 °C for the period 1961–2100	Dynamic single-zone energy balance equations in Simulink	National building stock	Typical	Heating energy demand is expected to decrease by 30%. The cooling energy demand is expected to increase but will remain rather low and can be mostly met by natural cooling.

results showed that the heating energy demand during 2081–2100 will decrease by around 25–30% compared to 2011, while the increase in the cooling energy demand can be covered by natural ventilation. Furthermore, Attia and Gobin [17] conducted an assessment of the influence of climate change on thermal comfort in a nearly zero-energy building located in Belgium using three representative concentration pathways (RCP). The results showed that in both static and adaptive thermal comfort models in 2050 and 2100 scenarios, the number of overheating hours exceeded the allowable upper thresholds for discomfort hours in residential buildings.

The present paper aims to propose a framework to assess the impact of climate change on daily, monthly and annual heating and cooling energy demands using a multi-zone approach applied to the building stock in Belgium, using the MAR regional atmospheric model that shows a high spatial resolution (5 km) [18]. This MAR model has been validated over the Belgium territory. This study utilizes multiple weather datasets, including one generated by a reanalysis model covering the historical period (2000–2020) and three generated by Earth System Models (ESM) encompassing the historical (1980–2014) and future periods (2015–2100) under various future scenarios. These datasets are used to generate diverse future projections and assess associated uncertainties for different SSP scenarios, namely SSP5-85, SSP3-70, and SSP2-45. The paper also develops the tree structure model that represents the residential building stock in Belgium initiated by Gendebien et al. [19], considering the updated measures to meet the renovation targets in Belgium by 2050. The final building stock is divided into 752 cases representing 4,675,433 buildings in the base scenario in 2012 which increases by 0.348% in 2050 to reach 6,152,311 dwellings in the business-as-usual (BAU) scenario by considering annual rates for demolition, construction and renovation.

The findings in this study address an increasing need among researchers and policymakers to look into how evolving weather patterns in the future will affect energy demand, particularly for cooling.

The paper is structured as follows. Section 2 presents the methodology of the study. The conceptual framework is presented in section2.1. The building stock tree structure is presented in section 2.3, the base scenario in (section 2.3.1) and the BAU scenario – up to 2050 in (section 2.3.2). Climate data is provided in section 2.4. The thermal model used to calculate the heating and cooling energy demands is presented in section 2.5. The results for the evolution of climate and the evolution of heating and cooling energy demands are shown in section 3, while section 4 discusses the key findings of the paper, strengths, and limitations and suggests the potential future research of the ongoing study. Section 5 concludes the paper.

2. Methodology

2.1. Conceptual framework

The conceptual framework used in this study is structured into four parts that guide the calculation and analysis of heating and cooling energy demands in the building stock, as shown in Fig. 1. This

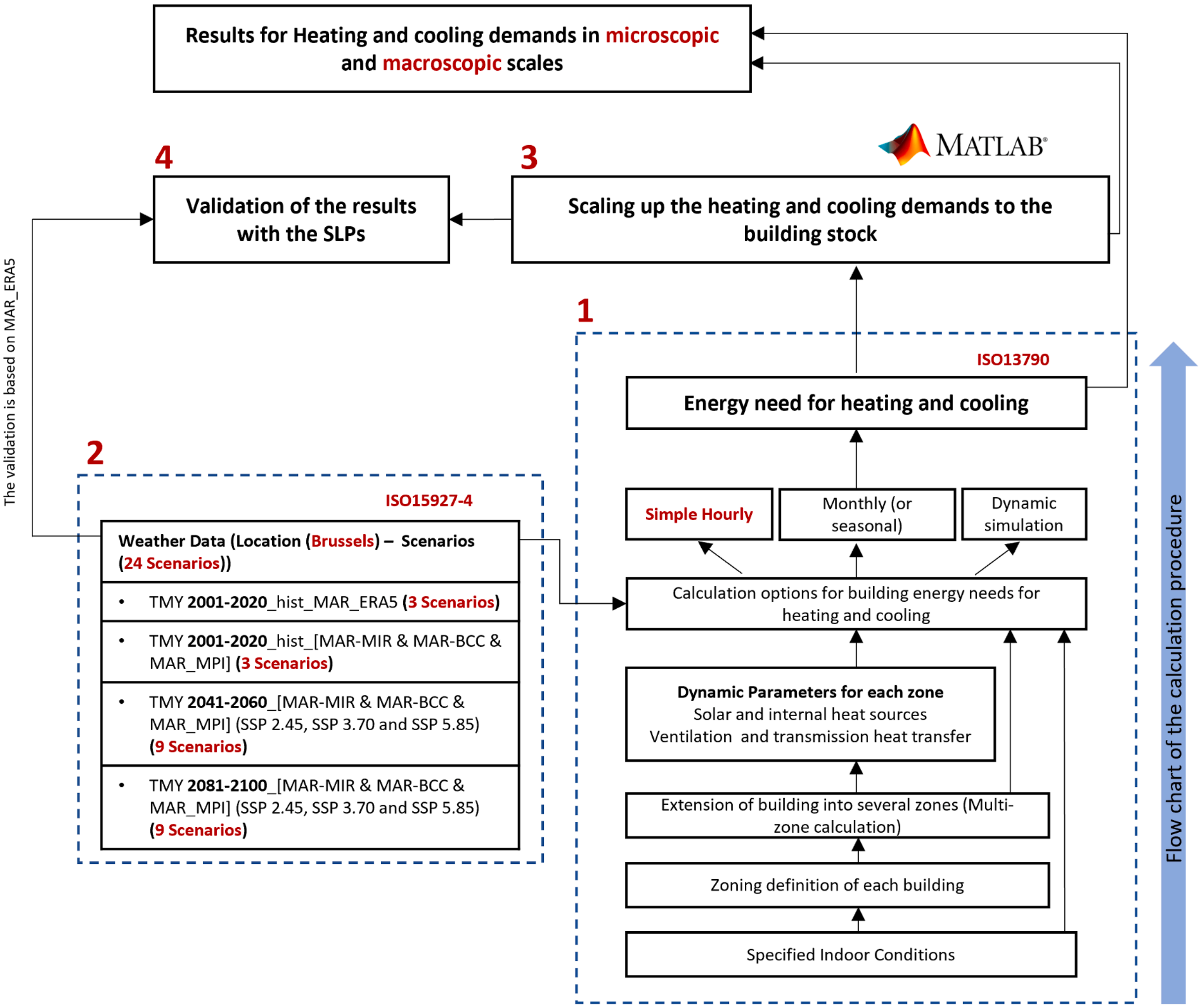

Fig. 1. Conceptual framework of the study.

framework offers a comprehensive and systematic approach to estimating the energy demand for the heating and cooling of buildings.

1. The first part, which is based on ISO 13790:2007, outlines the procedures involved in computing the energy requirements for heating and cooling. This section highlights the crucial steps that must be considered, such as defining the indoor conditions, zoning of each building, and the extension of the building into several zones (if the multi-zone approach is used). Additionally, it includes the dynamic parameters for each zone and the calculation options for building energy needs, whether it's simple hourly, monthly (or seasonal), or dynamic simulation. This study uses a simple hourly method which is a simplified dynamic simulation model with the same level of transparency and robustness as shown in section 2.5.1.1.
2. The second section specifies the weather data that is used in the calculations (based on ISO15927-4). In this study, the weather data for Brussels in the mid-term and long-term future scenarios through different emission scenarios are used, as explained in section 2.4.
3. The third section scales the heating and cooling needs from a single building to the building stock, utilizing the building stock model represented in the study (see section 2.3).
4. Finally, the fourth part focuses on validating the data obtained from the previous three sections. It involves comparing the results with real data and verifying the model's accuracy.

In addition to assessing the impact of climate change on heating and cooling energy demands on a macroscopic approach for the building stock, the study also included an assessment of the potential impact of climate change on heating and cooling energy demands at the building scale. Additionally, the study evaluated the impact of climate change on different archetypes of buildings, taking into account their insulation characteristics and other relevant factors using a microscopic approach.

To enhance the robustness and credibility of our framework, step 2 of the framework considers the uncertainty of climate by conducting three MAR simulations: medium, hottest, and coldest. These simulations encompass a range of climatic conditions to account for the inherent variability and uncertainty in climate projections. It is important to note that the MAR model used in this study has been thoroughly validated over the Belgium territory, as explained in section 2.4. Additionally, the study assesses associated uncertainties for different SSP scenarios. These scenarios represent different future SSPs that are commonly used in climate change research. The SSP5-85 scenario represents a high greenhouse gas emissions pathway, SSP3-70 represents a moderate emissions pathway, and SSP2-45 represents a low emissions pathway.

Furthermore, in step 3, when scaling up the results to the building stock, the study acknowledges the existence of uncertainties related to the renovation scenarios applied in Belgium. The uncertainty of the building stock is primarily influenced by the choice of renovation scenarios. These scenarios represent a range of possible outcomes, encompassing both optimistic and low renovation rates. Section 3.2.3 addresses this uncertainty by performing uncertainty analysis through eight different renovation scenarios for the Belgian building stock.

2.2. Top-down and bottom-up approaches

There are two approaches to describe the building stock model: top-down and bottom-up [20,21]. The top-down approach, in most cases, is utilized to study the connections between the energy end economic sectors [22], while there is no consideration given to end-use or potential improvements at the building stock level to assess the impact of various changes on energy performance [19,22]. The bottom-up approach starts with disaggregated buildings or building components and works its way up to the building stock level [21]. Therefore, it requires a large database of actual data to represent the building stock components [23]. As a result of the bottom-up approach, a very accurate building stock model with a high level of detail is produced [24]. The bottom-up approach is quite helpful for determining the energy consumption of existing building stocks, according to Reiter & Marique [22].

Worldwide, several studies were conducted using the bottom-up approach. In the US, Huang and Brodrick [25] used a bottom-up engineering approach to estimate the aggregate building energy end-use for commercial and residential buildings. Another study by Langevin et al. [26] discussed that all newly constructed buildings, as well as various existing building stock energy use intensities, are estimated using bottom-up appliance distribution models. Additionally, Ghedmasi et al. [27] used the bottom-up approach for modelling and predicting energy usage in Algerian residential buildings until 2040.

In Belgium, top-down and bottom-up approaches have been used in different steps of the same assessment. In addition to the necessary attributes from cadastral data, Nishimwe and Reiter [28] used the outputs of the top-down approach as the input data for the bottom-up approach. The mapping of heating consumption and heating energy demand on different scales in Wallonia utilized the outputs of the bottom-up approach. In another study, Reynders et al. [29] developed a reduced-order bottom-up dynamic model of the building stock to assess the potential for demand-side management through the structural storage capacity of buildings in Belgium.

The approach used in this paper adopted a bottom-up methodology to characterize the residential building stock in Belgium. As a first step, a dynamic multi-zone model was implemented to calculate heating and cooling energy demands. Secondly, a tree structure characterizing the residential building stock typology was developed, as shown in detail in Section 2.3. Following that, energy load profiles were created and calibrated to the Belgian context using stochastic probability curves. Lastly, the evolution of the building stock till 2050 following the new development trends was created to investigate the penetration of new technologies in the market while taking into consideration the renovation of the old buildings and also the newly constructed buildings.

2.3. Building stock structure

As part of this study, a tree structure model representing the residential building stock in Belgium has been developed within the framework. This tree structure can also be used as a tool to evaluate the impact of various penetration scenarios of HVAC technologies on electricity and gas load profiles at a national scale [30] and the annual consumption of the building stock [31]. Protopapadaki et al. [32] compared the aforementioned residential building stock with the TABULA one [33] to identify their differences and investigate how variations in the representation of building stock can influence the outcome of bottom-up modelling.

The architecture of the used tree structure is shown in Fig. 2. The entire housing stock is represented in two scenarios (base and BAU), as explained in section 2.3.1 and section 2.3.2, respectively.

Based on this building stock tree structure, the distribution of average U-values for walls and windows are shown in Fig. 3, along with their respective proportions within the building stock.

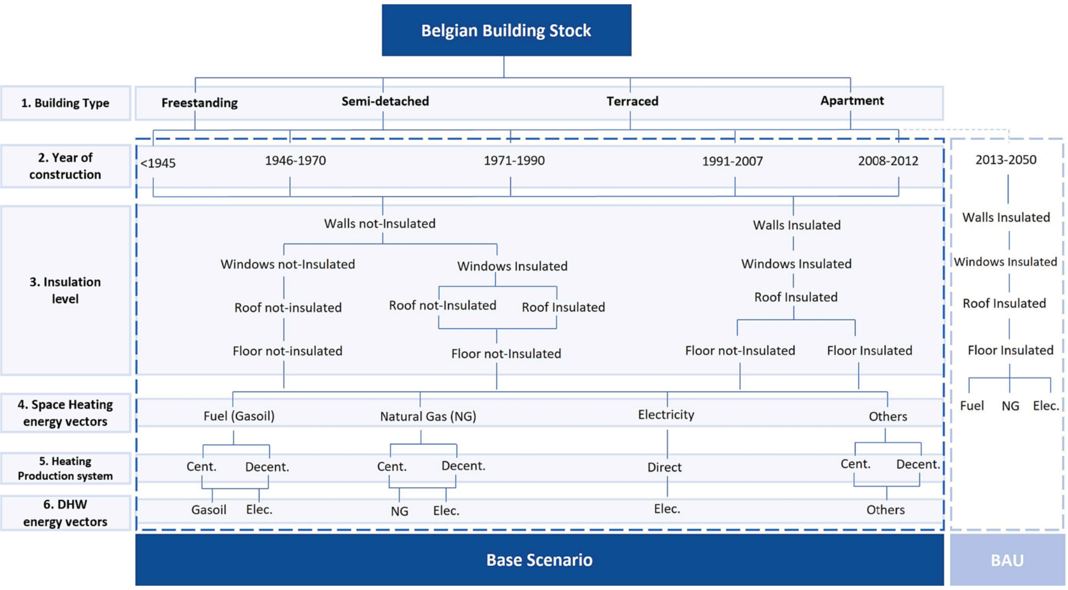

Fig. 2. Belgian residential building stock tree structure.

In this study, a "hybrid approach" is used, which combines elements of both the representative and typical approaches. There is a distinction between the two approaches used in the building stock typology: the "representative approach" and the "typical approach", as explained by Cyx et al. [33].

- The representative approach entails modelling a set of fictional buildings with average characteristics (U values, average efficiencies and different energy vectors) that represent the entire building stock. The parameters of these fictional buildings are adjusted to align with the energy consumption of the overall building stock, as recorded in energy balances.
- The typical approach, on the other hand, involves extending the characteristics of a typical building to a set of buildings that closely resemble existing buildings and their components [33–35]. These typical buildings are selected based on their representativeness in relation to the building stock, and actual buildings and their characteristics serve as the basis for this process. This approach provides a more detailed and specific picture of the building stock and allows for the examination of the impact of various energy-saving measures on specific individual dwelling types.

In the present work, the hybrid approach combines the strengths of each approach which allows for a balance between the general overview provided by the representative approach and the detailed information provided by the typical approach. The use of a hybrid approach provides a comprehensive understanding of the building stock and its energy consumption patterns, taking into account both average values and specific individual dwelling types. The hybrid approach addresses a weakness of the typical approach, which only investigates one case for a type of building. The hybrid approach overcomes this limitation by considering a set of several U values for different buildings, depending on the insulation level, for each type of building. Additionally, the hybrid approach has been validated for the Walloon housing stock, confirming its reliability for annual energy use [36].

The creation of the largest building stock tree structure involves considering all possible cases based on available statistics, leading to a significant number of investigated cases and the reliance on numerous assumptions, which takes more than two days to simulate all the cases for only one year. Due to this fact, simplifications need to be introduced.

After several simplifications, the tree structure is developed using a number of references. A set of 4 building types (freestanding, semi-detached, terraced and apartments) in four construction periods (pre-1945, 1946–1970, 1971–1990 and 1991–2007) taken from the work of Allacker [37] have been selected to represent the different building types for each age class. The existing plans are used to determine the geometry of the buildings. From the SuFiQuaD project [38], the share of each type of building in the overall stock was taken and updated using available information from the Belgian National Institute of Statistics [39]. The study by Kints provides information on the ratio of insulated to uninsulated building materials (walls, windows, roofs, and floors) according to the types and ages of buildings [40]. The TABULA study

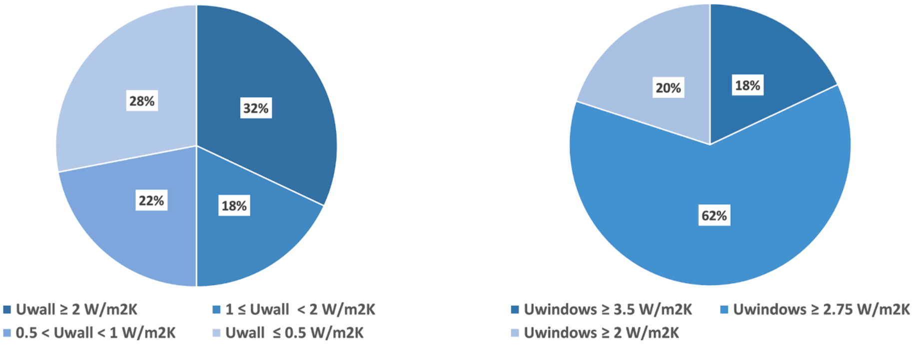

Fig. 3. U-values repartition for walls and windows.

provides information on the composition of uninsulated elements [33]. With the use of a weighted average of values provided by Kints et al. [40], the insulation levels for levels of walls, roofs, and floors were calculated. Additionally, the TABULA framework considered five construction periods by adding an additional period (2008–2011).

The methodology developed to create the tree structure is described in detail in the paper of Gendebien et al. [19]. In order to reflect the various typologies and age classes, the geometrical qualities of 16 typical buildings have been expanded to a set of buildings. The 16 typical buildings are represented by four types of buildings (freestanding, semi-detached, terraced and apartments) and five construction periods in the base scenario (pre-1945, 1946–1970, 1971–1990, 1991–2007 and 2008–2012) as shown in Fig. 2, while considering the same building geometry reference in the two construction periods (1991–2007 and 2008–2012). Within the same construction period and associated building geometry, the tree structure model further distinguishes various scenarios based on factors such as insulation level, the type of energy source used for space heating and domestic hot water (DHW), and the choice between centralized heating production systems (such as boilers) and decentralized heating production system (such as electric resistive heaters and gas convectors). The efficiency of heating production systems depends on whether both space heating and DHW are produced using the same energy source. In centralized systems, where space heating and DHW use the same energy source, their production efficiencies are set to the same value, with the boiler efficiency being influenced by the construction year. However, if DHW is produced using a different energy source, which is electricity, the production efficiency is set to 100%, taking losses into account in the tank model. In decentralized systems, where DHW is produced using a different energy source than space heating (excluding electricity), the efficiency is fixed at 0.9, regardless of the building's age.

The final structure of the building stock tree is determined by considering six parameters:

1. Building type: it categorizes buildings into freestanding, semi-detached, terraced, and apartments.
2. Year of construction: buildings are classified based on the periods they were constructed, including pre-1945, 1946–1970, 1971–1990, 1991–2007, 2008–2012, and 2013–2050 (for the BAU scenario).
3. Insulation level: this parameter describes the insulation level of the building envelope for walls, windows, roofs, and floors.
4. Space heating energy vectors: these indicate the energy sources used for space heating, such as fuel, natural gas (NG), electricity, and other alternatives such as coal or wood.
5. Heating production system: this parameter differentiates between centralized and decentralized heating systems.
6. DHW energy vectors: these represent the energy sources utilized for DHW, including fuel, NG, electricity, and other alternatives like coal or wood.

2.3.1. Base scenario

The base scenario is divided into 752 cases representing 4,675,433 buildings. There have been 202 cases studied in each of freestanding, semi-detached, and terraced homes and 146 cases in apartments. Fig. 4 (a) shows the distribution of Belgian dwelling types across five different construction periods in the base case, while Fig. 4 (b) presents the percentage of dwellings driven by different energy sources utilized for space heating. The majority of buildings are fulfilled by NG, accounting for 50.14% and fuel boilers for 40.02%. Meanwhile, electricity and other energy sources have a relatively smaller distribution, representing 5.76% and 4.08%, respectively. The building stock base scenario does not currently incorporate active cooling systems.

The base scenario discussed here is concerned with studying the evolution of heating and cooling energy demands with climate change but without the implementation of any demolition or renovation strategies. This scenario aims to assess the current building stock and understand how it will perform under changing climatic conditions without any interventions to improve energy efficiency.

2.3.2. Business-as-usual scenario (up to 2050)

The BAU scenario consists in updating the building stock up to 2050. The tree structure representing the building stock in 2012 was turned into an evolutionary tree structure, allowing for simulations of potential changes in the building stock over time. This involved considering annual rates of demolition, construction, deep retrofit, and shallow retrofit. The tree structure is initially updated to incorporate the newly constructed and demolished buildings from 2013 to 2050. n line with the long-term renovation strategies of Brussels, Wallonia, and Flanders in Belgium, the average annual rates of construction and demolition are set at 0.9% [39,42–44] and 0.075% [45], respectively. The total number of buildings for the year 2050 can be deduced from Eq. (1) [19]:

$$N_{2050} = N_{2012}\left(1 + \left(x_{con} - x_{dem}\right)\right)^{t} \tag{1}$$

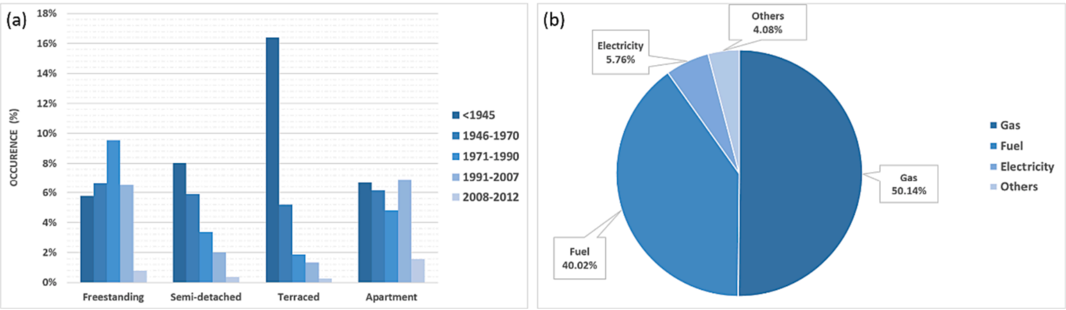

Fig. 4. Base scenario (a) distribution of the Belgian dwelling types by the five construction periods (b) percentage of dwellings driven by different energy sources for space heating [41].

With:
- N_{2012}: total number of buildings in 2012;
- N_{2050}: the total number of buildings in 2050;
- X_{con}: annual construction rate;
- X_{dem}: annual demolition rate;
- t: number of years considered (i.e. $t = 38$ years).

In the study, two renovation strategies have been considered - deep renovation and shallow renovation.

- Deep renovation refers to implementing extensive insulation measures across all components of a building, encompassing walls, windows, roofs, and floors. This strategy aims to improve the overall energy efficiency of the building, reducing heat loss and improving indoor comfort.
- On the other hand, shallow renovation is a more limited renovation strategy that focuses on the insulation of roofs and windows according to the Energy Performance of Buildings (EPB) Directive 2010 [46]. This strategy is intended to reduce heat loss through the roof and windows, which are typically the main sources of heat loss in a building. Shallow renovation can be considered a cost-effective alternative to deep renovation, particularly for buildings that are already well-insulated.

It has been assumed that priority was given first to the oldest non-insulated buildings (deep renovation) and, in the second time to the partially insulated buildings (shallow renovation).

Additionally, due to the uncertain renovation rates in the future, uncertainty analysis is carried out for various renovations. The renovation and demolition strategies can vary greatly depending on factors such as government regulations, consumer behaviour, and the availability of funding. As a result, it can be difficult to predict the exact renovation rate that will be achieved in the future. The study conducts an uncertainty analysis to assess the impact of the uncertain range of renovation rates on heating and cooling energy demands through eight renovation scenarios, as shown in Table 2. The table shows different scenarios with different rates of demolition, shallow renovation, and deep renovation. The total renovation rate represents the sum of the shallow and deep renovation rates.

Scenario 1 is the reference scenario, where all types of renovation are considered, and the rates are set at 0.075% for demolition, 0.8% for shallow renovation, and 0.5% for deep renovation, resulting in a total renovation rate of 1.3%. The renovation rate in the reference scenario is calculated based on the average number of retrofit grants awarded in the last 20 years in the Brussels region and then extended to the national building stock in Belgium [39,47]. However, to cover the uncertain range of renovation rates, other scenarios (scenario 2 to scenario 8) are used. These scenarios vary in the rates of renovation, ranging from very pessimistic scenarios with a 0% renovation rate to very optimistic scenarios where all building stocks are renovated with the maximum renovation rate. The purpose of these varied scenarios is to explore a wide range of possibilities and assess the impact of different renovation rates on the overall outcomes. Scenario 2 in the table shows the case where no buildings are renovated, but the demolition rate remains at 0.075%. This is essentially a BAU scenario, where no effort is made to reduce the energy demand of buildings through renovation. Scenario 3, on the other hand, assumes a higher demolition rate of 0.22% but also no renovation. This scenario implies a higher rate of demolishing older buildings and replacing them with new buildings that may have better energy efficiency, but still, no effort is made to retrofit or improve the energy efficiency of existing buildings. Scenario 4 has a moderate total renovation rate and a balanced distribution of shallow and deep renovation. Scenario 5 has a high deep renovation rate and no shallow renovation. Scenario 6 has a high shallow renovation rate and no deep renovation. Scenario 7 has a high total renovation rate and a relatively balanced distribution of shallow and deep renovation. Scenario 8 has the highest deep renovation rate and no shallow renovation. Scenario 8 has the highest shallow renovation rate and no deep renovation. The main difference between these scenarios is the allocation of renovation types and rates, which leads to different levels of energy demand and greenhouse gas emissions. The common factor in all scenarios is the implementation of renovation strategies to reduce energy demand and greenhouse gas emissions from buildings.

The expected distribution of dwellings in 2050 is shown in Fig. 5 (a). The number of dwellings for the reference year 2012 was 4,675,433 and reaches 6,152,311 dwellings in 2050. Fig. 5 (b) shows the percentage of dwellings driven by different energy sources used for space heating. The electricity share is 18.20% compared to 5.76% in the base scenario. This increase is attributed to various policies and regulations aimed at

Table 2
Different renovation scenarios for the Belgian Building stock.

Scenarios	Demolition rate [%]	Shallow renovation rate [%]	Deep renovation rate [%]	Total renovation rate [%]
Scenario 1 (reference)	0.075	0.8	0.5	1.3
Scenario 2	0.075	0	0	0
Scenario 3	0.22	0	0	0
Scenario 4	0.075	0.4	0.25	0.65
Scenario 5	0.075	0	1.3	1.3
Scenario 6	0.075	1.3	0	1.3
Scenario 7	0.075	0.95	0.85	1.8
Scenario 8	0.075	1.95	0	1.95

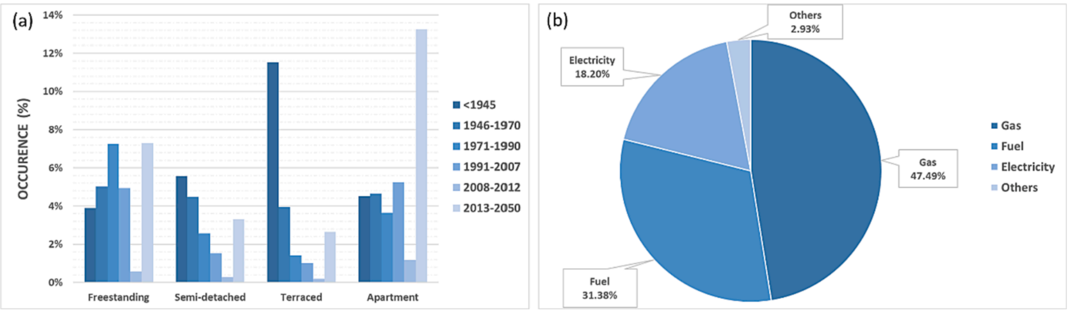

Fig. 5. BAU scenario (a) distribution of the Belgian dwelling types by the six construction periods (b) percentage of dwellings driven by different energy sources for space heating [41].

promoting the use of electricity and banning the use of oil boilers for newly constructed buildings and NG connections for large apartments as well. Even in the BAU scenario, the electricity share refers to the buildings that are driven by electric resistive heating systems for space heating, while heat pump systems and their impact on the final energy consumption in the Belgian residential building stock were studied by Elnagar et al. [41] in a different study as part of the framework of this study. Additionally, the share of NG and fuel is also reduced compared to the base scenario in 2012.

The BAU scenario takes into account the potential reduction of total demand due to retrofit strategies. By comparing the results of the BAU and Base scenarios, the effectiveness of retrofitting can be assessed in terms of reducing the total demand and mitigating the impact of climate change on buildings in the future since both the base scenario and the BAU scenario consider the impact of climate change on the heating and cooling energy demands of the building stock.

Table A.1 and Table A.2 in Appendix A show more details and the parameters used for modelling to obtain a more detailed understanding of the building stock. It is also recommended to read the study and the model description by Gendebien et al. [19].

2.4. *Climate data*

The regional climate model used in this study is the “Modèle Atmosphérique Régional” model (hereafter called “MAR”) in version 3.11.4 [18]. MAR aims to downscale a global model or reanalysis with a resolution of ~ 100 km/6_h and ~ 30 km/3h, respectively, to get weather outputs at a finer spatial and temporal resolution, typically 5 km/1_h. For more information about the MAR model, the reader is invited to check Doutreloup et al. (2022) [18]. This model has been validated over the Belgium territory by several studies [48–51]. For this study, the spatial resolution of MAR is 5 km over an integration domain (120 × 90 grid cells) centred over Belgium, as shown in Fig. 6.

This MAR model, like any regional climate model, must be forced at its boundaries by a global model (i.e. ESM), whether a reanalysis model. Firstly, the MAR model is forced by ERA5 (called hereafter MAR-ERA5 [52]) in order to have past simulation (1980–2020). As the ERA5 reanalysis model is forced by different kinds of observations, MAR-ERA5 can be considered the simulation closest to the observed climate.

Secondly, the MAR model is forced by three Earth System Models (ESM) coming from the Sixth Coupled Model Intercomparison Project (CMIP6 [2]). The choice is based on two criteria: ESM should represent (with the lowest possible bias) the main atmospheric circulation in the free atmosphere over Western Europe with respect to ERA5 over 1980–2014, and the three choosing ESMs must represent the CMIP6 models spread in 2100 for the same scenario (SSP5-8.5 in this study) [18]. For this study, the ESMs: BCC-CSM2-MR (MAR-BCC) [53], MPI-ESM.1.2 (MAR-MPI) [54] and MIROC6 (MAR-MIR) are selected [55].

These ESMs are not forced by observation and represent only the mean evolution of climate according to different kinds of carbon emissions and thus according to different kinds of socio-economical scenarios called Shared Socioeconomic Pathways (hereafter called SSPs [8]). Except for MAR-MIR, which noticeably overestimates summertime temperatures and solar radiation, MAR simulations successfully capture the current climate and its interannual variability. The ensemble mean of all MAR simulations is MAR-BCC, and MAR-MPI can be thought of as the MAR simulation that is the coldest. As a first step, MAR is forced by the ESM according to their historical scenario (1980–2014) to obtain a possible comparison with MAR-ERA5. In a second step, MAR is forced by the ESM according to their most warming scenario, namely the SSP5-8.5 scenario, in order to obtain the future climate evolution (2015–2100).

The specificity of these simulations is that to save computation time, the SSP5-8.5 scenario is used to reconstruct the SSP3-7.0 and SSP2-4.5 scenarios, as explained by Doutreloup et al. [18]. Indeed, the climate evolution included in SSP5-8.5 also contains the climate evolution of SSP3-7.0 and SSP2-4.5 but in different periods since the ESMs do not simulate general atmospheric circulation changes [57]).

The Typical Meteorological Year (TMY) reconstructed for this study are datasets that are widely used by building designers and others for modelling renewable energy conversion systems [58]. The TMY files are the synthetic years (on an hourly basis) constructed by representative typical months [59], which are selected by comparing the distribution of each month within the long-term (minimum ten years) distribution of that month for the available modelled data (using Finkelstein-Schafer statistics [60]. Many methods exist to reconstruct this kind of weather file [61], but for this study, a protocol for the construction of these typical years has been developed based on ISO15927-4 [62] and is described in Doutreloup et al.[18].

To enhance the study’s findings’ reliability within uncertain climate conditions, a key step was considered in relation to the weather data

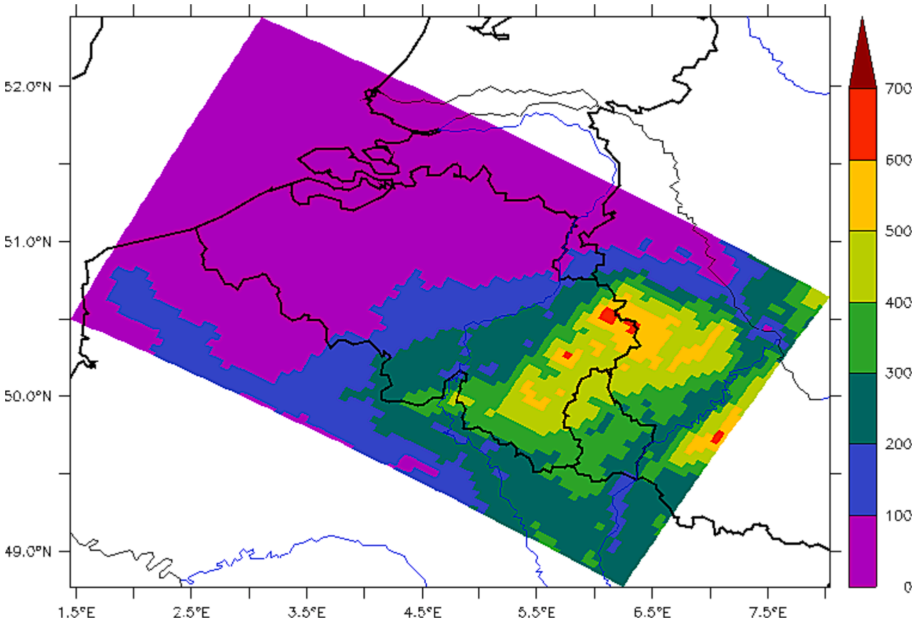

Fig. 6. Topography (in meters above sea level) of the MAR domain representing Belgian territory [56].

within the framework of the study. In addressing the inherent uncertainty of global climate models, three ESMs have been used to obtain an initial approximation of the range of possible outcomes. This approach helps to provide a broader picture of the possible range of future climate scenarios without having to downscale all 30 available models of the CMIP6.

2.5. *Energy demand for heating and cooling*

2.5.1. *Building thermal model*

According to ASHRAE [63], there are two types of building modelling methods: forward and data-driven. This study uses a forward method for building energy use with a physical description of various parameters (e.g., building geometry, location, characteristics, and operating schedules). The forward model is more suited for improvements due to its higher level of detail.

This study uses a dynamic multi-zone model which takes into account the interaction between the different zones of the buildings, whether they are humid or dry. In addition to that, setting different setpoint temperatures in the different zones allows an accurate calculation of the indoor heating and cooling energy demands.

2.5.1.1. Zone thermal model. The simplified building model of a zone is based on the simple hourly time step method described in ISO 13790:2007 [64]. The method is based on the thermal-electrical analogy between the analysed thermal zone and the equivalent 5R-1C (5 resistances and 1 capacity) network, as shown in Fig. 7 [65]. The model uses an hourly time step and allows a high flexibility level of detail accuracy while still being relatively straightforward to implement. However, it can also be computationally intensive, requiring a large number of calculations to be performed for each hour of the simulation. The simple hourly method calculates the energy demand of a building by using a series of hourly calculations to simulate the heat transfer through the building envelope and the thermal storage of the building structure. This allows for a detailed simulation of the heating and cooling energy demands of a building over time, taking into account factors such as the temperature and weather conditions outside the building and the insulation properties of the building envelope.

It is acknowledged that ISO 13790:2007, which utilizes the 5R1C method, has been replaced by ISO 52016–1, which introduces a more comprehensive model with several resistances and capacitances for each building element. However, it is important to note that the use of ISO 13790:2007 in our work was not without consideration. ISO 13790:2007, with its simple hourly method (5R1C method), has been widely used and validated in previous studies. Numerous studies demonstrated the reliability and practicality of the 5R1C method in estimating heating and cooling energy demands in buildings [66–68]. Additionally, ISO 13790:2007 is more simple and requires less computational time compared to the new ISO 52016–1, especially while dealing with a building stock model with numerous cases [69].

The thermal-electrical network is characterized by temperature nodes (θ), thermal resistances (1/H), heat fluxes (Φ) and a capacity (C_m).

The calculation approach is based on heat transfer simplifications between the internal and external environment. Solar and internal heat gains are distributed over different nodes, as shown in Fig. 7: the internal air node θ_{air}, the surface node θ_s and the mass node θ_m. The five resistances in the 5R1C network allow describing the heat transfers coefficients (expressed in Watts per Kelvin) as follows:

- Heat transfers due to ventilation H_{ve}, which is connected to the air temperature node θ_{air} and the supply air temperature θ_{sup} (R1).
- Heat transfer by thermal transmission $H_{tr,is}$ due to thermal conductance (between air temperature node θ_{air} and the surface temperature node θ_s) (R2).
- Heat transfer by thermal transmission through windows $H_{tr,w}$ (R3).
- Heat transfer by transmission through opaque components $H_{tr,op}$, which is divided into $H_{tr,em}$ and $H_{tr,ms}$ (R4 and R5) [66].

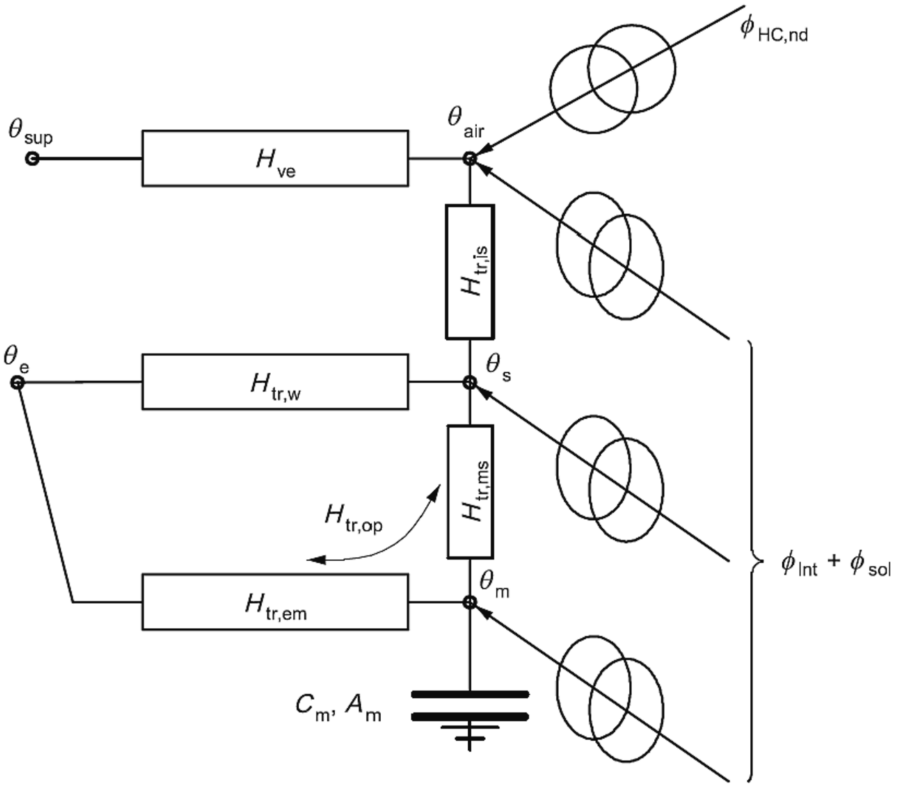

Fig. 7. The equivalent 5R-1C network based on the simple hourly method of EN ISO 13790:2007 [64].

- o $H_{tr,em}$ represents the external part of the heat transfer coefficient by the transmission for the non-window part of opaque elements.
- o $H_{tr,ms}$ represents the internal part of the heat transfer coefficient by the transmission for the non-window part of opaque elements.

The thermal mass is represented by a single thermal capacity C_m. The 5R-1C network also includes the heat flow rate due to internal heat source Φ_{int} and heat flow rate due to solar heat source Φ_{sol} split over the three temperature nodes.

Overall, the five resistances in the 5R1C model represent thermal resistance due to the building's envelope, and they are tuned based on the building's geometry and construction properties. While the capacitance represents the thermal mass of the building, and it is tuned based on the building's construction materials and volume.

2.5.1.2. Extension to several zones. In the current study, a multi-zone approach is adopted to analyse the heating and cooling energy demands in buildings. The multi-zone calculation is carried out without thermal coupling between zones, i.e. no heat transfer by thermal transmission or ventilation between zones is considered. The multi-zone approach has also been used in previous studies in Belgium and worldwide [19,30,70]. There are a total of five zones that have been defined in all buildings for this purpose, which are:

1- Living area: this zone includes the living room and kitchen.
2- Sleeping area: this zone encompasses the bedrooms.
3- Bathroom: this zone is dedicated to the bathroom.
4- Circulation zone: this zone is used for circulation purposes and includes the hallways and staircases.
5- Unconditioned zone: this zone encompasses all other areas in the building that are not conditioned for heating or cooling, such as attics, garages, or storage spaces.

The heating and cooling loads for the first four zones (living area, sleeping area, bathroom, and circulation zone) are determined through the RC network described in the previous section. The total energy demand for heating and cooling is the sum of the energy demand calculated for the individual zones, as explained in detail in ISO 13790:2007 [64]. This approach allows for a detailed analysis of the energy requirements in each of these zones, enabling the identification of areas where energy-saving measures can be implemented effectively.

2.6. Calculation of the internal temperature required for heating and cooling needs

In this section, the process for calculating the internal temperature and required heating or cooling power for a given hour in a building zone is described based on ISO 13790:2007 [64]. To calculate the internal temperature for any amount of heating or cooling need $\Phi_{HC,nd}$ for each hour, the RC network enables the determination of the internal temperature as a linear function of $\Phi_{HC,nd.}$ Fig. 8 shows the heating setpoint temperature $\theta_{int,set,H,}$ cooling setpoint temperature $\theta_{int,set,C}$ and the maximum available heating and cooling power, which can change hourly. Five potential cases can occur based on this calculation.

- Insufficient heating power: building needs heating but not enough power. The heating need, in this case, will be limited to the maximum power provided ($\Phi_{H,max}$), and the internal temperature will be lower than the heating setpoint.
- Sufficient heating power: building needs heating, and there is enough power, the temperature reaches the heating setpoint. In this case, the calculated heating need is less than the maximum power.
- Free-floating conditions: building neither needs heating nor cooling.
- Sufficient cooling power: building needs cooling, and there is enough power, the temperature reaches the heating setpoint. In this case, the calculated cooling need is less than the maximum power.

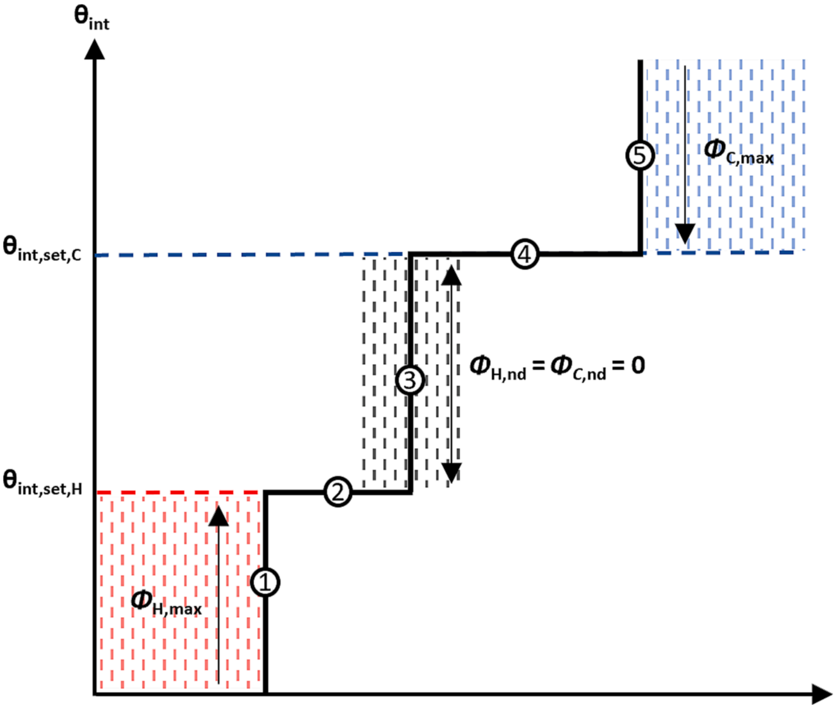

Fig. 8. Calculation of internal temperature and required heating or cooling needs.

- Insufficient cooling power: building needs cooling but not enough power ($\Phi_{C,max}$). The Cooling need, in this case, will be limited to the maximum power provided, and the internal temperature will be higher than the cooling setpoint.

2.7. Internal gains and indoor air temperature set points schedule

In addition to the external climate conditions, internal gains are also a crucial factor in determining the heating and cooling loads of buildings. Internal gains are generated from a range of sources, including occupancy, lighting, and the use of appliances. In the present study, internal gains are considered in the building energy simulation model to more accurately capture the overall heating and cooling energy demands of the building [71,72].

One of the primary sources of internal gains is occupancy. In Belgium, households have an average of 2.3 occupants per household [73], and this is used in the simulations to estimate the heat generated by the occupants through their activities, such as body heat and respiration. The total metabolic rate at rest conditions (100 Watts). The perspiration losses in rest conditions are 40 Watts. Sensible gains represent the amount of heat that is transferred to the body through convection and radiation, and they are calculated as the difference between the total metabolic rate and the perspiration losses. The energy need for latent heating and cooling loads is not included in this calculation.

Another significant source of internal gains is lighting, which is accounted for in the simulations by estimating the number of light fixtures and their wattage. Finally, the use of appliances such as refrigerators, TVs, computers, and other household equipment is also taken into account in the simulations to estimate the heat generated by these devices.

The temperature control of a zone involves a set of parameters that determine the comfort level of the occupants. The heating and cooling schedules are designed based on set point temperatures, morning and evening starting times, and durations. The set points are fixed values that dictate the desired temperature in the zone, while the starting times and durations are determined based on Gaussian probabilities characterized by averages and standard deviations, as shown in Fig. B1. These parameters differ for weekdays and weekends to reflect the occupants' different activities and preferences. Moreover, the ISO 17772–1 standard specifies the minimum set point temperature for heating in winter and the maximum set point for cooling in summer, which are 20 and 26 °C, respectively [74].

2.8. Ventilation and infiltration

In the framework of this study, natural ventilation is carried out by infiltrations in buildings which are not perfectly tight. This is the case for most existing dwellings in the building stock. To assess the air change rate per hour for infiltration (ACH) associated with natural ventilation, ASHRAE proposed a simplified method that considers the airtightness level of the building, the site location (suburb, city centre, countryside), wind speed, and building height [75]. The ACH under a pressure difference of 2 Pa pressure difference can be calculated using equation (2):

$$ACH_{2Pa} = K_1 + K_2 * |T_{out} - T_{in}| + K_3 * V_{wind} \tag{2}$$

$$V_{wind} = a + V_{wind,0} * h^b \tag{3}$$

Where T_{out} is the outdoor temperature, T_{in} is the indoor temperature, V_{wind} is the wind speed and K_1, K_2 and K_3 are given coefficients depending on the level of airtightness (tight, medium and high) as shown in equation (2). Additionally, The wind speed is provided in the weather conditions hourly data but has to be corrected to include the influence of the surrounding environment as follows h is the average building height and a and b are coefficients depending on the site location (suburb, city centre, countryside) as shown in equation (3).

2.9. Model validation

The validation process of the building stock model has been thoroughly undertaken to ensure the accuracy and reliability of its outputs. As pointed out by Ballarini et al. [68], several studies have investigated the reliability of the simple hourly method proposed in ISO 13790:2007 [64]. The results obtained for the estimation of the annual energy demand for heating and cooling with this method were compared with either result of detailed simulation tools such as EnergyPlus [66,76] or real data sets [77]. In all cases, good agreements were found in the results.

In addition, for this study, model validation for the heating energy demand was performed by comparing the model results to a historical data set. The historical data set is based on the "Synthetic Load Profiles (SLPs) in Belgium, which are designed to represent the aggregated consumption of an average dwelling based on a statistical selection of 2500 residential dwellings. These profiles provide data on electricity consumption at a 1/4 hourly resolution and gas consumption at an hourly resolution.

To ensure the accuracy of the model results, firstly, the annual gas consumption profiles in 2019 are shown in Fig. 9 (a), providing a macroscopic view of energy consumption trends over time. Secondly, the focus zooms in to capture the essence of daily consumption patterns, achieved by analysing gas load profiles for an average day, as shown in Fig. 9 (b). The profile is obtained by dividing the actual demand by the total annual demand. Thirdly, the validation is extended to encompass multiple days, where gas load profiles for consecutive days are evaluated, as shown in Fig. 9 (c). This comprehensive validation strategy shows the robustness of the model under varying temporal and usage contexts.

Finally, between the years 2017, 2018, and 2019, the annual consumption per average dwelling, as indicated by the SLPs, ranged from 23.5 to 24.6 MWh, as shown in Fig. 9 (d). The tree-structure building model of this study predicted gas consumption with a relatively small mismatch error of only 4–6% in the three years, which thereby confirmed the conclusions reached by the above-mentioned studies and the previous validation of the model by Georges et al. [30]. In particular, the conversion of heating energy demand to final heating energy consumption is a focal point of the model validation, which includes the heating production systems efficiency, an essential component in reflecting the actual energy consumed by various heating systems. As shown in Table B.1 in Appendix B, this efficiency factor takes into account the efficiency of heating production systems based on the type of energy vector used in SH and DHW and the construction year of the building. Additionally, the percentage and number of dwellings relying on different energy sources for SH and DHW, as shown in Fig. 4, have been integrated into the conversion process.

However, an important practical consideration emerges when validating cooling energy consumption. Given Belgium's temperate climate, active cooling systems are infrequently integrated within the existing building stock, and no data set is available to validate the model at the building stock level further than already achieved by the other studies. As a result, the validation of cooling energy consumption is not a primary focus of this study.

3. Results

3.1. Evolution of climate

The average monthly outdoor temperatures for Brussels for current and future TMYs from MAR forced by BCC-CSM2-MR (MAR-BCC), MPI-ESM.1.2 (MAR-MPI) and MIROC6 (MAR-MIR) are shown in Fig. 10, Fig. 11, and Fig. 12, respectively. The TMY for historical scenarios (2001–2020) is used as a reference TMY (the 2010s). The results for MAR-BCC simulation show that the average monthly temperature is expected to increase between 0.5 and 2.7 °C in 2050s_SSP5-8.5

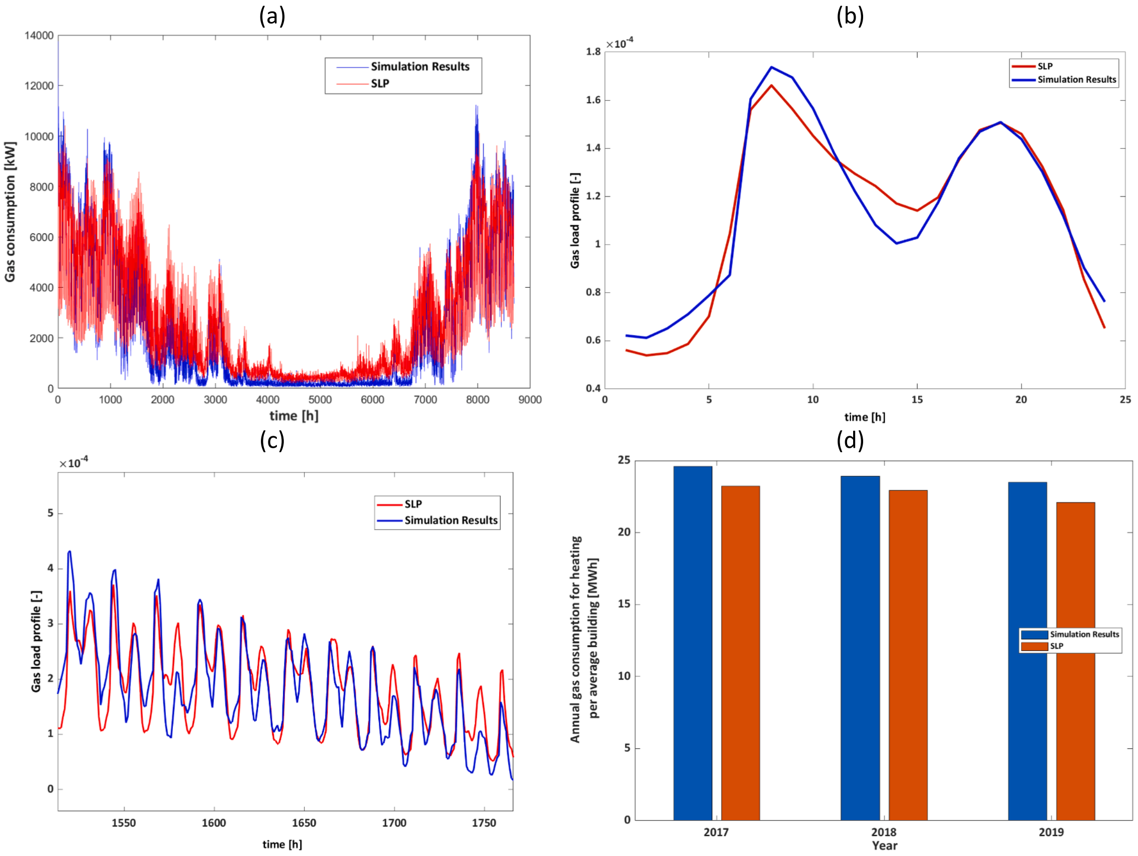

Fig. 9. Model validation by comparing the simulation results and Synthetic Load profiles (SLP) results (a) yearly gas consumption profiles, (b) gas load profiles for an average day [the profile is obtained by dividing the actual demand by the total annual demand], (c) gas load profiles foe several consecutive days, (d) average gas consumption per an average building.

compared to 2010s and between 1.1 and 4.1 °C in 2090s_SSP5-8.5 compared to 2010s as shown in Fig. 10. Overall, In the MAR-BCC simulation, the temperature is expected to increase over the years in the different SSP scenarios except in September 2050s in SSP2-4.5, in which the temperature is expected to decrease by 0.24 °C.

In the second MAR simulation (MAR-MPI), which is considered the coldest MAR simulation, as shown in Fig. 11, the temperature is expected to decrease in winter, mainly in December and January, between 1.9 and 2 °C and to increase between 0.9 and 1.4 °C by 2050s in the summer compared to 2010s. Additionally, the temperature is expected to decrease in winter by 2090s between 0.6 and 2 °C in SSP3-7.0 and SSP2-4.5, respectively, while the temperature is expected to increase in the winter of the SSP5-8.5 scenario in 2090s by 0.6 °C compared to 2010s. In the summer of 2090s, the temperature is expected to increase by 1.3 °C, 2.8 °C and 3.9 °C in SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively, compared to the 2010s.

The third MAR simulation (MAR-MIR) overestimates summertime temperatures and solar radiation. The results indicate that the average

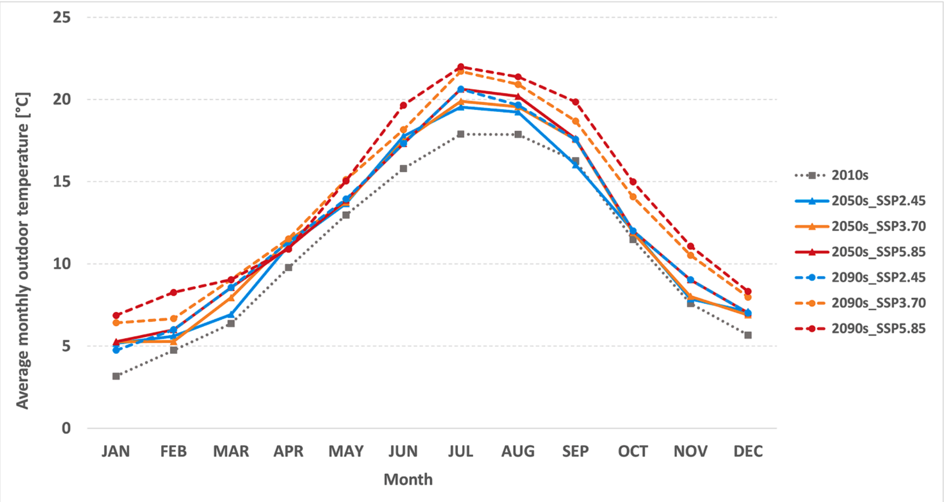

Fig. 10. Average monthly outdoor temperature in Brussels based on MAR forced by BCC-CSM2-MR ESM.

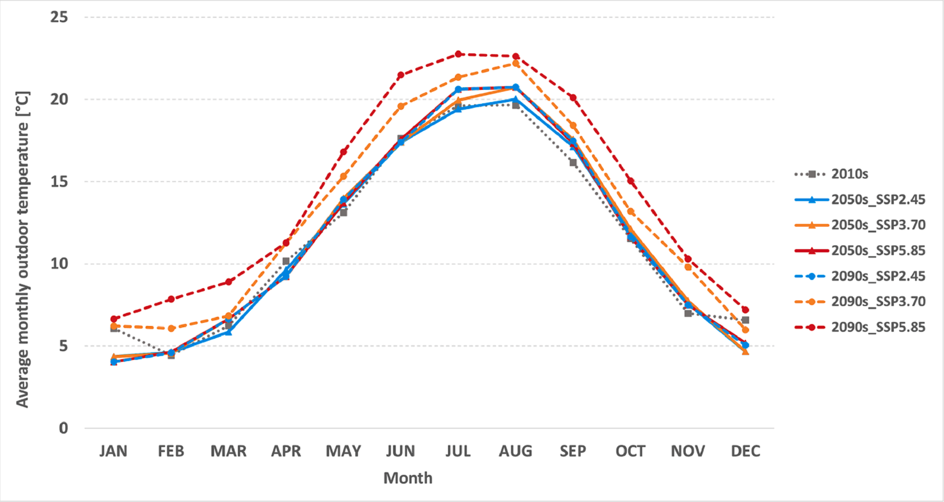

Fig. 11. Average monthly outdoor temperature in Brussels based on MAR forced by MPI-ESM.1.2.

monthly temperatures exhibit fluctuations under different scenarios, as shown in Fig. 12. The findings reveal that, particularly in the SSP5-8.5 scenario, there could be a substantial increase in temperature of approximately 9 °C by the 2090s compared to the 2010s.

After assessing the three MAR-ESMs, it was determined that the differences in temperature change were not significant. Therefore, to reduce the computational time required for the simulations and to study the different SSP scenarios as they provide a range of possible futures for different socioeconomic conditions and their impact on climate change. It was decided to use MAR-BCC as the representative scenario for the energy simulations to calculate the future heating and cooling energy demands, as shown in section 3.2.

3.2. Evolution of heating and cooling energy demands

3.2.1. Base scenario

The share of heating and cooling energy demands over the total demand in the base scenario is shown in Fig. 13. The results of the study indicate that there is a notable shift in the demand for heating and cooling in the building stock over time. In particular, the results show that the cooling energy demand share is expected to increase from 6% in the 2010s scenario to 12% in the 2050s and to 16% in the 2090s. Meanwhile, the share of heating energy demand is anticipated to decrease from 94% in the 2010s scenario to 88% in the 2050s and 84% in the 2090s.

Fig. 14 shows the expected change in the heating and cooling energy demands in the different weather scenarios. Specifically, in the 2050s, the results show that the heating energy demand is expected to decrease by 8%, 11% and 13% in SSP2-4.5, SSP3-7.0, and SSP5-8.5, respectively, compared to the 2010s. In contrast, the cooling energy demand is anticipated to increase substantially, with a 39% increase in SSP2-4.5, a 59% increase in SSP3-7.0, and a 65% increase in SSP5-8.5 compared to the 2010s. Additionally, the heating energy demand in the 2090s is expected to decrease by 13%, 20% and 22% in SSP2-4.5, SSP3-7.0, and SSP5-8.5, respectively, compared to 2010s, while the cooling energy demand is expected to increase by 61% in SSP2-4.5, 88% in SSP3-7.0 and a significant increase by 123% in SSP5-8.5 compared to the 2010s.

These results also showed that the impact of climate change on energy demand varies significantly depending on the type of building. Fig. 15 illustrates the expected change in heating and cooling energy demands for four different building types: freestanding, semi-detached, terraced, and apartment buildings. The results show that the decrease in heating energy demand is expected to be between 13% and 14% by the 2050s and between 22% and 23% by 2090s for all building types compared to the 2010s scenario. However, the increase in cooling energy demand varies for different building types. For freestanding houses,

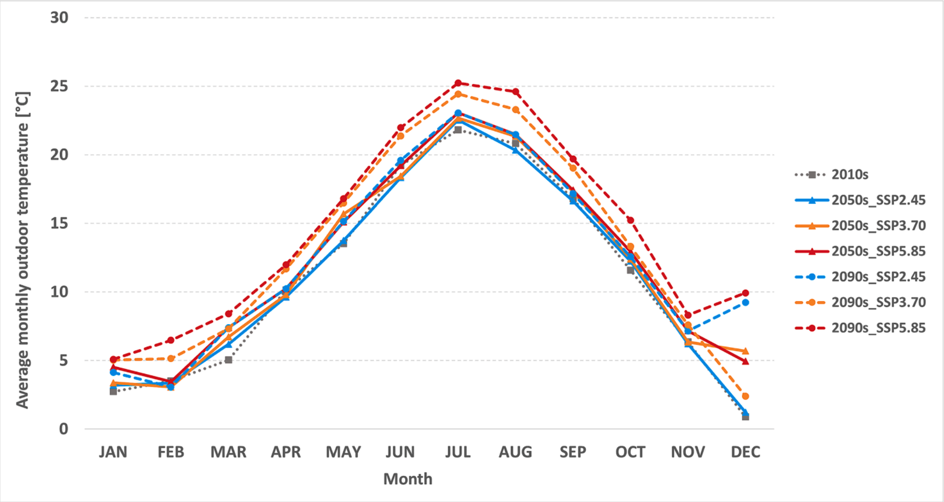

Fig. 12. Average monthly outdoor temperature in Brussels based on MAR forced by MIROC6 ESM.

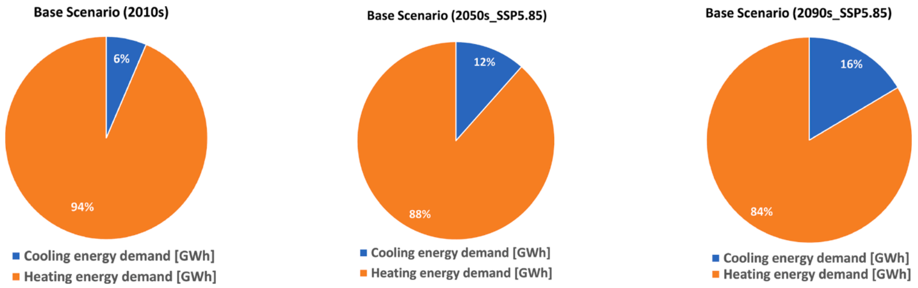

Fig. 13. Share of heating and cooling energy demands in the base scenario.

the cooling energy demand is expected to increase by 70% in the 2050s and 140% by the 2090s compared to the 2010s. For semi-detached houses, the cooling energy demand is expected to increase by 92% in the 2050s and 198% in the 2090s compared to the 2010s. In terraced buildings, the cooling energy demand is anticipated to increase by 77% in the 2050s and 151% in the 2090s compared to the 2010s. Interestingly, the increase in cooling energy demand for apartment buildings is expected to be the lowest among the four types, with an increase of 45% in the 2050s and 72% in the 2090s compared to the 2010s.

3.2.2. BAU scenario

The BAU scenario is based on current trends in the country and takes into account average demolition and construction rates of 0.075% and 0.9% per year, respectively. This means that 0.075% of the building stock is demolished and replaced by new constructions each year, while 0.9% of the building stock is added through new constructions. The scenario also includes average retrofit scenarios as a baseline, as shown in Table 2, with a 0.8% per year shallow renovation rate and a 0.5% per year deep renovation rate. It should be mentioned that the BAU scenario also considers a wide range of renovation rates for both shallow and deep renovation due to the uncertain rates in the country.

As explained in the base scenario, the study found that there will be a significant change in the requirement for heating and cooling in the building stock over time. This pattern is also observed in the BAU scenario, which is demonstrated in Fig. 16. The BAU scenario considers the effects of demolition, construction, and renovation rates, and the outcomes indicate that by the 2050s, the proportion of heating energy demand will decrease to 14%, while the proportion of cooling energy demand will increase to 86%. This represents a slight variation from the base scenario, which predicts heating and cooling energy demand proportions of 12% and 88%, respectively. Furthermore, by the 2090s, the cooling energy demand is expected to reach 19%, while the heating

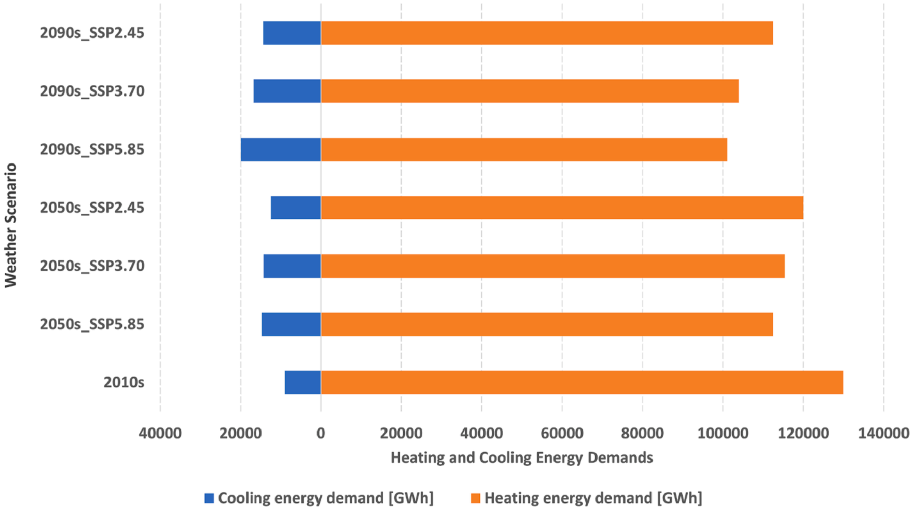

Fig. 14. Heating and cooling energy demands in the Base scenario [Comparison between the 2010s, 2050s for SSP2-4.5, SSP3-7.0 and SSP5-8.5 and 2090s for SSP2-4.5, SSP3-7.0 and SSP5-8.5].

Fig. 15. Heating and cooling energy demands per average building type in the base scenario.

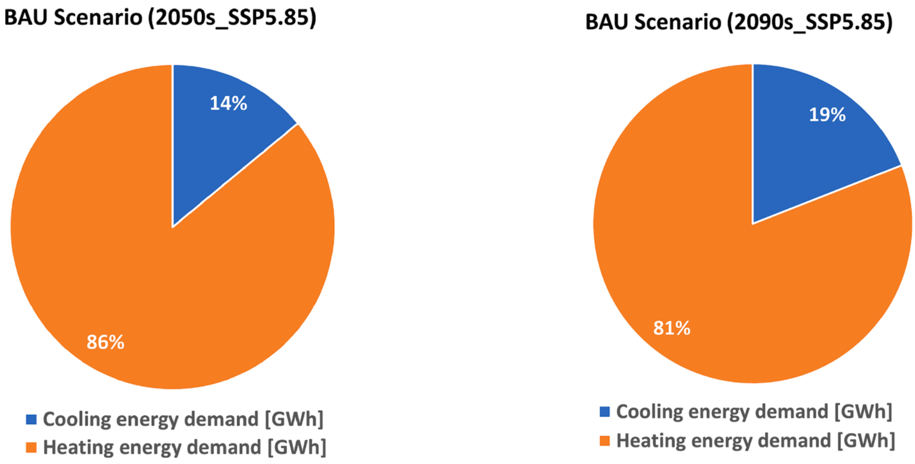

Fig. 16. Share of heating and cooling energy demands in the BAU scenario.

energy demand will decrease to 81%. This is also slightly different from the base scenario's forecast, which predicts a proportion of 16% for heating and cooling energy demand, respectively.

The results of the BAU scenario for SSP5-8.5 reveal a significant increase in the demand for cooling in the building stock, while the heating energy demand decreases over time, as shown in Fig. 17. By the 2050s, the heating energy demand is expected to decrease by 12% compared to the base scenario in the 2010s, while the cooling energy demand is expected to increase by 109%. This trend continues into the 2090s, and the heating energy demand is projected to decrease by 21%, while the cooling energy demand is expected to increase by 170% compared to the base scenario in the 2010s.

The study also presents results on the building scale regarding the heating and cooling energy demand per average building. Fig. 18 compares the heating and cooling energy demand for an average building for different building types in the base scenario and BAU scenario in SSP5-8.5. The results indicate that in the BAU scenario, the cooling energy demand for an average building is expected to increase between 25% and 71% in the 2050s and by 77% and 154% in the 2090s compared to the base scenario in the 2010s. This decrease is attributed to the retrofit strategies applied to different building types. Moreover, the results show that in the BAU scenario, the heating energy demand for an average building is expected to decrease by 15% to 42% in the 2050s and by 24% to 48% in the 2090s compared to the base scenario in the 2010s.

3.2.3. *Uncertainty analysis for renovation strategies*

Additionally, uncertainty analysis for the renovation strategies is also assessed in this study. The analysis takes into consideration various scenarios, including slow, moderate, and fast renovation rates, and the results are used to determine the most likely outcome and the potential impact on the overall demand for heating and cooling. This information can be used to inform decision-makers and help them make informed decisions about energy-efficiency initiatives and policies. As explained in Table 2, scenario 1 is considered the reference scenario, and the other scenarios show the different renovation rates for the uncertain range of renovation strategies. The heating energy demand and cooling energy demand in the different renovation strategies for the whole building stock in the 2050s and 2090s are shown in Fig. 19 and Fig. 20, respectively.

The results of the renovation strategies for the 2090s are also shown in the figures above, where the change in heating and cooling energy demands compared to scenario 1 are listed. Notably, the change in demand by the 2090s follows the same trend as in the 2050s for the different renovation strategies, with changes in heating and cooling demands. Scenarios 2 and 3 both show an increase in cooling energy demand between 9% and 10%, while the heating energy demand increases by 27% and 25%, respectively. Similarly, scenarios 4 and 6 showed a slight increase in cooling energy demand (3% and 5%, respectively), while heating energy demand increases by 12% and 22%, respectively. Scenario 5 and scenario 7 show a 2% decrease in cooling energy demand, while heating energy demand decreases by 11%.

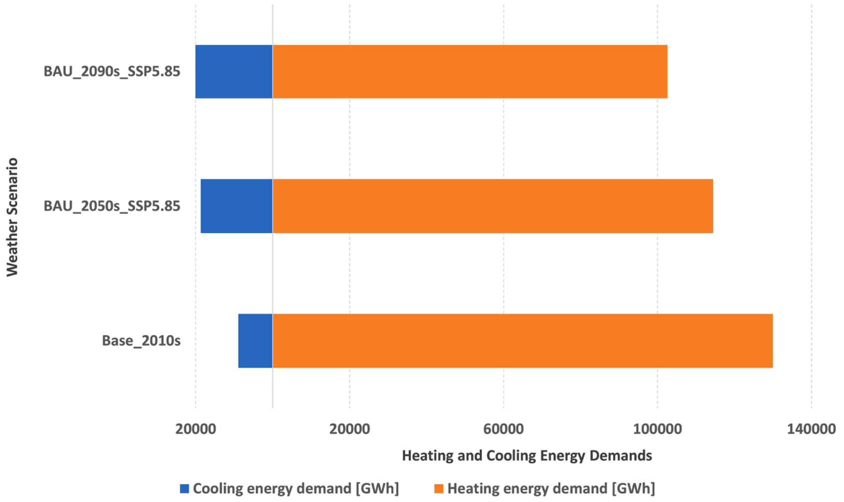

Fig. 17. Heating and cooling energy demands in the BAU scenario [Comparison between the 2010s, 2050s for SSP5-8.5 and 2090s for SSP5-8.5].

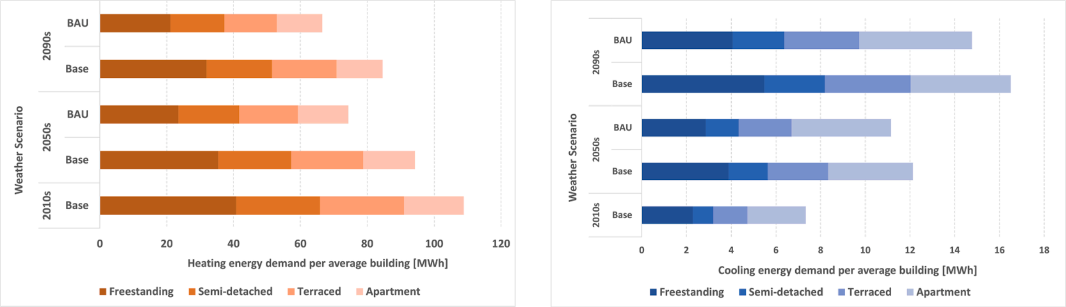

Fig. 18. Heating and cooling energy demands per an average building type [comparison between the Base and BAU scenarios].

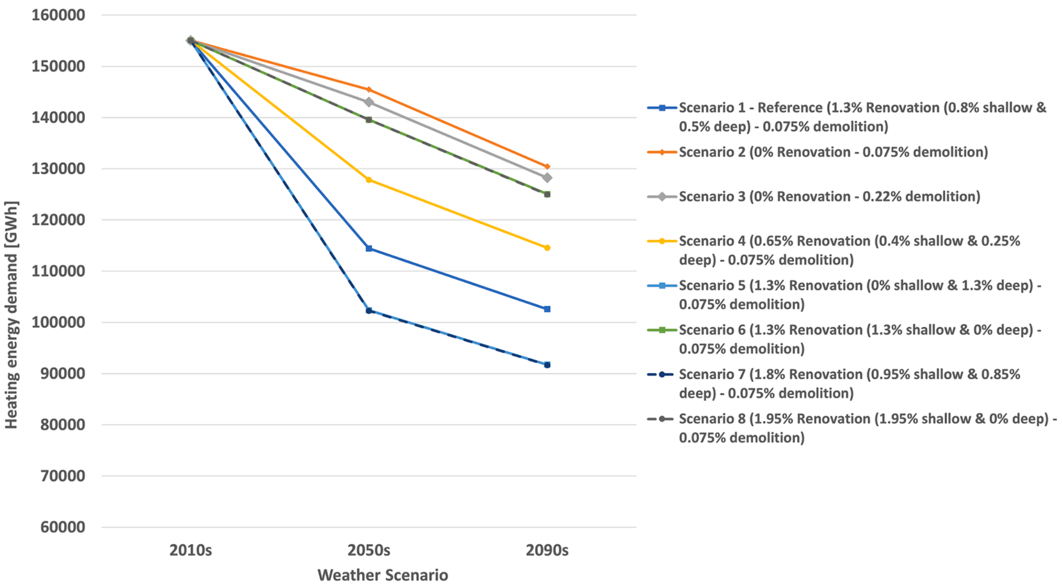

Fig. 19. Heating energy demand in the different renovation scenarios for the whole building stock.

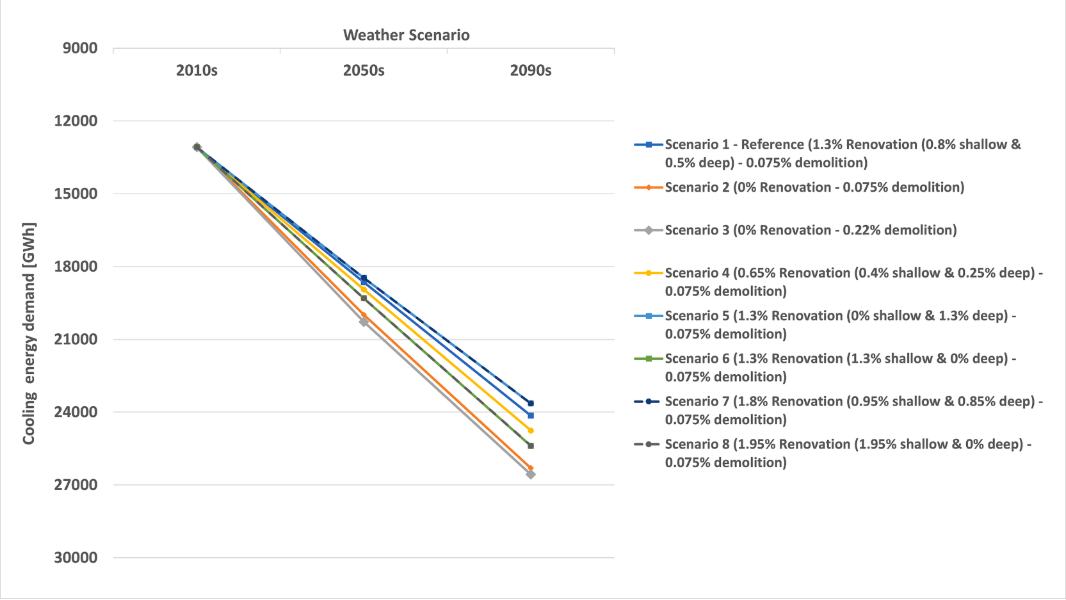

Fig. 20. Cooling energy demand in the different renovation scenarios for the whole building stock.

Finally, scenario 8 shows an increase in cooling energy demand by 5%, while heating energy demand increases by 22%.

Comparing the BAU base scenario with the BAU deep renovation and shallow renovation strategies shows significant variations in heating and cooling energy demands, as shown in Fig. 21. Notably, the BAU base scenario has a 0.8% per year shallow renovation rate and a 0.5% per

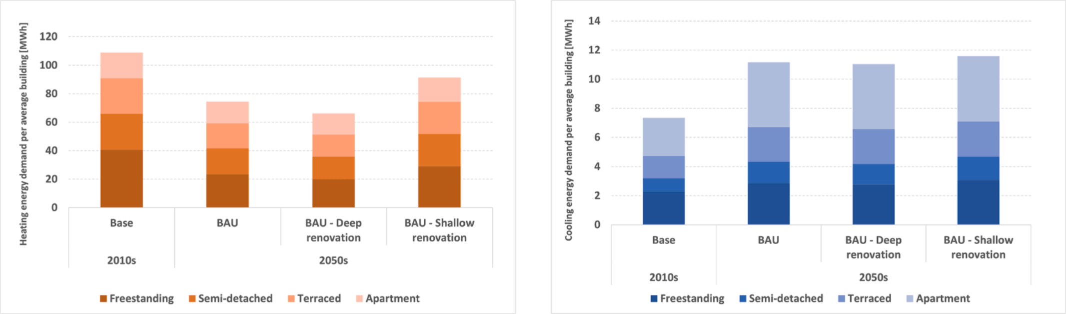

Fig. 21. Average heating and cooling energy demands in deep and shallow renovation scenarios.

year deep renovation rate, the deep renovation strategy characterized by the highest deep renovation rate of 1.3% per year (scenario 5). Conversely, the shallow renovation approach features the highest shallow renovation rate of 1.95% per year (scenario 8). These findings emphasize the influence of the renovation rate on the effectiveness of each strategy in achieving energy efficiency gains. In the BAU deep renovation scenario, all building types exhibit substantial reductions in heating energy demand. Freestanding buildings show a remarkable decrease of approximately 15%, indicating the efficacy of comprehensive retrofitting measures. Semi-detached and terraced buildings also benefit from notable reductions of around 12% and 11%, respectively. Apartments display a more moderate reduction of about 2%. In the BAU shallow renovation scenario, heating energy demand tends to increase in comparison to the BAU baseline. Freestanding, semi-detached, and terraced buildings experience rises of approximately 24%, 25%, and 28%, respectively. Apartments also show an increase of about 13%.

The BAU deep renovation demonstrates a positive impact on cooling energy demand, with freestanding and semi-detached buildings experiencing reductions of approximately 3% and 4%, respectively. In contrast, terraced buildings display a marginal increase of about 1%, while apartments show a minimal increase of around 0.1%. On the other side, the BAU shallow renovation strategy shows different patterns, leading to varying degrees of increase in cooling energy demand. Freestanding buildings demonstrate a noticeable rise of approximately 8%, while semi-detached buildings experience an increment of about 9%. Terraced buildings exhibit a modest increase of approximately 1%, and apartments show a small increase of around 0.72%.

4. Discussion

4.1. Findings and recommendations

The IPCC predicts that global temperatures will increase by 1.5 °C above pre-industrial levels by mid-century if greenhouse gas emissions are not rapidly reduced. If emissions continue to rise at their current rate, the global temperature could rise in the range of 1–5.7 °C by the end of the century, depending on the SSP scenario, with significant impacts on the environment, human health, and socio-economic systems. This study analysed the average monthly outdoor temperatures in Brussels using three different MAR simulations. The results showed that the temperature is expected to increase between 0.5 and 4.1 °C in the future compared to the 2010s, with the highest increase in the SSP5-8.5 scenarios.

This study considers three MAR simulations to analyse the impact of climate change on energy demand in Brussels. These simulations, namely MAR-BCC, MAR-MPI, and MAR-MIR, are based on different Earth System Models and are used to generate future climate scenarios for the 21st century. The MAR-ESM BCC-CSM2-MR, one of the 30 ESMs used in climate research, simulates warming that is close to the ensemble mean for the year 2100 using the SSP5-8.5 scenario. The SSP5-8.5 scenario represents a future where greenhouse gas emissions continue to rise, leading to high levels of warming and significant climate change impacts. In contrast, the MAR-ESM MIROC6 simulates larger warming than the ensemble means for the same scenario and time horizon. This suggests that MIROC6 may be more sensitive to changes in greenhouse gas concentrations and feedback mechanisms than other models in the ensemble. The MIROC6 model's projections indicate that the impacts of climate change could be more severe than anticipated by the ensemble mean. On the other hand, the MAR-ESM MPI-ESM.1.2 simulates lower warming than the ensemble means by the year 2100. This indicates that the MPI-ESM.1.2 model may be less sensitive to changes in greenhouse gas concentrations and feedback mechanisms than the other models in the ensemble. This highlights the inherent uncertainty in climate modelling and the need for a range of models to provide a more comprehensive picture of potential future climate scenarios. Overall, the differences in the warming projections between these three ESMs illustrate the range of potential outcomes that could occur by the year 2100, highlighting the importance of continued research and action to mitigate the impacts of climate change.

The study assessed the shift in the demand for heating and cooling in the building stock over time. The changes in weather conditions are more conducive to modifications of cooling energy demand than heating energy demand. This shift in the demand for heating and cooling has significant implications for energy demand patterns and resource use, highlighting the need for effective policy interventions to promote sustainable energy use and mitigate the impact of climate change. The results of the base scenario indicate that the share of cooling energy demand over the total demand is anticipated to increase from 6% in the 2010s scenario to 12% in the 2050s and to 16% in the 2090s, while the share of the heating energy demand over total demand is expected to decrease from 94% in the 2010s scenario to 88% in the 2050s and 84% in the 2090s. The study also showed that heating energy demand is expected to decrease by 8% to 13% in the 2050s and 13% to 22% in the 2090s, while cooling energy demand is expected to increase by 39% to 65% in the 2050s and 61% to 123% in the 2090s, depending on the scenario.

Furthermore, the study found that, in the base scenario, without the implementation of any demolition or renovation strategies, the impact of climate change on energy demand varies depending on building types. The increase in the cooling energy demand for semi-detached houses and terraced houses is expected to be bigger than freestanding houses since they share common walls and are not properly insulated, which can increase heat transfer between the houses. Additionally, they have fewer walls exposed to the outside which can trap heat inside and hence require more cooling to maintain comfortable indoor temperatures. This means that if one house is cooled, it will also affect the temperature of the adjacent house, increasing the overall cooling energy demand. In contrast, freestanding houses do not share common walls, which means that they are less affected by heat transfer from neighbouring houses and have more space between the walls and the surrounding environment, allowing for more natural ventilation. Moreover, apartments tend to have shared walls and are often located in multistory buildings, which means they have less exposed surface area, which also helps to regulate temperatures and reduce the cooling energy demand. The insulation and characteristics of the buildings are key factors in determining their heating and cooling energy demands. Buildings with higher insulation and more efficient characteristics generally have lower demands compared to those with lower insulation and less efficient characteristics.

Additionally, in this study, the BAU scenario considers current trends in the country, with average demolition and construction rates of 0.075% and 0.9% per year, respectively and an average renovation rate of 1.3% per year. By the 2050s, the share of heating energy demand will decrease to 14%, while the share of cooling energy demand will increase to 86%. By the 2090s, the share of cooling energy demand is expected to reach 19%, while the share of heating energy demand will decrease to 81%. In the BAU scenario for SSP5-8.5, cooling energy demand is projected to increase by 109% in the 2050s and 170% in the 2090s, while heating energy demand is expected to decrease by 12% and 21% in the 2050s and the 2090s, respectively, compared to the base scenario in the 2010s. The total demand is expected to decrease by 4% in the 2050s and decrease by 9% in the 2090s compared to the base scenario in the 2010s.

Retrofit strategies applied to different building types in the BAU scenario contribute to lowering the increase in the cooling energy demand in the 2050s and the 2090s compared to the base scenario. The cooling energy demand in the BAU scenario is expected to increase with a range of 25% to 71% in the 2050s compared to 45% to 92% in the base scenario and 77% to 154% in the 2090s compared to 72% to 198% in the base scenario compared to the 2010s. In contrast, the heating energy demand for an average building is expected to decrease more substantially than in the base scenario, with a range of 15% to 42% in the 2050s and 24% to 48% in the 2090s compared to the base scenario in the 2010s.

Overall, the BAU scenario, with its retrofit strategies and climate change projections, demonstrates the complex and dynamic nature of the building stock and the importance of considering long-term planning and strategies to achieve sustainable energy use. The results of the renovation scenarios on a macroscopic scale for the whole building stock show that the increase or decrease in the renovation rates has a significant impact on the heating, cooling and total demand in buildings. As shown in Table 2, scenarios without renovation or when the renovation rate decreases lead to a slight increase in cooling energy demand and a moderate or significant increase in heating and total demand. This can be attributed to the fact that when buildings are not renovated, they have poor insulation and are unable to retain heat in cold weather, leading to an increase in heating energy demand. Conversely, in warm weather, buildings without proper insulation have difficulty keeping cool air inside, leading to an increase in cooling energy demand. On the other hand, when the renovation rate increases, the heating and total demands significantly decrease while the cooling energy demand slightly decreases or increases according to the indoor and outdoor conditions and the building type and characteristics. This is due to the fact that an increase in renovation and insulation of the buildings helps to reduce heat loss during cold weather and keep the building cooler during warm weather. However, in cases where the indoor temperature is higher than the outdoor temperature, such as during hot summer days, the increase in renovation and insulation of the buildings can lead to an increase in the cooling loads due to the trapped heat inside the building. In highly-insulated buildings, the exchange of heat between the indoor and outdoor environments will be reduced. This can result in the accumulation of heat generated from various sources inside the building, such as appliances, lighting, and human activity [78,79].

On a microscopic level, it is noteworthy that apartment buildings have the highest increase in cooling energy demand compared to other building types due to their high insulation, which makes it more difficult to extract the solar gains and the internal gains out of the building. In contrast, after applying renovation to the building stock in the BAU scenario, freestanding houses have the lowest increase in cooling energy demand and the highest decrease in heating energy demand.

Additionally, the comprehensive retrofitting measures of the deep renovation scenario outperform the more modest changes in the shallow renovation strategy, leading to notably higher energy efficiency gains. These findings underscore the significance of prioritizing comprehensive retrofitting approaches to effectively address heating and cooling energy demands and contribute to sustainable energy consumption practices.

When comparing these results with studies conducted in different countries, it becomes evident that variations exist across different climate regions. For instance, studies conducted in the United States, Brazil, and Mediterranean climate regions indicate a higher decrease in heating energy demand compared to Belgium, suggesting potential differences in climate sensitivity and energy efficiency measures. In contrast, studies conducted in Canada and the United States show a similar average increase in cooling demand as observed in Belgium, implying shared challenges in addressing rising temperatures. Notably, a study conducted in Switzerland stands out, revealing a much more significant increase in cooling demand compared to Belgium. Lastly, another study has been conducted in Belgium by Elnagar et al. [80] aligns with the aforementioned trends, reporting similar results for a multi-zone apartment building. The study found that by the end of the century, there was a projected increase in cooling energy end-use by 187% and a decrease in heating energy end-use by 40%.

The list below is given as a summary of the main findings and recommendations.

- It is recommended to use different climate models and four different SSP scenarios to provide a range of future climate scenarios.
- The results showed that the increase in cooling energy demand is expected to be higher than the decrease in heating energy demand due to climate change.
- It is also recommended to assess various renovation strategies for the building stock, as the study found that the insulation and characteristics of the buildings are key factors in determining their heating and cooling energy demands.
- The study highlights the importance of effective policy interventions to promote sustainable energy use and mitigate the impact of climate change.

4.2. *Strengths and limitations*

This study provides a framework to assess climate change impact on heating and cooling energy demands in residential building stock by 2050 and 2100 with a case study applied to Belgium. This section emphasizes the strength and limitations that were encountered in the study.

The first strength of the paper relies on the use of the multi-zone dynamic approach, which allows for a more accurate and detailed description of each building in the building stock, including the accurate calculation of indoor conditions and heating and cooling energy demands [81,82]. This level of detail is important for accurately assessing energy use and potential savings in the building stock and can help inform policy decisions and building retrofit strategies. Another strength of the paper is that it provides a framework for calculating the heating and cooling energy demands in the future under different climate change scenarios. This approach allows for both microscopic and macroscopic results for individual buildings and the building stock as a whole. This allows for the identification of specific buildings that may require more attention or intervention based on their unique characteristics and heating and cooling energy demands. It also provides a more comprehensive view of the entire building stock and how it may be impacted by climate change, allowing for more informed decision-making and policy development. The third strength of the paper is related to the accuracy and reliability of the weather data used in the simulations. The study used the MAR model, which is known for its high spatial resolution of approximately 5 km since it allows for more accurate and detailed modelling of weather patterns and their impacts, such as the effects of climate change on building design and energy management systems [83]. Additionally, having high-resolution data can help bridge the gap between regional and global climate models, which often have significant differences in their predictions. This model also takes into account mesoscale phenomena, which are atmospheric processes that occur at regional scales (i.e. urban heat island), and it has been specifically tuned for the studied region of Belgium. As a result, the weather data used in this study is considered to be highly valid and representative of the climate in Belgium. Finally, the paper also demonstrates a significant strength by evaluating the effects of various renovation strategies on the heating and cooling energy demands of the building stock. This approach assists in identifying the degree of uncertainty related to the renovation rates and their effects on the energy demand of the building stock. By using different renovation scenarios, the research provides a broader understanding of the potential strategies that could be used to enhance the energy efficiency of the building stock.

However, the study has some limitations. First, the limited number of representative building types may not be sufficient to characterize the diversity of the building stock in different regions of Belgium, which highlights the need for more detailed and comprehensive data on the Belgian building stock to improve the accuracy and reliability of the findings. The second limitation of the study is related to not taking into account the active air conditioning system in the residential building stock. As in temperate climate regions like Belgium, the use of active air conditioning systems in residential buildings is not very common or necessary in the past years. The third limitation is the premise that the weather data for the entire building stock is representative of the Brussels weather pattern, as it assumes that it represents the average weather of Belgium. This assumption may be subject to limitations since the weather patterns may exhibit slight variations from one city to another. Lastly, It is acknowledged that this study utilizes ISO 13790:2007, which utilizes the 5R1C method, which has been replaced by ISO 52016–1. The new ISO standard introduces a more detailed and comprehensive model with several resistances and capacitances for each building element. However, it is worth noting that our research on the building stock modelling was initiated before the introduction of the new ISO standard, and this study built upon ISO 13790:2007 model to calculate the heating and cooling demands for buildings.

4.3. Implication on Practice and future research

The findings of this study have significant implications for both practice and future research. The study highlights the importance of taking several actions to mitigate the impacts of climate change, including retrofit strategies and the use of energy-efficient HVAC systems. Therefore, there is a need for effective policy interventions to promote sustainable energy use and mitigate the impact of climate change on the mandatory energy performance standards for residential buildings, which would require all new buildings to meet minimum energy efficiency standards. It could also apply to existing buildings during major renovations or refurbishments.

The study primarily focuses on the impact of climate change on future heating and cooling demands in buildings. Furthermore, it is important to note that another study utilizing a similar framework proposed by Elnagar et al. [41] specifically focused on the impact of climate change on future heating energy consumption using electric and gas heat pumps. This complementary study enhances our understanding of the implications of climate change on energy consumption and reinforces the importance of considering various energy carriers and sources in future energy scenarios. Additionally, this study is part of an ongoing project that aims to comprehensively analyse the impact of climate change on building energy demands. In the next phase, the research will explore different mitigation strategies, including the assessment of cooling energy consumption and the potential of active and passive cooling systems. By studying both heating and cooling demands, a comprehensive understanding of the future energy requirements can be achieved, facilitating the identification of effective strategies for energy-efficient building design and operation in the face of climate change.

The study shows that the impact of climate change on energy demand varies depending on building types, highlighting the importance of considering building characteristics in energy demand and policy interventions. Buildings with higher insulation and more efficient characteristics, such as energy-efficient HVAC systems and the use of sustainable building materials, generally have lower heating and cooling energy demands compared to those with lower insulation and less efficient characteristics. Thus, policymakers should focus on promoting sustainable building practices and retrofitting existing buildings to be more energy-efficient through the introduction of subsidies or tax incentives to encourage homeowners to retrofit their properties to make them more energy-efficient. Moreover, the study highlights the inherent uncertainty in climate modelling and the need for a range of models to provide a more comprehensive picture of potential future climate scenarios. Future research should continue to focus on improving climate models to reduce uncertainty and provide more accurate predictions [84,85]. Additionally, there is a need for more research on the impact of climate change on energy demand in different regions and building types to inform effective policy interventions. Finally, the following future research ideas are recommended. First, to develop decision-making frameworks and tools that account for uncertainties related to climate change, energy consumption, and GHG emissions and provide guidance to policymakers and building owners on the selection of appropriate air conditioning systems and adaptation strategies. Second, future research to assess the impact of climate change on thermal comfort in the different building types is also recommended. Third, future research is needed to conduct a comparative analysis of the performance of different air-conditioning systems in different climate zones, considering both energy efficiency and GHG emissions.

5. Conclusion

Climate change has drawn great attention in recent years because of its large impact on many aspects of building energy use. The methodology adopted in this study involved using future climate data to assess the heating and cooling energy demands in the Belgian building stock by 2050 and 2100. A dynamic building simulation model was used to focus on the future evolution in base and BAU scenarios. The findings revealed a projected decrease in heating energy demand in the base scenario, ranging from 8% to 13% in the 2050s and 13% to 22% in the 2090s. The study also found that the various retrofit strategies in the BAU scenario contribute to lessening the increase in cooling energy demand in the BAU scenario compared to the base scenario. The cooling energy demand in the BAU scenario is expected to increase with a range of 25% to 71% in the 2050s compared to 45% to 92% in the base scenario and 77% to 154% in the 2090s compared to 72% to 198% in the base scenario compared to the 2010s. The findings emphasize the need for proactive measures and effective strategies to mitigate the energy requirements for cooling in future scenarios.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

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Appendix A

Table A1 summarizes the average coefficients of heat transmission (U-values) for the different building types and the different years of construction according to the insulation level. The source for the insulation values is according to, Tabula (value before renovation), LEHR (added insulation thickness for renovated elements of houses constructed before 1990), and EPB 2010 (for renovated elements of houses constructed after 1990) [33,46,86].

Table A2 summarizes the average elements of total thermal capacity (K-values) for the different building types and the different years of construction according to the insulation level. The source for the insulation values is according to, Tabula (wall composition) and LEHR (added insulation thickness for renovated elements of houses constructed before 1990) [33,86].

Table A3 summarizes the infiltration rates at 50 Pa in m^3/hm^2 for different building types based on construction years, including values for walls that have undergone external insulation retrofits, as provided by TABULA [33] and EPB 2010 [46].

Appendix B

Table B1 provides average heating production systems efficiencies, expressed based on lower heating values (LHV) for both centralized heating systems and decentralized heating systems. The table provides the efficiency for space heating (SH) and domestic hot water (DHW) based on the type of energy vector used in both and the construction year of the building.

Fig. B1 shows the heating schedules approach for the building zones. Set points are imposed to fixed values; (W = 21 °C, A = 20 °C, X = 16 °C, and B = 10 °C), whereas the starting times and durations are obtained based on Gaussian probabilities characterized by averages and standard deviations.

Table A1
Average U-values for the different types of buildings and different years of construction.

		U_{wall} [W/m^2K]		$U_{windows}$ [W/m^2K]		U_{roof} [W/m^2K]		U_{floor} [W/m^2K]		U_{door} [W/m^2K]
Insulation		NI[1]	WI[2]	NI	WI	NI	WI	NI	WI	Mean
Year of construction	<1945	2.25	0.59	5	2.75	4.15	0.44	3.38	0.77	3.3
	1946–1970	1.56	0.53	5	2.75	3.33	0.43	3.38	0.77	3.3
	1971–1990	0.98	0.44	3.5	2.75	0.77	0.3	1.14	0.43	3.3
	1991–2007	0.49	0.4	3.5	2	0.43	0.3	0.73	0.4	3.3
	>2008	0.4		2		0.3		0.4		3.3

[1] Not Insulated.
[2] With Insulation.

Table A2
Average K-values for the different types of buildings and different years of construction.

		K_{wall} [kJ/m^2K]		K_{roof} [kJ/m^2K]		K_{floor} [kJ/m^2K]	
Insulation		NI	WI	NI	WI	NI	WI
Year of construction	<1945	453.6	472.1	30.9	43.8	235.2	236.4
	1946–1970	483.9	502.4	42.6	55.5	235.2	236.4
	1971–1990	349.2	412.7	44.7	57.5	347.5	348.7
	1991–2007	396.2	414.8	46.7	50.9	348.1	349.2
	>2008	397.3		50.3		0.3	

Table A3
Infiltration rate at 50 Pa per type of building and year of construction.

Infiltration rate at 50 Pa [m^3/hm^2]						
		Initial walls				Insulated walls after retrofit
Building type		Freestanding	Semi-detached	Terraced	Apartment	All types
Year of construction	<1945	18	18	14.9	14.9	6
	1946–1970	17.1	16.3	14.1	14.1	6
	1971–2007	12	12	10	10	6
	2008–2012	6.1	6.3	6	6	6
	>2012	2.5				

Table B1
Heating production systems efficiency based on the lower heating values (LHV).

	Construction year	Energy vector SH	Energy vector DHW	Efficiency SH [-]	Efficiency DHW [-]
Centralized heating systems	< 2007	Gas	Gas	0.85	0.85
		Fuel	Fuel	0.8	0.8
		Gas	Electricity	0.85	1
		Fuel	Electricity	0.8	1
		Other	Other	0.8	0.8
	> 2007	Gas	Gas	1	1
		Fuel	Fuel	0.97	0.97
		Gas	Electricity	1	1
		Fuel	Electricity	0.97	1
		Other	Other	0.97	0.97
Decentralized heating systems	/	Electricity	Electricity	1	0.9
		Other	Other	1	1

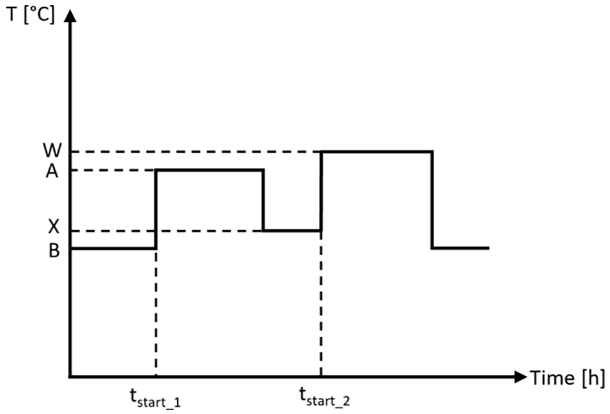

Fig. B1. Heating Schedules - statistical model parameters.

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